Optimization of Irrigation of Wine Grapes with Brackish Water for Managing Soil Salinization

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Abstract: Water scarcity and quality are critical impediments to sustainable crop production. In this study, HYDRUS-2D was calibrated using field measurements of water contents and salinities in the soil under wine grapes irrigated with river water (Rw, 0.32 dS/m). The calibrated model was then used to evaluate the impact of (a) four different water qualities ranging from 0.32 (Rw) to 3.2 dS/m (brackish water, Gw) including blended (Mix) and monthly alternating (Alt) irrigation modes; (b) two rainfall conditions (normal and 20% below normal); and (c) two leaching options (with and without 30 mm spring leaching irrigation) during the 2017–2022 growing seasons. Irrigation water quality greatly impacted root water uptake (RWU) by wine grapes and other water balance components. Irrigation with brackish water reduced average RWU by 18.7% compared to river water. Irrigation with blended water or from alternating water sources reduced RWU by 8.8 and 7%, respectively. Relatively small (2.8–8.2%) average annual drainage (Dr) in different scenarios produced a very low (0.05–0.16) leaching fraction. Modeling scenarios showed a tremendous impact of water quality on the salts build-up in the soil. The average electrical conductivity of the saturated soil extract (ECe) increased three times with Gw irrigation compared to Rw (current practices). Blended and alternate irrigation scenarios showed a 21 and 28% reduction in ECe, respectively, compared to Gw. Irrigation water quality substantially impacted site-specific actual basal (Kcb act) and single (Kc act) crop coefficients of grapevine. Threshold leaching efficiency estimated in terms of the salt mass leached vs. added (LEs; kg/kg) for salinity control (LEs > 1) was achieved with LFs of 0.07, 0.12, 0.12, and 0.15 for the Rw, Mix, Alt, and Gw irrigations, respectively. Applying annual leaching irrigation (30 mm) before bud burst (spring) in the Mix and Alt with Rw and Gw scenarios was found to be the best strategy for managing irrigation-induced salinity in the root zone, lowering the ECe to levels comparable to irrigation with Rw. Modeling scenarios suggested that judicious use of water resources and continuous root zone monitoring could be key for salinity management under adverse climate and low water allocation conditions.

Keywords: grapevine; water quality; water balance; soil salinity; leaching; crop coefficients; drought seasons rainfall; leaf area index; HYDRUS-2D

1. Introduction

Water scarcity is a common occurrence and severely impacts irrigated agriculture in arid and semi-arid regions where rainfall totals are far less than the evapotranspiration demand. This skewed relationship is further widened by rapid population growth, industrialization, and increased living standards that compete directly with irrigated agriculture...
for supplementary water sources [1–3]. Water scarcity is increasing and is expected to become more severe with an unabated rise in greenhouse gas emissions, rising temperatures, frequent droughts, and changing precipitation patterns [4]. A rise in temperatures, for instance, could lead to soil moisture deficits and a growing risk of vegetation desiccation due to increased evapotranspiration [5,6], requiring more irrigation water for crop production [7,8] and reaching yield potentials [9]. Agroecological and economic consequences of climate change are expected to vary widely [10–12], and uncertainty in water availability will remain a crucial factor influencing irrigated agriculture, which already consumes 69% of freshwater resources on the planet [13].

Water allocations for irrigation in the river basins worldwide depend on rainfall, runoff, and resulting flows in the river system. Climate variability and uncertainty in irrigation water allocations can severely impact irrigated crops’ sustainability, including viticulture. For example, in Australia, water allocations for irrigation during the Millennium drought (2002–2009) were severely reduced to as low as 18% of normal allocations, severely affecting the sustainable production and resilience of vineyards and other irrigated crops. Similar conditions of unreliable and limited water availability for irrigation also occur in other arid and semi-arid regions worldwide. Judicious integration of other water sources, such as brackish water, into irrigation schedules would enhance water security and increase the resilience of cropping systems to climate variability, resulting in long-term sustainability and economic viability of irrigated production systems. This additional natural resource is often poorly understood, undervalued, mismanaged, or abused [14].

Irrigation with marginal quality and brackish water has been practiced on various crops with varied impacts on yield and associated environments depending on site-specific climate, soil, water quality, crop sensitivity, and management practices [15–22]. Numerous wine-grape growing regions use groundwater or recycled water of varying quality (0.8–3.5 dS/m) for irrigation [23–26]. Saline/brackish water irrigation with unsuitable management practices can increase soil salinity [21,25–28]. Pitt and Stevens [29] reported that rootzone electrical conductivity of the soil saturation extract (ECe) in the soil under the vine was four times higher than mid-row (1.5 dS/m) in a vineyard that has received long-term groundwater irrigation. Other studies also reported the development of saline and sodic conditions in the soil under grapevines [27,30,31] and other crops [15,18,32–34], which negatively impacts the soil physicochemical conditions and the growth and yield of crops. However, judicious site-specific use of brackish water following appropriate ameliorative management techniques can help reduce the harmful impacts on soils and provide long-term sustainable production of irrigated crops [21].

Grapevine growth, yield, and berry composition are affected to a varied extent by the degree and duration of salinity stress imposed by saline and brackish water irrigation [35]. Adverse impacts of high salinity on grapevines are two-pronged [36]: (a) reduced water uptake due to high osmotic pressure [35,37] and (b) vine mortality induced by high Na+ and Cl− concentrations in the leaves. Numerous studies have reported high Na+ and Cl− concentrations in leaves, juice, and wine [23,25,26,38], depending on the cultivar, rootstock, salt concentrations, and exposure time to saline conditions. High salt concentrations in the wine can exceed maximum residue limits, preventing sales in specific markets and producing adverse sensory outcomes [39]. However, Martinez-Moreno et al. [40,41] reported that deficit irrigation of grapevine with chloride- and sulfate-dominated saline water of 5 dS/m over five years showed an insignificant impact on vine growth and yield. Additionally, the wine received the best sensory scores in well-drained soil, highlighting the importance of drainage for salinity control. They concluded that site-specific soil type, climate, and drainage conditions created a favorable environment for rapid leaching of salts and reduced the detrimental impact on vine performance.

The use of saline water for irrigation can be managed through appropriate leaching of salts from the root zone depending on the level of crop salt tolerance [42]. The traditional irrigation management strategy is to provide extra water so that the ratio of the actual drainage depth to the irrigation depth, i.e., the leaching fraction (LF), satisfies the leach-
ing requirement (LR) [42], maintaining the root zone salinity below the crops’ tolerance threshold. Due to the complexities of the interactions between water, soil, and plant uptake, estimating and matching LF with LR is not always straightforward [43]. The unavailability of good-quality water and the complexity of implementing proper LR strategies for salinity control under drip irrigation systems may lead to enormous amounts of salt deposition in the soils [27,44].

Numerous studies describe multiple approaches to maintain the root zone salinity below the crop threshold, such as (a) the intra/inter-seasonal or physiological stage alternated use of fresh and saline waters for irrigation [26,31,45,46], (b) blending waters from multiple water sources [47–49], and (c) applying additional leaching irrigation if rainfall is insufficient to manage excessive salts [27,43,44,50]. Typically, these options have varied responses for managing the accumulation of salts in the root zone and require site-specific approaches, which are a function of soil type, climate, crop, and the composition of the irrigation water. Complex soil heterogeneity, widespread stratification (as it exists in Australian grapevine growing areas), and poor drainage conditions may further confound the efforts to ward off the salts buildup in the root zone [27,51,52].

Long-term field experiments involving numerous variables under varied soil, water, and climate conditions are expansive and labor-intensive. Mathematical models are excellent, cost-effective tools for studying the impact of climate, soil, water, and crop variables on water and solute transport in the soil [21]. Among available agro-hydrological models, HYDRUS (2D/3D) [53] has been widely used to simulate the water movement and salinity dynamics under drip irrigation [27,54–58]. The model became popular because of its flexibility to accommodate different types of complex boundary conditions, consider root water uptake, and account for the coupled impact of water and salinity stresses and its ease of use due to its user-friendly graphical interface.

The objectives of this investigation are two-pronged, viz., (1) to estimate the water balance components and actual single crop (\(K_{c,act}\)), basal crop (\(K_{cb,act}\)), and evaporation (\(K_e\)) coefficients for improving site-specific irrigation practices; and (2) to optimize the integration of brackish water in the irrigation schedule of wine grapes while managing the root zone salinity for sustainable production. To achieve these objectives, HYDRUS-2D was first calibrated for water balance and salinity dynamics in the soil under wine grapes during one season (2021–22). The calibrated model was then used to evaluate the impact of sixteen scenarios involving two qualities of irrigation water (river water—\(R_w\), \(EC_{iw} = 0.4 \, \text{dS/m}\) and brackish water \(G_w\), \(EC_{iw} = 3.2 \, \text{dS/m}\)); two modes of application [blended \(R_w\) and \(G_w\) in a 1:1 ratio, \(EC_{iw} = 1.87 \, \text{dS/m}\) and monthly alternate use of \(R_w\) and \(G_w\)]; two types of rainfall occurrence [normal (n) and 20% reduced (d) annual rainfall]; and two leaching irrigation options [no leaching irrigation and annual leaching irrigation (l, 30 mm)] over multiple seasons (2017–2022) in heterogeneous soil. Subsequently, the model-predicted water and salt balance components were used to estimate the leaching fractions (LF) and leaching efficiency (LE) under different scenarios. Thus, the assessment of the entire growing system and potential water quality options aims to evaluate the incorporation of brackish water in the wine grapes’ irrigation schedule while controlling soil salinization to maintain sustainable production with effective leaching strategies.

2. Materials and Methods
2.1. Description of the Experimental Site

An experimental site was established at Kimbolton Wines (Lat –35.32681, Long 139.06178) in the Langhorne Creek (LHC) Geographic indication in South Australia, between the Mount Lofty Ranges and Lake Alexandrina in the flood plains of the Angas and Bremer rivers. The Cabernet Sauvignon wine grapes were planted in 2001 on the Teleki 5C rootstock at a spacing of 2 m between vines and 3 m between vine lines. The vineyards were trained on a single wire double cordon spur pruned system. Vineyard rows are oriented in a North-South direction, facilitating better absorption of photosynthetically active radiation. A drip irrigation system was laid out to irrigate the wine grapes, placing
a dripline along the vine line with pressure-compensated emitters spaced at 75 cm with a discharge rate of 2.4 L/h. Irrigation was scheduled based on the estimated soil water regime and local climate conditions in the Langhorne Creek region. Measurements of soil, water, and crop parameters were carried out over the entire growing season (July 2021 to June 2022) as described in the following sections.

Climate data were obtained from the nearest Landscape SA weather station (Langhorne Creek Central). Rainfall during the simulation period (2017–18 to 2021–22) varied from 283 to 504 mm, with an average of 372 mm, which is close to the long-term average rainfall (390 mm) at Langhorne Creek [59]. Most rain events during this period were smaller than 5 mm, which tended to wet the soil surface only and evaporate back into the atmosphere. Above-normal rainfall years potentially generate precipitation surplus during winter months when most rainfall occurs because the LHC region has a Mediterranean climate with hot and dry summers and cool and moist winters. Large rain events (>20 mm) play a key role in regulating the salts in the crop root zone. There were 1, 2, 5, 3, and 0 rain events of >20 mm during the 2017–18, 2018–19, 2019–20, 2020–21, and 2021–22 growing seasons, respectively. Seasonal reference crop evapotranspiration ($ET_0$) values estimated by a modified Penman-Monteith approach [60] varied in a narrow range (1015–1096 mm), showing small year-to-year variation.

2.2. Soil Water and Canopy Growth Measurements

Soil water distributions were monitored using in situ calibrated capacitance probes installed close to an emitter in the vine row by the vineyard manager with sensors every 10 cm to a depth of 120 cm. The soil moisture probe was installed to support irrigation scheduling for the vineyard. Soil solution extractors were installed at 30, 60, and 90 cm depths at two locations in the vine row near the lateral and adjoining the moisture probe. Soil solutions were collected at fortnightly intervals to estimate soil solution electrical conductivity ($EC_{sw}$). Soil solution samples could not be collected during the summer when deficit irrigation was imposed. Alternatively, salinity ($EC$) in the 1:5 soil-to-water solution was measured on soil samples collected from 0–15, 15–30, 30–60, and 60–90 cm soil depths near the extractors during the summer season. These measurements were used to supplement the calibration of the model.

A high-definition (1080 p) time-lapse camera was installed between two vines to monitor the canopy growth (Figure 1a). The camera was located at ground level and orientated upward to ensure that the sky was equally visible on each side of the image. Images were collected during the early morning to avoid overexposure of the image sections by the sun. Collected images were stored on an SD card and emailed using the 4G network so that the camera operations could be confirmed.

![Figure 1: Grapevine canopy images (a,b) taken by an HD camera and (c) leaf area index (LAI) estimated by image analysis.](https://imagej.nih.gov/ij/index.html version 1.53k/Java1.8.0_172; accessed 27 August 2021).

Images were analyzed using the ImageJ software (https://imagej.nih.gov/ij/index.html version 1.53k/Java1.8.0_172; accessed 27 August 2021). The canopy size for the entire growing season was indirectly assessed as the leaf area index (LAI), improving the methodology described in previous studies [61–64]. The algorithm used in these studies...
defines three fractions, which are the fractions of foliage of the projective cover \( (f_f) \), the crown cover \( (f_c) \), and the crown porosity \( (\Phi) \). The field view of the full canopy captured by the image is shown in Figure 1a. However, as the canopy keeps growing, the field view of the canopy eventually outgrows the vertical field view of the camera (Figure 1b). Under such conditions, fractional covers \( (f_f \text{ and } f_c) \) are not estimated correctly using the partial image of the canopy and are usually ignored in the LAI analysis [61]. For such situations, an approximate correction factor for the crown cover can be applied, assuming the \( f_f/f_c \) ratio of the extended canopy is similar to the measurements of the field view by the camera. Therefore, Equation (A3) in [63] can be rewritten as

\[
LAI_M = -f_c \ln \Phi \left( \frac{W_{cci}}{W_c} \right)
\]

where \( W_c \) is the width of the field view of the canopy captured by the camera, \( W_{cci} \) is the maximum width of the canopy measured at the cordon, \( W_c \) is the daily interpolation of width protruding the field view of the camera, and \( LAI_M \) is the measured \( LAI \), which corresponds to the ground area covered by the vertical projection of the foliage and branches [62,63]. \( LAI_M \) was further corrected to obtain the effective \( LAI \) (\( LAI_e \)), as reported in previous studies [61–63]. However, the estimated \( LAI_e \) deviates from the usual definition of grapevine \( LAI \), defined as the ratio of total green surfaces (leaves, shoots, and fruits when present) to the unit of the land area allocated to each vine [65,66]. Therefore, the second correction factor was applied to the \( LAI_e \) to obtain corrected \( LAI \) for the vine spacing (\( LAI_{es} \)) as given below:

\[
LAI_{es} = LAI_e \left( \frac{W_{cc}}{W_r} \right)
\]

where \( W_r \) is the width between vine rows. \( LAI_{es} \) estimated using Equation (2) indicated a continuous canopy growth from bud burst to harvest (Figure 1c). These methodology modifications reduced the average \( LAI_{es} \) of mid to late grapevine season by half of \( LAI_e \), measured using the previous method. The LAI values were comparable to those estimated by the Plant Canopy Analyser (LAI-2200C, LI-COR Biosciences, Lincoln, NE, USA). The \( LAI \) values for other seasons (2017–18 to 2020–21) were estimated from the NDVI drawn from the Datafarming portal (https://www.datafarming.com.au/about-us/(accessed 27 August 2021)). A linear relationship \( (Y = 4.07X; R^2 = 0.83) \) was fitted between NDVI and measured \( LAI \) during the 2021–22 season. This conversion was applied to the NDVI values from the other seasons (2017–18 to 2020–21) for estimating \( LAI \). Similar relationships have been reported for the vineyards across various regions [63] and vineyards in other parts of the globe [67].

The \( LAI \) data and other soil, climate, and plant parameters were used to estimate the daily values of potential evaporation and transpiration following the FAO-56 dual crop coefficient approach [60,68]. These values served as inputs for the numerical model HYDRUS-2D [53], which was used to simulate the water and salinity dynamics in the soil.

2.3. Irrigation Application and Water Quality

The property manager controlled irrigation application decisions at the study site. Irrigations were applied based on the profile’s total available water (TAW) and the capacitance probe data. Profile water availability in the spring is key in initiating irrigation at the start of a new season. In-season irrigations were applied based on the phenological stage of the crop, climate conditions, and water deficit in the soil profile. Irrigation was applied when the stored water in the profile declined to a level lower than the readily available water (Table A1).

In-season irrigation water was collected in a catch can installed at the terminal point of the lateral irrigating vines at the study site. Water samples were collected fortnightly to measure electrical conductivity \( (EC_{iw}) \). The measured \( EC_{iw} \) values during 2021–22 varied from 0.17 to 0.38 dS/m and served as the current irrigation water quality for calibrating the
model. For the rest of the simulated period (2017–21), the daily EC\textsubscript{iw} values of the River Murray water (Rw) measured at the Langhorne Creek pipeline pumping station were used. Estimated EC\textsubscript{iw} values ranged from 0.16 to 0.61 dS/m, lower than the tolerance threshold (0.95 dS/m) of salinity-sensitive crops in Australia and New Zealand [69].

The groundwater quality at the Langhorne Creek Prescribed Groundwater Area is predominantly brackish, with salinity ranging between 300 and 30,000 mg/L [59]. The estimated groundwater salinity (Gw) in the nearest prescribed well used for irrigation remained around 3.2 dS/m, and this value was adopted in the simulations. The rainfall chemistry analyzed by Cresswell et al. [59] in the study region provides reliable information about rainfall salinity (EC\textsubscript{rw}; 0.16 dS/m) used in simulations.

2.4. Estimation of Soil Hydraulic Properties

Soil hydraulic parameters were estimated from water retention curves determined on undisturbed soil samples. These samples were collected in 75 mm diameter and 50 mm tall rings from 0–15, 15–30, 30–50, 50–100, and 100–120 cm soil depths at two locations, representing the site-specific textural heterogeneity. Intact soil rings were first saturated overnight, and then saturated hydraulic conductivity (K\textsubscript{s}) values were measured using the constant head method [70]. Subsequently, the cores were used to measure the saturated water content (\(\theta_s\)) and volumetric water contents (\(\theta\)) at −3 and −6, and −10, −33, −100, −300, and −1500 kPa pressure heads using hanging columns and the pressure plate apparatus, respectively. Measured K\textsubscript{s} and water content (\(\theta\))—pressure head (\(h\)) data of each soil layer were used to estimate the soil hydraulic parameters (SHP) according to the van Genuchten-Mualem model [71]. Estimated SHPs were further finetuned by trial and error during model calibration. The final values used in HYDRUS-2D to simulate water movement in the soil are given in Table 1.

Table 1. Calibrated soil hydraulic properties (\(\theta_r\) = saturated water content, \(\theta_s\) = air dry water content, \(\alpha\) = inverse of air entry value, K\textsubscript{s} = saturated hydraulic conductivity, \(\eta\) = pore size distribution parameter, and \(l\) = pore connectivity parameter) of different textural layers at the Langhorne Creek study site.

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Texture</th>
<th>(\theta_r) cm\textsuperscript{3} cm\textsuperscript{-3}</th>
<th>(\theta_s) cm\textsuperscript{3} cm\textsuperscript{-3}</th>
<th>(A) cm\textsuperscript{-1}</th>
<th>(\eta)</th>
<th>K\textsubscript{s} cm day\textsuperscript{-1}</th>
<th>(l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–15</td>
<td>Sandy Loam</td>
<td>0.041</td>
<td>0.4259</td>
<td>0.0353</td>
<td>1.743</td>
<td>141.238</td>
<td>0.5</td>
</tr>
<tr>
<td>15–30</td>
<td>Sandy Loam</td>
<td>0.053</td>
<td>0.347</td>
<td>0.058</td>
<td>1.774</td>
<td>98.61</td>
<td>0.5</td>
</tr>
<tr>
<td>30–50</td>
<td>Sandy Clay Loam</td>
<td>0.1527</td>
<td>0.3942</td>
<td>0.0339</td>
<td>1.495</td>
<td>10.93</td>
<td>0.5</td>
</tr>
<tr>
<td>50–100</td>
<td>Sandy Loam</td>
<td>0.1044</td>
<td>0.3413</td>
<td>0.0226</td>
<td>1.795</td>
<td>7.75</td>
<td>0.5</td>
</tr>
<tr>
<td>100–120</td>
<td>Sandy Clay Loam</td>
<td>0.1908</td>
<td>0.3731</td>
<td>0.0403</td>
<td>1.363</td>
<td>6.93</td>
<td>0.5</td>
</tr>
</tbody>
</table>

2.5. Estimation of Potential Evaporation and Transpiration

HYDRUS-2D requires daily inputs of potential evaporation (\(E_a\)) and transpiration (\(T_p\)), representing the evaporative flux from the partially wetted soil surface and the transpiration flux via the canopy, respectively. In this study, these parameters were estimated using the FAO Penman-Monteith dual crop coefficient approach [60,68]:

\[
ET_C = (K_{cb} + K_c) ET_0
\]

where \(ET_C\) is evapotranspiration (LT\textsuperscript{-1}), \(ET_0\) is reference evapotranspiration (LT\textsuperscript{-1}), \(K_{cb}\) is the basal crop coefficient, which represents the plant transpiration component, and \(K_c\) is the soil evaporation coefficient. Generic values of the grapevine \(K_{cb}\) [60] were adjusted for the local climate and crop conditions, considering crop height, wind speed, and minimum relative humidity averages. Other crop and soil-related parameters for estimation of \(T_p\) and \(E_a\) using the FAO 56 approach, e.g., readily available water (RAW), total available water (TAW), readily evaporable water (REW), total evaporable water (TEW), and fractions
of wetted and shaded areas \((f_c, f_w)\), were estimated from the measured data as reported in previous studies \([8,72]\). Important climate and other parameters used in FAO-56 for different years are provided in the Appendix A (Figure A1 and Table A1).

### 2.6. Model Construction, and Initial and Boundary Conditions

Brief theoretical details on water movement and solute transport processes in the soil adapted in the model are given in the Appendix A. More information on the HYDRUS-2D software (version 5.02.0530) and related references can be found at https://www.pc-progress.com/en/Default.aspx?HYDRUS-3D (accessed 27 August 2021). A two-dimensional model domain was constructed to represent a vertical cross-section perpendicular to the vine line and equally spaced between mid-rows (Figure 2). The simulated domain was 120 cm deep and 300 cm wide (the row spacing at the field site), perpendicular to a vine row. The transport domain was divided into 13,048 finite elements with a very fine grid below the dripper (0.5 cm) and gradually increasing element sizes laterally (up to 3 cm) and vertically (up to 10 cm) from the dripper. Surface drip irrigation was simulated assuming an infinite line source, which was shown previously to be a good representation of the drip irrigation system \([44,73]\).

![Figure 2. Model domain showing field observation setup (camera, moisture probe, and solution extractor), soil textures, and imposed boundary conditions.](image)

Different textural layers (see different colors in Figure 2) were assigned to the domain depending on the measured depths of textural layers at the study site. A drip line runs along the vine line, and irrigation water is applied through the drippers placed on the soil surface. Measured values of the initial water content and soil solution salinity in different textural layers were used as initial conditions for water flow and solute transport in the soil. The soil surface was subjected to the atmospheric boundary condition (BC) and a variable flux BC imposed by dripper discharge (2.3 L/h), resulting in a two-dimensional flow. A free drainage boundary condition was assigned at the bottom, while a no-flow boundary condition was imposed on the sides of the domain. Concentration flux conditions were set as top and bottom boundary conditions for solute transport. Initial conditions reflected the effects of rainfall, irrigation, evaporation, and transpiration on soil salinity before the start of the experiment.

Root water extraction from the soil was computed using the macroscopic model approach \([74]\). This model adjusts plant root water uptake according to the local soil water
pressure head, \( h \), at any point in the root zone. It defines how potential transpiration (\( T_p \)) is reduced when the soil can no longer supply the plant’s required water under the prevailing climatic conditions. Values of critical pressure heads for grapevine were taken from previous investigations in South Australia \([8,72]\). The multiplicative model for osmotic pressure head reductions is considered in this study. The model states that water is extracted at the maximum rate below the crop threshold osmotic head (\( EC_e = 2.1 \text{ dS/m} \)). The slope of the curve determines the fractional reduction of water uptake per unit increase in the osmotic head (12.8% / \( EC_e \) unit) beyond the threshold. These parameters for grapevine were obtained from previous regional salinity tolerance studies \([75]\).

Soil solution salinity (\( EC_{sw} \)) was simulated as a non-reactive solute, similarly as in many previous studies \([57,72,76]\). These studies showed good correspondence between model predictions and observed soil salinity dynamics in the soil under conditions involving intensive irrigation and fertigation environments. Other solute transport parameters, such as longitudinal and transverse dispersivities, initially assumed to be one-tenth of the modeling domain size and one-tenth of the longitudinal dispersivity, respectively \([77]\), were optimized during the calibration.

Model calibration was performed to optimize the soil hydraulic and solute transport parameters in the soil to mimic the field conditions over the entire growing season. Subsequently, a calibrated model was used to simulate the soil’s water balance and salinity dynamics under different climate and water quality scenarios.

2.7. Water Quality and Water Management Scenarios

Different scenarios were designed to assess the impact of using two water sources on seasonal evapotranspiration components and salinity dynamics. Water qualities (\( EC_{iw} \)) of the two sources were involved in various scenarios. For the drought season scenario, a rainfall reduction of 20% was assumed, which matches the future climate projections for South Australia \([78]\). An annual leaching irrigation (\( l \)) of 30 mm of \( Rw \) was incorporated in various scenarios based on the historical salinity issues in the Langhorne Creek area and a previous leaching study \([79]\). Sixteen scenarios were designed to evaluate the impact of various quantities and qualities of irrigation water and their use in different application modes, such as mixing \( Rw \) and \( Gw \) in a 1:1 ratio (\( Mix \)) and alternate monthly use (\( Alt \)) of \( Rw \) and \( Gw \) (Table 2).

### Table 2. Scenarios involving combinations of different water qualities (\( Rw = \text{river water}, \ Gw = \text{brackish water}, \ Mix = \text{mixed} \ Rw \text{ and } Gw \text{ in a 1:1 ratio}, \ Alt = \text{a monthly alternate use of} \ Rw \text{ and } Gw \), the amount of annual rainfall (normal, \( n \); and 20% less, \( d \)); and annual pre-season leaching irrigation (\( LI \)) of 30 mm simulated over the five consecutive grapevine growing seasons (2017–22).

<table>
<thead>
<tr>
<th>Water Quality</th>
<th>Normal Rainfall (n)</th>
<th>Drought Season (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Leaching</td>
<td>Leaching Irrigation (l)</td>
</tr>
<tr>
<td>River water (( Rw ))</td>
<td>( Rw_n )</td>
<td>( Rw_nl )</td>
</tr>
<tr>
<td>Brackish water (( Gw ))</td>
<td>( Gw_n )</td>
<td>( Gw_nl )</td>
</tr>
<tr>
<td>Mixing ( Rw ) and ( Gw )</td>
<td>( Mix_n )</td>
<td>( Mix_nl )</td>
</tr>
<tr>
<td>Alternate use of ( Rw ) and ( Gw )</td>
<td>( Alt_n )</td>
<td>( Alt_nl )</td>
</tr>
</tbody>
</table>

The calibrated model was used to understand the impact of different scenarios (Table 2) on the soil’s water balance and salinity dynamics over the five seasons (2017–18 to 2021–22), using the growers’ actual irrigation schedule.

2.8. Statistical Analysis

Model-simulated (\( S \)) spatiotemporal water content distributions and \( EC_{sw} \) values were compared with corresponding measured (\( M \)) values using three error statistics, i.e., mean error (\( ME \)), mean absolute errors (\( MAE \)), and root mean square error (\( RMSE \)). Relevant
equations for the error statistics can be found in [80]. The two-sided Dunnett’s analysis test (XLSTAT) was applied to compare the differences in the average values of water balance components, namely, actual evapotranspiration (\(ET_{C\text{ act}}\)), root water uptake (RWU) or actual transpiration (\(T_{p\text{ act}}\)), soil evaporation (\(E_s\)), and deep drainage (\(D_r\)); leaching fractions (\(LF\)); and rootzone soil salinities (\(EC_e\)) obtained for the current irrigation practice and different water quality, drought, season, and leaching irrigation scenarios at a 95% confidence interval.

3. Results and Discussion

3.1. Model Calibration

HYDRUS-2D was calibrated for spatiotemporal water content distribution and salinity dynamics in the soil over the entire grapevine growing season (2021–22). Statistical errors (\(RMSE\), \(ME\), \(MAE\)) estimated for water content and salinity dynamics in the soil are shown in Table 3. \(RMSE\), \(ME\), and \(MAE\) values at different depths varied from 0.02 to 0.05, 0.00 to 0.05, and 0.02 to 0.05 cm\(^3\)/cm\(^3\), respectively, showing slightly higher deviations at the soil surface than deeper in the soil profile. The average values for the entire profile varied in a much narrower range (0.02–0.04 cm\(^3\)/cm\(^3\)), showing a good agreement between measured and model-predicted water contents in the soil (Table 3). Similar error estimates between measured and modeled values have been reported in several studies in different soils, crops, and climate conditions [54,57,72,81,82]. It is well understood that soil water contents measured with sensors such as capacitance probes are not error-free. The magnitude of error estimates observed in the current study is equivalent to those often seen in the field measurements with capacitance probes [83].

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Water Content (cm(^3)/cm(^3))</th>
<th>(EC_{sw}) (dS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 cm</td>
<td>40 cm</td>
</tr>
<tr>
<td>(RMSE)</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>(ME/MBE)</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>(MAE)</td>
<td>0.04</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The profile-averaged values of \(RMSE\), \(ME\), and \(MAE\) for soil solution salinity (\(EC_{sw}\)) were 0.61, −0.13, and 0.42 dS/m, respectively (Table 3). Chen et al. [54] reported \(RMSE\) and \(MAE\) values ranging between 0.23 and 0.55 dS/m, respectively, while Phogat et al. [84] reported error estimates between 0.35 and 0.86 dS/m for the measured and HYDRUS-2D predicted soil salinities. Similarly, Ramos et al. [57] estimated \(ME\), \(MAE\), and \(RMSE\) in the range of −0.21 to −0.67, 0.6 to 1.25, and 0.85 to 1.76 dS/m, respectively, for similar calibration of HYDRUS-2D for the salinity distribution in the soil. There are varied reasons for the disparity between measured and model-predicted \(EC_{sw}\) values, such as measurement errors in the model input parameters, soil solution collection, and measurement errors. Phogat et al. [85] pointed out that the estimation of \(EC_{sw}\) of the soil solution extracted from the soil under suction (a region of an uncertain size) may vary from \(EC_{sw}\) simulated by the model at a specific point in the soil. The statistical comparison supports the ability of the model to simulate the distribution of water content and salinity dynamics in the soil.

3.2. Soil Water Balance

Average annual rainfall (\(P\)) and seasonal irrigation (\(I\)) applied during drought season (\(d\)) and leaching irrigation (\(l\)) scenarios differed significantly from the current irrigation practices (the \(n\) scenarios) (Table 4). This means that assumed drought season conditions and ameliorative salt management strategies have been appropriately applied. The average values of wine grape \(ET_{C\text{ act}}\) estimated for the scenarios where leaching irrigation is applied (\(Gw_{nl}, Alt_{nl}, \text{and Mix}_{nl}\)) showed insignificant differences compared to the
current practice (river water, $Rw_n$). It implies that integration of leaching irrigation ($l$) in the current irrigation schedule ($n$) in the brackish water ($Gw_l$), 1:1 blending ($Mix_l$), and monthly alternating ($Alt_l$) of river and brackish water irrigations can reduce the salt pressure in the root zone and provide a soil environment similar to the current practice. The blending and alternate mode scenarios without leaching irrigation also showed $ET_{C_{act}}$ values comparable to current practices.

Table 4. Components of the annual water balance ($P = \text{precipitation/rainfall}, I = \text{irrigation, RWU = root water uptake, } Es = \text{evaporation, and } Dr = \text{drainage}, \text{leaching fraction (LF), and average rootzone salinity (EC}_e, \text{dS/m)}$ estimated for different irrigation scenarios including the current irrigation practice ($Rw_n$). Statistical significance was estimated using Duncan’s two-sided analysis of the difference between $Rw_n$ (control) and other scenarios at a 95% confidence interval.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>$P$ (mm)</th>
<th>$I$ (mm)</th>
<th>$ET_{C_{act}}$ (%)</th>
<th>RWU (mm)</th>
<th>$Es$ (mm)</th>
<th>$Dr$ (mm)</th>
<th>LF</th>
<th>$EC_e$ (dS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Rw_n$</td>
<td>373</td>
<td>209</td>
<td>424</td>
<td>218</td>
<td>206</td>
<td>39</td>
<td>0.07</td>
<td>2.2</td>
</tr>
<tr>
<td>$Rw_d$</td>
<td>299 *</td>
<td>209</td>
<td>382 *</td>
<td>201</td>
<td>181 *</td>
<td>15 *</td>
<td>0.03 *</td>
<td>2.7</td>
</tr>
<tr>
<td>$Rw_nl$</td>
<td>373</td>
<td>237 *</td>
<td>438</td>
<td>223</td>
<td>216 *</td>
<td>53</td>
<td>0.09</td>
<td>1.6</td>
</tr>
<tr>
<td>$Rw_dl$</td>
<td>299 *</td>
<td>237 *</td>
<td>401</td>
<td>210</td>
<td>192 *</td>
<td>26</td>
<td>0.05</td>
<td>2.2</td>
</tr>
<tr>
<td>$Gw_n$</td>
<td>374</td>
<td>209</td>
<td>409</td>
<td>177 *</td>
<td>232 *</td>
<td>53</td>
<td>0.09</td>
<td>4.5 *</td>
</tr>
<tr>
<td>$Gw_d$</td>
<td>299 *</td>
<td>209</td>
<td>366 *</td>
<td>154 *</td>
<td>213</td>
<td>31</td>
<td>0.06</td>
<td>5.5 *</td>
</tr>
<tr>
<td>$Gw_nl$</td>
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<td>237 *</td>
<td>426</td>
<td>218</td>
<td>216 *</td>
<td>53</td>
<td>0.09</td>
<td>3.9 *</td>
</tr>
<tr>
<td>$Gw_dl$</td>
<td>299 *</td>
<td>237 *</td>
<td>401</td>
<td>210</td>
<td>192 *</td>
<td>26</td>
<td>0.05</td>
<td>2.2</td>
</tr>
<tr>
<td>$Mix_n$</td>
<td>374</td>
<td>209</td>
<td>417</td>
<td>198 *</td>
<td>219 *</td>
<td>45</td>
<td>0.07</td>
<td>3.6 *</td>
</tr>
<tr>
<td>$Mix_d$</td>
<td>299 *</td>
<td>209</td>
<td>375 *</td>
<td>177 *</td>
<td>197 *</td>
<td>22</td>
<td>0.04</td>
<td>4.3 *</td>
</tr>
<tr>
<td>$Mix_nl$</td>
<td>374</td>
<td>237 *</td>
<td>434</td>
<td>208</td>
<td>226 *</td>
<td>53</td>
<td>0.09</td>
<td>2.9</td>
</tr>
<tr>
<td>$Mix_dl$</td>
<td>299 *</td>
<td>237 *</td>
<td>395</td>
<td>190 *</td>
<td>205</td>
<td>31</td>
<td>0.06</td>
<td>3.8 *</td>
</tr>
<tr>
<td>$Alt_n$</td>
<td>374</td>
<td>209</td>
<td>418</td>
<td>202 *</td>
<td>216 *</td>
<td>44</td>
<td>0.08</td>
<td>3.2</td>
</tr>
<tr>
<td>$Alt_d$</td>
<td>299 *</td>
<td>209</td>
<td>376 *</td>
<td>183 *</td>
<td>193 *</td>
<td>21</td>
<td>0.05</td>
<td>3.9 *</td>
</tr>
<tr>
<td>$Alt_nl$</td>
<td>374</td>
<td>237 *</td>
<td>434</td>
<td>210</td>
<td>224 *</td>
<td>57</td>
<td>0.09</td>
<td>2.6</td>
</tr>
<tr>
<td>$Alt_dl$</td>
<td>299 *</td>
<td>237 *</td>
<td>396</td>
<td>194 *</td>
<td>202</td>
<td>30</td>
<td>0.06</td>
<td>3.4</td>
</tr>
<tr>
<td>CD (0.05)</td>
<td>16.5</td>
<td>0.005</td>
<td>13.5</td>
<td>16.3</td>
<td>8.9</td>
<td>19</td>
<td>0.03</td>
<td>1.3</td>
</tr>
</tbody>
</table>

* Statistically significant at a $p$-value of 0.05. Irrigations with river water ($Rw$, 0.32 dS/m) under normal ($n$) rain ($Rw_n$), brackish water ($Gw$, 3.2 dS/m) under normal rain ($Gw_n$), a blend of $Rw$ and $Gw$ in a 1:1 ratio under normal rain ($Mix_n$), monthly alternate use of $Rw$ and $Gw$ under normal rain ($Alt_n$), $Rw + 20\%$ less rain ($Rw_d$), $Gw + 20\%$ less rain ($Gw_d$), $Mix + 20\%$ less rain ($Mix_d$), $Alt + 20\%$ less rain ($Alt_d$), $Rw_n + annual\ leaching\ irrigation\ of\ 30\ mm\ before\ bud\ burst$ ($Rw_nl$), $Gw_nl$, $Mix_nl$, $Alt_nl$, $Rw_dl$, $Gw_dl$, $Mix_dl$, and $Alt_dl$.

Seasonal vine water uptake (RWU) accounts for 40–51% (154–223 mm) of the total water application, including irrigation and rainfall during the growing season (Table 4). The maximum water uptake was predicted for the $Rw_nl$ scenario, representing the most favorable conditions for grapevine growth, i.e., river water irrigation coupled with annual leaching irrigation ($l$) of 30 mm before the bud burst. The simulated daily water balance responded to the diurnal changes in the weather conditions, irrigation, canopy characteristics, soil water regime, and osmotic conditions in the soil (Figure 3). Actual daily root water uptake (RWU) of grapevines under current practices ($Rw_n$) varied between 0.02 and 3.4 mm during the simulation. Note that higher RWU values were observed over the December to March period, which coincides with the maximum canopy size and LAI (Figure 1). Numerous studies have reported that transpiration in crops without full ground cover, such as grapevine (an energy surplus system), responds to the canopy size, ground cover, leaf area index [86–88], and canopy density [68,89,90] under non-saline conditions.

Rootzone salinity ($EC_e$) is an important factor affecting $ET_{C_{act}}$ and RWU ($TP_{act}$) of grapevines. Both parameters decreased linearly in response to rootzone salinity. However, the impact of $EC_e$ was more pronounced for RWU, which decreased by 6.8% ($R^2 = 0.96$) for a unit increase in the rootzone $EC_e$ (dS/m). The impact of salinity on $ET_{C_{act}}$ decreased to less than half ($3.1\%, R^2 = 0.42$) as the surface evaporation component increased under brackish water irrigation. Ben-Asher et al. [91] reported a 20 and 65% reduction in potential
vine transpiration for 1.8 and 4.8 dS/m saline water irrigation. Such a drastic reduction in vine transpiration occurred due to 4 times higher irrigation applications in different climatic conditions. A linear reduction in $ET_c$ in response to saline water irrigation and rootzone salinity was reported by many [50,92–95].

![Figure 3](image_url)

**Figure 3.** Model-predicted daily values of precipitation ($P$), irrigation ($I$), root water uptake (RWU), evaporation ($Es$), and drainage ($Dr$) below the root zone (120 cm) of a grapevine irrigated with river water under normal rainfall conditions ($Rw_n$; current practice) during 2017 to 2022.

Water quality and water stress impacted the seasonal water balance components. The minimum RWU was observed in the $Gw_d$ scenario, where brackish water of 3.2 dS/m was used for irrigation coupled with 20% less rain (drought season, $d$), representing an adverse soil environment for grapevine growth. Average seasonal RWU under the brackish, blending, and alternate mode scenarios showed significant differences compared to the current practices ($Rw_n$), except in the alternate mode with leaching irrigation ($Alt_nl$) and 1:1 blending ($Mix_nl$) scenarios (Table 4). This suggests that brackish water irrigation in the blending ($Mix$) and alternate ($Alt$) modes could be a viable irrigation strategy if appropriate leaching of salts from the root zone is maintained with annual leaching irrigation of 30 mm before the bud burst. The $Alt$ scenarios, where the application of $Rw$ and $Gw$ is alternated, performed better in terms of greater RWU than the mixing scenarios ($Mix$), where the two water sources were blended before irrigation. The average seasonal RWU for the $Gw$, $Mix$, and $Alt$ irrigation scenarios was reduced by 18.7, 8.8, and 7.0%, respectively, compared to $Rw$ irrigation. Although the mixing and alternate modes of irrigation applications improved vine water uptake over $Gw$ alone, the impact of salts was still visible compared to $Rw$ irrigation. The reduction in RWU in the $Gw$ and other scenarios can be ascribed to the osmotic stress in the root zone due to salt buildup in the soil, which reduces the ability of vine roots to extract water from the soil [96]. Ben-Asher et al. [65] reported a significant impact of saline water (4.8 dS/m) irrigation on the seasonal transpiration of grapevines. Irrigation with saline water not only induced an osmotic effect on the roots but also severely impacted the green area index, gaseous exchange processes, and photosynthetic activity in the leaves.

Seasonal evaporation losses ($Es$) accounted for 46–56% of the water applied, including rainfall during the growing season (Table 4). Significant differences in $Es$ were observed in all scenarios relative to $Rw_n$, except for $Gw_d$, $Mix_d$, and $Alt_d$. Leaching irrigation ($l$) scenarios enhanced $Es$ losses as 30 mm irrigation was applied in spring when a large portion of the soil surface was exposed. In the $Gw$, $Mix$, and $Alt$ scenarios, a reduction in RWU due to osmotic stress allowed for an increased $Es$ flux from the soil surface. Under reduced rainfall conditions (20% less), $Es$ decreased significantly compared to $Rw_n$, although drought season scenarios with leaching irrigation ($l$) promoted surface water evaporation similar to $Rw_n$. Daily evaporation ($Es$) losses across different scenarios ranged between 0.01 and 5.6 mm (Figure 3), and high $Es$ losses were observed during spring (August–September) to mid-summer (December–January). During the early growing period of
crops with partial ground cover, such as grapevines, post-winter moist soil water regimes provide favorable soil surface conditions for evaporation losses. On the other hand, during mid-summer (December–January), the hot and dry season encourages high $E_s$ losses.

Seasonal $E_s$ losses of a similar extent in the current study have been reported in other studies in surface and subsurface drip-irrigated grapevines with similar spacing and climate [72, 97]. In contrast, Fandiño et al. [98] reported an $E_s$ component comprising 8–15% of $ET$ under different climate conditions due to using a low wetted fraction (0.01) in their estimation. In sparse vegetation such as grapevine, evaporation often constitutes a large fraction of $ET$ due to the considerable area between the mid-rows exposed to the atmosphere [99].

Modeled average seasonal drainage ($D_r$) was remarkably low and varied from 2.8 to 8.2% of the total water application in different scenarios (Table 4). The lowest $D_r$ value was observed in the $Rw_d$ scenario, while the maximum $D_r$ was recorded in the $Gw_nl$ scenario. These scenarios significantly differed from the current practice ($Rw_n$) and showed the impact of drought season and annual leaching irrigation, respectively (Table 4). Low $D_r$ values cannot leach the rootzone salts and favor the deposition of salts in the soil during the growing season. Daily values of $D_r$ below the root zone (120 cm) varied in response to rainfall, irrigation, and leaching conditions during 2017–22 (Figure 4). Daily $D_r$ varied from 0 to 1.2 mm and represented a negligible volume of leaching below the root zone over the low rainfall period (November 2017 to November 2019). Winter (June–August) rainfall during 2017 was also much lower (112 mm) than the long-term average (160 mm) in the study area [59]. The extent of winter rainfall plays a crucial role in generating the bottom flux below the root zone, which triggers the leaching of salts and maintains a favorable environment in the soil for water uptake. During the following two vintages (2017–18 and 2018–19), there was an extended period of below-average winter rainfall during late spring, when no leaching occurred (Figure 4). Therefore, most rain and irrigation events during this period were unable to generate drainage surplus below the root zone. This resulted in the rapid accumulation of salts in the root zone, which could impact the normal growth and yield of the vineyard.

Three major leaching events occurred below the root zone over the simulation period from 2017–18 to 2021–22 (Figure 4). These were related to above-average annual rainfall and large rain events during late 2019–20 and throughout 2020–21; this triggered the rapid flushing of salts from the root zone and restored soil conditions. Phogat et al. [85] found that profile establishment is an essential management strategy early in the season to facilitate a
favorable environment for root development, canopy growth, and profitable horticultural production in Mediterranean climates. The vineyards in the study region rely heavily on winter rainfall and flood events in the rain-induced local river catchments to flush the salts accumulated in the soil profile [100]. Therefore, to enhance the drainage volume, leaching irrigations play an important role in managing the accumulation of salts in the root zone, reducing the impact of osmotic stress, and providing a congenial medium for plant growth.

### 3.3. Crop Coefficients

The model predicted daily values of $T_{p \text{act}}, E_s$, and $ET_{C \text{act}}$ for different scenarios were used to compute the monthly actual basal crop coefficients ($K_{cb \text{act}}$), evaporation coefficients ($K_e$), and actual single crop coefficients ($K_{c \text{act}}$) of wine grapes under current irrigation practices ($R_{w \text{n}}$) over the five seasons (Figure 5). The $K_{c \text{act}}$ values during the initial period ($K_{c \text{act ini}}$) in the current study varied from 0.33 to 0.84 and showed a large variation between growing seasons (Figure 5b). A comparison of average values of $K_{c \text{act ini}}$ (0.56) and $K_{cb \text{act ini}}$ (0.13) (average of September and October) showed a much higher contribution of evaporation during this period, which corresponds to the bud burst and initial canopy development. Normally, high $K_{c \text{act ini}}$ values and seasonal fluctuations largely reflect the variability in winter rainfall. For example, monthly rainfall of 61 and 65 mm during September and October 2020 (compared to 12 and 9 mm during 2018–19) resulted in a doubling of $K_{c \text{act ini}}$. A high value of $K_{c \text{act ini}}$ (0.33) was also reported by Silva et al. [101]. The maximum $K_{c \text{act}}$ (0.58) and $K_{cb \text{act}}$ (0.33) were recorded during November-December, which coincides with the maximum canopy size [102].

During the mid-season (November-February), large variations were recorded in the $K_{c \text{act mid}}$ values (0.23–0.73). The $K_{cb \text{act}}$ values for the mid-season ($K_{cb \text{act mid}}$) varied from 0.23 to 0.44, with a mean value of 0.31, much lower than the average $K_{cb \text{mid}}$ (0.6) adjusted for the study site under the prevailing climatic conditions. This indicates that grapevines were irrigated at an almost 50% deficit level. Yunusa et al. [97] and Cancela et al. [103] reported similar $K_{c \text{act}}$ values during the mid-season to the current study. The mean value of $K_{c \text{act}}$ during the post-harvest period ($K_{c \text{act end}}$) was, on average, 0.36, although higher in April (0.43). The end season $K_{cb \text{act}}$ ($K_{cb \text{act end}}$) ranged from 0.02 to 0.51 (average 0.21) and showed immense variability depending on post-harvest irrigation and soil water regime. The average $K_{cb \text{act end}}$ is less than half of the corresponding adjusted value (0.48), indicating deficit moisture regimes adopted by the growers. Very low values of $K_{cb \text{act end}}$ (0.02–0.04) for the 2017–18 and 2018–19 seasons represent extreme moisture-deficit conditions during that period (Figure 5). Significant seasonal fluctuations in the crop coefficients suggest that irrigation decisions made based on the same/standard $K_e$ values across seasons may lead
to under- or over-irrigation, affecting the grapevine growth, yield, and efficiency of the irrigation system.

Irrigation water quality had a drastic impact on the crop coefficients. Mean $K_{cb\text{ ini}}$ values for the $Gw$ irrigation were reduced by 7–21% compared to the corresponding values for the $Rw$ irrigation (Figure 6). The maximum reduction was observed for the drought ($d$) scenario, whereas the $Gw$ irrigation with additional annual leaching irrigation (30 mm) showed the lowest impact. The $K_{cb\text{ mid}}$ for the $Gw$ irrigation was reduced by 19, 23, 16, and 20% for the normal rain ($n$), drought ($d$), $l$ with normal rain ($nl$), and $l$ with drought ($dl$) scenarios, respectively, compared to the respective $K_{cb\text{ mid}}$ for the $Rw$ scenario (Figure 6b). A similar reduction pattern (19–27%) in the $K_{cb\text{ end}}$ values was observed for the $Gw$ irrigation and $K_{cb\text{ act}}$ values with other irrigation water quality scenarios ($Mix$ and $Alt$). The $K_{cb\text{ ini}}$, $K_{cb\text{ mid}}$, and $K_{cb\text{ end}}$ for the $Mix$ and $Alt$ water qualities decreased by 4–12, 7–11, 8–14% and 2–7, 5–8, 8–15%, respectively, compared to the respective values for the $Rw$ irrigation (Figure 6c,d). The reduction in the $K_{cb\text{ act}}$ values corresponds to the extent of the impact of rootzone salinity on RWU by the grapevine, which deviates from the standard conditions [60]. Rosa et al. [104] reported similar responses on the $K_{cb\text{ act}}$ for maize under saline conditions.

A wide range of $K_c\text{ act}$ and $K_{cb\text{ act}}$ values of grapevines have been reported in many studies reviewed by Rallo et al. [90]. These studies have shown that site-specific growing conditions, including climate, cultivar, training system, ground cover, crop management, and soil conditions, impact evapotranspiration and crop coefficients of grapevines. Timing, variability, and extent of these factors lower the generic crop coefficient values [60,68] estimated by different methods [101,105,106]. Darouich et al. [107] evaluated the crop coefficients of grapevines at three locations in Italy and Portugal using the SIMDualKc model based on FAO-56 [60]. In their study, low values of $K_{cb\text{ ini}}$ (0.09–0.14), $K_{cb\text{ mid}}$ (0.27–0.4), and $K_{cb\text{ end}}$ (0.17–0.32) emphasized the impact of site-specific climate, soil, cultivars, and management conditions. In contrast, some studies [108–110] reported high $K_c\text{ mid}$ values (0.8–1.31). Normally, such deviations in crop coefficients from the generic values occur due to variable crop conditions due to insufficient or non-uniform irrigation, variable plant density and canopy cover, soil salinity, and/or agronomic management [111].

A wide variation was observed in the evaporation coefficient ($K_e$) estimated for the current practice ($Rw$) over the five seasons (Figure 6c). During the initial growth period under the current practice ($Rw_n$), large $K_e$ values were recorded (0.23–0.70) because a large portion of the soil surface was wetted by irrigation and rainfall was exposed to the
atmospheric evaporative flux. However, the $K_e$ values during the mid-season declined (0.09–0.41; average 0.2) in response to a reduced fraction of the wetted and exposed surface Phogat [112]. $K_e$ towards the end of the season was only 0.15, except after the post-harvest irrigation, when it slightly increased (0.2) during April.

### 3.4. Salinity Dynamics in Soils

The spatial distributions of $EC_e$ in the soil under the $Rw_n$ irrigation scenarios were compared at four phenostages of grapevines, i.e., bud burst, flowering, veraison, and harvest (Figure 7). At bud burst, $EC_e$ in the upper 40–50 cm of the soil was <1.5 dS/m, except during the 2018–19 season, which received below-normal rainfall. Without appropriate leaching, pockets of $EC_e$ in the 1.5–3 dS/m range developed in the surface soil alongside the vine row. At deeper depths, $EC_e$ usually varied in the 1.5–3 dS/m range, but some pockets of $EC_e$ in the 3–7 dS/m range were observed. Such variation in $EC_e$ in the soil profile is normal as salt concentrations dynamically vary in space and time in response to irrigation, rainfall, evaporation, and transpiration. Similar salt distributions were observed until flowering/full bloom, which provided favorable conditions for growth and good vine health during the initial stages of development sensitive to salinity.

**Figure 7.** Spatiotemporal prediction of salinity dynamics ($EC_e$) in the soil under river water ($Rw$) irrigation at indicated dates (31 August—bud burst, 31 October—flowering, 31 January—veraison, and 30 April—harvest) during (a) 2017–18, (b) 2018–19, (c) 2019–20, (d) 2020–21, and (e) 2021–22 under a grapevine.

At veraison, the soil region with an $EC_e$ of 1.5–3 dS/m expanded, and pockets of much higher $EC_e$ (3–5 and 5–7.5 dS/m) also developed, especially during 2018–19 and 2019–20. These high salinity zones expanded further during the veraison to harvest period (February–April). During this stage, regulated deficit irrigation was applied to enhance the wine quality traits [113,114]. The imposition of deficit conditions results in the upward movement of water and salts in the soil in response to evaporative fluxes at the soil surface and transpiration fluxes from the root zone. This phenomenon (capillary rise) increases $EC_e$ in the region below the tree line compared to the mid-row region. Numerous studies reported similar observations under varied climate, cultivar, and irrigation conditions [28,31]. The salts deposited in the root zone need to be leached deeper into the soil before the start of the next growing season. Therefore, winter rainfall during the dormant stage plays a critical role in managing irrigation-induced salt accumulation in the soil.

The brackish water ($Gw$) irrigation scenario resulted in a rapid increase in $EC_e$ in the soil (Figure 8). At harvest in the 2017–18 season, $EC_e$ in the soil varied between 3
and 25 dS/m. These pockets of high salinity were normally observed in the upper soil layer (0–40 cm) away from the drip line as the lateral wetting front pushed the salts outward from the vine row [44]. Although subsequent winter rain in the following season (2018–19) reduced the high salinity regions, $EC_e$ remained very high at the time of bud burst and increased continuously during the growing season. In the subsequent seasons (2019–22), high $EC_e$ regions further expanded as there was limited rainfall to aid leaching, and more salts were added through irrigation. Eventually, a large region of high salinity (7.5–25 dS/m) developed during the five years of irrigation with Gw, which could impact the sustainability of irrigated vineyards. High soil salinity due to brackish water irrigation of grapevines has been previously reported in the study region [27,79] and other parts of the world under similar climates [36]. These results suggest that grapevine irrigation with Gw is unsustainable and would result in a rapid salt buildup in the soils. Spatiotemporal $EC_e$ distributions in other scenarios are expected to vary between the two extreme examples of irrigation water quality (Figures 6 and 7).

Figure 8. Spatiotemporal prediction of salinity dynamics ($EC_e$) in the soil under brackish water (Gw) irrigation at indicated dates during (a) 2017–18, (b) 2018–19, (c) 2019–20, (d) 2020–21, and (e) 2021–22 under a grapevine.

The model-predicted average daily rootzone salinity ($EC_e$) distributions for the 16 scenarios from 2017 to 2022 are compared in Figure 9. The data showed that the $EC_e$ values remained close to or lower than the tolerance threshold for the river water (Rw) irrigated scenarios except for reduced rainfall (Rw_d) where the salinity was slightly higher due to a rapid reduction in the drainage component. Alternating Rw and Gw irrigations (Alt_nl) and blending Rw and Gw in a 1:1 ratio (Mix_nl) with leaching irrigation scenarios showed rootzone $EC_e$ comparable to the Rw irrigation. These results suggest that these scenarios are promising approaches for the adaptation to drought seasons or low water allocations from the river. In all other scenarios, rootzone $EC_e$ increased consistently with time until April 2020. Thereafter, $EC_e$ decreased in response to good winter rainfall and a couple of large rain events (30 and 61 mm) occurring in April 2020, which generated intense leaching, pushing the salts deeper into the soil. Salinity ($EC_e$) increased again during the post-2021 vintage and then decreased gradually during the post-spring season (October 2021). These troughs and peaks in the rootzone salinity are normal occurrences and reflect the extent of leaching triggered by winter rainfall and irrigation. Normally, troughs contribute significantly to salt leaching below the root zone and help reduce the salinity to a great extent. Thus, spatiotemporal salinity dynamics in different scenarios represent a dynamic system that needs constant monitoring and appraisal of drainage, leaching, and soil degradation.
Figure 9. Model predicted average daily rootzone salinity ($EC_e$) in the soil under a grapevine irrigated with different water qualities and reduced rainfall scenarios ($Rw =$ river water, $Gw =$ brackish water, $Alt =$ an alternate application of river and brackish water, $Mix =$ mixing river and brackish water in a 1:1 proportion, $n =$ normal rainfall, $d =$ 20% less rainfall, and $l =$ 30 mm annual leaching irrigation) during 2017–22. The red dotted line shows the threshold $EC_e$ (2.1 dS/m) for the grapevine salinity tolerance.

The daily average $EC_e$ values predicted by the model for different scenarios are box-plotted in Figure 10. All scenarios with $Rw$ irrigation ($Rw_n$, $Rw_nl$, $Rw_d$, and $Rw_dl$) and alternate mode irrigation ($Alt_n$) showed median rootzone $EC_e$ values close to the grapevine tolerance threshold. Rootzone salinity ($EC_e$) under all $Gw$, $Mix$, and $Alt$ scenarios under drought season ($d$) showed significantly higher values than $Rw_n$ (current practice). The average $EC_e$ under the brackish water ($Gw$) irrigation with reduced rain ($Gw_d$) increased three times relative to $Rw_n$. The $Mix$ and $Alt$ scenarios with reduced rainfall (drought season) also resulted in salt concentrations higher than the grapevine tolerance threshold. This indicates increased exposure of grapevine roots to high osmotic pressure, which may restrict plant uptake. Ben-Asher et al. [65] observed a four-fold increase in the rootzone salinity (from 2 to 8 dS/m) in sandy loam soil with an $EC_{iw}$ of 4.8 dS/m irrigation of grapevine over a single growing season.

Figure 10. Distributions of predicted daily average rootzone salinity ($EC_e$, dS/m) in different scenarios ($Rw =$ river water, $Gw =$ brackish water, $Mix =$ mixing $Rw$ and $Gw$ in a 1:1 proportion, $Alt =$ monthly alternate use of $Rw$ and $Gw$, $n =$ normal rainfall, $d =$ 20% less rainfall, and $l =$ 30 mm annual leaching irrigation) during 2017–22. The red dotted line shows the threshold $EC_e$ (2.1 dS/m) for the grapevine salinity tolerance.

Blended water ($Mix_n$) showed a 21% reduction in salinity compared to brackish water irrigation ($Gw_n$). Monthly alternating $Rw$ and $Gw$ ($Alt_n$) irrigation reduced the salinity by 28% compared to $Gw_n$. Despite a reduction in salinity in these scenarios,
the average $EC_e$ values (4.5 and 3.8 dS/m) remained higher than the corresponding $EC_e$ observed under the current practice ($Rw_n$). Average rootzone $EC_e$ values in the Alt ($Alt_n$) and Mix ($Mix_n$) scenarios under normal rainfall ($n$) were further reduced to 3.3 and 3.6 dS/m, respectively, but were still higher than the crop tolerance level. The $Alt_n$ scenario showed non-significant differences in average $EC_e$ compared to the current irrigation practice ($Rw_n$).

The annual leaching irrigation of 30 mm during spring (1st September) showed a drastic reduction in the rootzone salinity values in all water quality scenarios ($Rw$, $Gw$, Mix, and Alt). Under normal rain ($n$), leaching irrigation ($l$) decreased the average rootzone salinity by 17–24% in different water quality scenarios, and the mean $EC_e$ values decreased to 2.5 and 2.9 dS/m, respectively, in the $Alt_nl$ and $Mix_nl$ scenarios, which were statistically at par with $Rw_n$ and fell in the range of suitable for grapevines [78]. The reduction in $EC_e$ varied from 8 to 17% only under $l$ for reduced rain scenarios ($Gw_dl$, $Mix_dl$, and $Alt_dl$) compared to their respective scenarios without leaching ($Gw_d$, $Mix_l$, and $Alt_l$) and $EC_e$ (3.2–4.9 dS/m) remained above the tolerance threshold for grapevines. These results suggest that annual leaching irrigation of more than 30 mm is required for salinity control in the heterogeneous soils at the study site.

3.5. Leaching Fraction

The fraction of applied water leaving the root zone (leaching fraction, $LF$) plays a key role in flushing the soluble salts and chemicals out of the root zone and helps facilitate the congenial environment for root water and nutrient uptake essential for plant growth. The estimated annual $LF$ in the current study varied from 0.05 to 0.16 in different scenarios over the simulation period (2017–22) (Figure 11). Typically, $LF$ smaller than 0.1 may favor the salt buildup in soils, posing a threat to the long-term sustainability of crops. Under the current irrigation practice ($Rw_n$), the $LF$ was larger than 0.1 only during 2020–21 due to several large rainfall events (>30 mm) early in the season. It was able to produce an appreciable volume of drainage that transported salts below the root zone. It signifies the importance of large rain events to flush the irrigation-induced salinity below the root zone. However, high-intensity rain events may generate more runoff than infiltration into the soil, depending on the soil type and surface conditions.

![Figure 11. Annual leaching fractions ($LF$) below the root zone (120 cm) of a grapevine under different water quality ($Rw = river water, Gw = brackish water, Mix = mixed $Rw$ and $Gw$ in a 1:1 ratio, Alt = monthly alternate use of $Rw$ and $Gw$) and management scenarios ($n = normal rainfall, d = 20\% less rainfall, and l = 30 mm annual leaching irrigation$) during 2017–22 estimated from model predicted water balance components.](image-url)

Extremely low $LF$ values (0.005–0.021) were observed during the 2018–19 season across all scenarios, as annual rainfall (283 mm) was lower than the long-term average of 392 mm [59] in the region, and a few rain events >20 mm (which could generate $LF$) were almost negligible. Application of drought season conditions (20% reduction in the annual rain; the ‘$d$’ scenarios) had a tremendous impact on the drainage volume because the annual...
LF was reduced by 7–74% during different years. Average LF decreased by 33 to 52% in the reduced rainfall scenarios (the ‘d’ scenarios) as compared to the normal rainfall scenarios (the ‘n’ scenarios) under different water qualities (Gw, Mix, and Alt); the reduction was highest in Rw and the lowest in the Gw scenarios. The development of high salinity regions in the root zone of the Gw irrigation scenarios reduced RWU and allowed more water to drain below the root zone. Negative correlations were observed between the reduction in RWU and LF under Gw (−0.98), Mix (−0.98), and Alt (−0.98) irrigation scenarios. Other studies have also reported a similar negative correlation between transpiration and LF [115]. However, numerous other factors, such as soluble chemical constituents, soil physical state, and flow conditions, may also profoundly impact LF.

The application of annual leaching irrigation (l) of 30 mm in the spring over multiple growing seasons had a tremendous impact on the extent of drainage and leaching of soluble salts in all seasons (Figure 11). LF increased from 3 to 225% in the normal irrigation scenarios (nl) and from 9 to 220% in the reduced rainfall scenarios (dl). The mean increase in LF for river (Rw), brackish (Gw), 1:1 blending (Mix), and monthly alternate (Alt) irrigation under normal and reduced rainfall was 31, 18, 26, and 21% and 55, 22, 38, and 33%, respectively, compared to the corresponding no-leaching irrigation scenarios. Among the seasons, 2018–19 recorded a four-fold increase in LF, although it was still less than 0.1. Even this small leaching fraction can greatly impact the salt balance in the soil. The LF increased above 0.1 during the 2017–18, 2020–21, and 2021–22 seasons, rapidly flushing the salts out of the root zone. The application of annual leaching irrigation (l) under Rw irrigation (Rw_nl) showed an overall depletion of 1.2 t salts/ha over the simulation period (Figure 12a). However, in all other scenarios, salt deposition varied from 2.2 to 16.7 t/ha in response to the salts added through different modes of irrigation application. Therefore, rootzone salt depletion occurred only in the Rw_nl scenario over the simulation period. Nonetheless, annual leaching irrigation with the Gw, Mix, and Alt irrigation modes produced a 1.8–2.2 t/ha reduction in the rootzone salts, indicating this as a viable management option to manage the irrigation-induced salts in the soil.

Figure 12. Leaching efficiency (a) in terms of salts leached/salts applied (LEs, kg/kg), salts leached/drainage volume (LEd, kg/m³), and salts deposited (+)/depleted (−) in the soil root zone (120 cm) at the end simulations (b) for different scenarios (Rw = river water, Gw = brackish water, Mix = mixed Rw and Gw in a 1:1 ratio, Alt = monthly alternate use of Rw and Gw) and managements (under normal n, drought season d, and leaching irrigation l scenarios).

3.6. Leaching Efficiency

The leaching efficiency of salts (LEs) is defined as the ratio of the salt mass leached below the crop root zone and the salt mass added through irrigation and rainfall during a given time (e.g., an annual or crop cycle), which offers a more quantitative measure of the salt balance [27,116] under drip irrigation. The maximum value of LEs (1.5 kg salts leached/kg added) was observed in the river water with the leaching irrigation (Rw_nl) scenario, followed by Rw_n (1.14 kg salts leached/kg added), while the lowest LEs values (0.2–0.3 kg salts leached/kg added) were found in the reduced rainfall scenarios (Gw_d,
indicating a profound influence of drought period conditions, which lead to a rapid reduction in the leaching fraction and drainage volume (Figure 12b). Annual leaching irrigation (l) (30 mm) increased $LE_s$ by 31, 18, 29, and 34% in the $Rw$, $Gw$, $Mix$, and $Alt$ scenarios, respectively, with normal rainfall compared to their respective scenarios without leaching irrigation. The annual leaching irrigation also showed a much higher increase in $LE_s$ (32–139%) in the reduced rain (drought season) scenarios.

Leaching efficiency in terms of the amount of salts leached with a drainage volume ($LE_d$) below the root zone varied from 1.3 to 4.5 kg/m² between scenarios (Figure 12b). The maximum value was observed in $Gw_{dl}$ whereas the lowest was observed under $Rw_d$ because of a higher amount of salts in the former scenario. It suggests that a small leaching fraction in the $Gw_{dl}$ scenario triggered large quantities of salts transported out of the root zone that had accumulated from the $Gw$ irrigation. The average $LE_d$ was larger than 1 in all scenarios, which may not imply that rootzone salinity has been reduced below the crop threshold. For example, even in the $Rw_n$ scenario, the salt balance showed an increase of the initial salt mass by 0.53 t of salts/ha out of 4.05 tons/ha of salts added over the simulation period (2017–22) (Figure 12a). It suggests that $LE_d$ represents only the intensity factor for salt leaching and may not provide a valid criterion to estimate the leaching requirement (LR) for salinity management.

The LR is $LF$, which, when passed through the root zone, reduces the rootzone salts below the crop threshold [117]. Estimation of LR following steady state uniform soil conditions typically overestimates LR required for heterogeneous soils that have variations in their wetting patterns under drip and micro irrigation systems [118,119]. Hanson et al. [44] observed that, in drip-irrigated systems, it is hard to determine LR due to spatially variable soil wetting patterns that lead to localized leaching below the drip line, depositing large amounts of salts laterally along the wetting fronts, as observed in the current study (Figures 7 and 8). Calibrated numerical models that accurately simulate water and salt movement under drip irrigation can help develop better salinity management guidelines [19]. Phogat et al. [27] estimated $LE_s$ in various soils, climatic conditions, water qualities, and irrigation schedules applied to vineyards. They reported large differences in $LE_s$ values obtained for light-textured deep uniform soil (>1 kg salts leached/kg added) compared to heavy-textured heterogeneous soils (0.12–0.13 kg salts leached/kg added), showing a tremendous influence of inherent soil transmission properties. They concluded that in drip irrigation systems, $LF$ that corresponds to $LE_s \geq 1$ could potentially leach annually added salts from the root zone. Such $LF$ can serve as a good estimate for the leaching of irrigation-induced salts from the root zone. In the current study, $LE_s > 1$ was observed in the $Rw_{nl}$ and $Rw_n$ scenarios, which had an average $LF$ of 0.09 and 0.07 (Figure 13), respectively, and the average rootzone salinity less than the tolerance threshold of grapevines (Figure 13), maintaining a favorable environment for normal vine growth. This suggests that $LE_s > 1$ proposed in the previous study [27] can serve as a good indicator for sustainable crop production for different soils, climates, and irrigation managements. However, restricted drainage conditions [31], high SAR of irrigation water, and high soil $ESP$, especially in the subsoils, have an immense impact on the mobility of salts in the soil [116,120,121] and require different management options for salinity control [21].

Water quality and annual rainfall strongly influence the salt leaching in the soil. A strong positive linear relationship ($R^2 = 0.99$) was found between irrigation water sources ($Rw$, $Gw$, $Mix$, and $Alt$) and the corresponding leaching fractions ($LF$) (Figure 13). A threshold $LE_s$ for salinity control ($LE_s > 1$) was achieved with an $LF$ of 0.07, 0.12, 0.12, and 0.15 for $Rw$, $Mix$, $Alt$, and $Gw$ water quality irrigation, respectively. This suggests that LR increased proportionately to the salts added through irrigation. Irrigating the grapevines below the water requirement added a smaller mass of salts in the soil but could not provide adequate leaching for salinity control in the study region [79]. The $LE_s$ also showed a very weak but positive linear relationship with annual rainfall, suggesting that an increase in annual rainfall influenced the mobilization of salts out of the root zone, depending on the timing, amount, and intensity of the rain events. It is worth noting that under the
current irrigation practice (Rw), annual rainfall equal to the long-term average (390 mm) can generate LEs > 1, suggesting a typical threshold for maintaining appropriate salt balance in the soil for irrigated viticulture at the study site (Figure 13b).

Numerous other studies have shown a strong influence of rainfall on leaching salts out of the crop root zone. Cucci et al. [122] found that rainfall in autumn and winter produced a good salt-leaching effect in a sandy clay loam in southern Italy. Isidoro and Grattan [120] also reported that winter rainfall increased leaching compared to rainfall distributed uniformly throughout the year. Similar observations were reported for monsoonal climates [18], where annual rainfall with high-intensity events occurred during a short period (July–September).

4. Conclusions

An appropriate risk assessment is required for integrating brackish water (Gw) into crops’ irrigation schedules to provide effective soil salinity management. Estimated low values of actual basal (Kcb act) and single (Kc act) crop coefficients estimated in this study over five seasons demonstrated that grapevines were irrigated under sustained deficit conditions. Under the Mediterranean-type climate, winter rainfall is considered to generate appropriate leaching to maintain a favorable environment. Simulated results confirm that rainfall reduction (20%) over the five years potentially leads to rapid soil salinization across all modes of irrigation scenarios [river water (Rw, 0.32 dS/m); brackish water (Gw, 3.2 dS/m); 1:1 blending of brackish and river water; and monthly alternate use of Rw and Gw], severely impacting the sustainable production of wine grapes. Under these conditions, it becomes quite imperative to manage the rootzone salts by applying appropriate leaching to maintain the sustainability of vineyards.

Models suggested that in the absence of favorable rainfall, leaching irrigation (l) with good-quality water (Rw) at the beginning of the growing season could best use this high-quality but low-availability water source. This strategy significantly increased the salt leaching efficiency (LEs), and a threshold LEs for salinity control (LEs > 1) was achieved with a leaching fraction (LF) of 0.07, 0.12, 0.12, and 0.15 for Rw, Mix, Alt, and Gw water quality irrigation, respectively.

Results further demonstrated that blending or alternating saline brackish water with non-saline surface water reduced the extent of salt deposition in the soil relative to the application of Gw only. These options can be explored further depending on the extent of salts in brackish water under projected climate change.

This study recommends applying leaching irrigation early in the season before bud burst when the soil is almost saturated with winter rain. It provides a strategic management
option during drought season and periods of low freshwater allocation to develop resilience for maintaining sustainable production. However, these options need location-specific evaluation and continuous monitoring of climate, soil, and plant systems to enable long-term adaptation and resilience for irrigated viticulture and other crops.

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Appendix A

Appendix A.1. Brief Description of the Model

This study used a numerical model (HYDRUS-2D; [53]) to simulate the water flow and salt transport in the soil under wine grapes. The governing two-dimensional water flow equation for an isothermal and isotropic medium is described as follows:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( K(h) \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial z} \left( K(h) \frac{\partial h}{\partial z} + K(h) \right) - S(h, h_s, x, z, t) \tag{A1}
\]

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

Water extraction \( S(h, h_s, x, z, t) \) from the soil was computed according to the Feddes macroscopic approach [74]. In this method, the potential transpiration rate, \( T_p \), is distributed over the root zone using the normalized root density distribution function, \( \beta(x, z, t) \), and multiplied by the dimensionless water \([\alpha_1(h)]\) and salinity stress \([\alpha_1(h_s)]\) response functions as follows:

\[
S(h, h_s, x, z, t) = \alpha_1(h, h_s, x, z, t)S_p(x, z, t) = \alpha_1(h, h_s, x, z, t)\beta(x, z, t)T_p(t) \tag{A2}
\]

This model calculates plant root water uptake rates according to the local soil water pressure head, \( h \), at any point in the root zone. It defines how potential transpiration (Tp) is reduced below potential when the soil can no longer supply the amount of water required by the plant under the prevailing climatic conditions. The multiplicative model for the osmotic head reduction is considered in this study as follows:

\[
\alpha_1(h, h_s) = \alpha_1(h)\alpha_1(h_s) \tag{A3}
\]
The reduction of root water uptake due to the water stress, $\alpha_1(h)$, is described as

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

(A4)

where $h_1, h_2, h_3$, and $h_4$ are the threshold model parameters. Water uptake is at the potential rate when the pressure head is between $h_2$ and $h_3$, decreases linearly when $h > h_2$ or $h < h_3$, and becomes zero when $h < h_4$ or $h > h_1$. These critical values of pressure heads for grapevine were taken from previous investigations in South Australia [8,72].

Similarly, the threshold model was used to simulate the impact of osmotic (salinity) stress $\alpha_1(h_s)$, which states that water is extracted at the maximum rate below the crop threshold ($EC_e = 2.1$ dS/m) osmotic head and the slope of the curve determines the fractional reduction of water uptake per unit increase in osmotic head (12.8%/ECe unit) beyond the threshold. These parameters for grapevine were obtained from previous regional salinity tolerance studies [75].

The spatial root distribution is defined in HYDRUS-2D according to Vrugt [123]:

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

(A5)

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. These parameters for grapevine were optimized depending on the system design parameters and local soil and crop conditions [72].

Appendix A.2. Solute Transport/Salinity Distribution in the Soil

The governing advection-dispersion equation for the simulation of the transport of a single non-reactive ion in a homogeneous medium is described as

$$
\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial x} \left( \theta D_{xx} \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial z} \left( \theta D_{zz} \frac{\partial c}{\partial z} \right) + \frac{\partial}{\partial z} \left( \theta D_{xz} \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial x} \left( \theta D_{zx} \frac{\partial c}{\partial z} \right) - \frac{\partial}{\partial x} (\theta q_x c) - \frac{\partial}{\partial z} (\theta q_z c)
$$

(A6)

where $c$ is the concentration of the solute/salts in the liquid phase (ML$^{-3}$), $D$ is the dispersion coefficient (L$^2$T), and $q$ is the volumetric flux density (LT$^{-1}$). Soil solution salinity ($EC_{sw}$) is simulated as a non-reactive solute in the soil, as described in previous studies [57,76,85]. These studies showed good predictions of soil salinity dynamics in the soil under intensive irrigation and fertigation conditions.

The longitudinal dispersivity was assumed to be one-tenth of the size of the transport domain, with the transverse dispersivity being one-tenth of the longitudinal dispersivity Cote [77]. These values were additionally optimized during the calibration. The salinity of irrigation ($EC_{iw}$) was obtained from the water quality analysis available in the literature and from previous studies. The rainfall chemistry analysis by Cresswell and Herczeg [59] for the study region provided reliable information about rainfall salinity ($EC_{rw}$; 0.16 dS/m).
Figure A1. Daily values of reference crop evapotranspiration ($ET_0$), rainfall, and irrigation applied to wine grapes at the study site during (a) 2017–18, (b) 2018–19, (c) 2019–20, (d) 2020–21, and (e) 2021–22. Annual amounts of $ET_0$, rainfall, and irrigation are also given.

Table A1. Values of different parameters used to estimate daily transpiration ($T_p$) and daily evaporation ($E_s$) for wine grapes for the field site following the FAO-56 DCC approach.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Season</th>
<th>Value</th>
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<td>Min RH (%)</td>
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<td>$\theta_c$</td>
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<tr>
<td>$K_{cb mid}$ (generic)</td>
<td>0.20</td>
<td>2019–20</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>$K_{cb end}$ (generic)</td>
<td>0.65</td>
<td>2020–21</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>$K_{cb end}$ (generic)</td>
<td>0.50</td>
<td>2021–22</td>
<td>0.46</td>
<td></td>
</tr>
</tbody>
</table>

1 Basal crop coefficient values for medium-density wine grapes from Allen and Pereira [68].
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