Agricultural Water Management 237 (2020) 106167

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Impact of long-term recycled water irrigation on crop yield and soil chemical properties

V. Phogat[a,b,c,*], Dirk Mallants[d], J.W. Cox[a,b], J. Šimůnek[e], D.P. Oliver[d], T. Pitt[a,b], P.R. Petrie[a,b,f]

[a] South Australian Research and Development Institute, GPO Box 397, Adelaide SA 5001, Australia
[b] The University of Adelaide, PMB1 Glen Osmond SA 5064, Australia
[c] CCS Haryana Agricultural University, Hisar 125 004, India
[d] CSIRO Land and Water, PMB No.2, Glen Osmond, SA 5064, Australia
[e] Department of Environmental Sciences, University of California, Riverside, CA 92521, USA
[f] The University of New South Wales, Sydney, NSW 2052, Australia

ARTICLE INFO

Keywords:
Recycled water
irrigation
salinity
SAR
ESP
HYDRUS-1D
UNSATCHEM
horticultural crops

ABSTRACT

The variably-saturated flow and multi-component transport module UNSATCHEM of HYDRUS-1D was used to evaluate the impact of the long-term (2018-2050) application of recycled water (RCW) for irrigating perennial horticulture (almonds, pistachios), viticulture (grapevines), annual horticulture (carrot, onion, and potato), and pasture crops in representative soils from the Northern Adelaide Plains (NAP), South Australia. The input parameters for soil hydraulic, soil solution, and cation exchange data were determined for 14 soil profiles from the NAP region. For a warm-up period from 1970 to 2017, the model used historical climate data and low-salinity irrigation water. In the subsequent period (2018-2050), irrigation continued with RCW and projected meteorological conditions were obtained by considering expected future climate change. The average soil water salinity (EC_{sw}) at the end of the simulation period ranged from 2.9-10.5 dS/m across all soils and crops. Potential yields of salt-sensitive crops such as annual horticulture and almonds were reduced by 4-32% due to increased salinity in the soil. Similarly, the model predicted that the sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) would increase above threshold values, typically considered as indicative of poor growing conditions for most crops. Relationships between SAR and ESP were developed for four representative soils, providing the threshold soil SAR that corresponds to a critical ESP (> 6), which would lead to adverse soil health and crop growth impacts. Threshold SARs were derived for calcareous (SAR = 4), hard red-brown (SAR = 3.5), sand over clay (SAR = 6), and deep uniform to gradational (SAR = 3) soils. An increase in SAR and ESP in soils adversely affects soil structural stability and soil water movement, which can severely impact the sustainable crop production in the NAP region. Relationships such as those between SAR and ESP help in identifying critical soil constraints and assist in devising better guidelines for the sustainable use of recycled water for irrigated agriculture.

1. Introduction

Increasing demand for food by a burgeoning global human population requires large amounts of freshwater to be allocated to agriculture. However, in many parts of the world, especially under arid and semiarid climate, water demand has already exceeded water supply provided by fresh surface and groundwater resources (FAO, 2012; Famiglietti, 2014; UN Environment, 2019). The scarcity of water supplies, coupled with the need for urban communities to manage large quantities of water from sewage treatment plants, has led to increasing interest in the recirculation of this water for irrigating crops. Consequently, treated wastewater is recognized as an important alternative water source for supporting crop production (Qadir et al., 2010; Grattan et al., 2015) and is increasingly being adopted in irrigation water allocation schemes for arid and semiarid regions where water scarcity is severe (Hamilton et al., 2007; Otoo and Drechsler 2018).

Generally, usage of RCW can have both positive and negative impacts on crops and soils depending on the water quality, and the extent and duration of exposure. The benefits include: reducing freshwater demand, recycling nutrients, and minimizing the discharge of pollutants into waterways (Hanjraa et al., 2012; Hassena et al., 2018). Furthermore, several investigations have reported improvements in soil

* Corresponding author at: South Australian Research and Development Institute, GPO Box 397, Adelaide SA 5001, Australia.
E-mail address: vinod.phogat@sa.gov.au (V. Phogat).

https://doi.org/10.1016/j.agwat.2020.106167
Received 18 February 2020; Received in revised form 20 March 2020; Accepted 23 March 2020

fertility status, nutrient uptake, plant growth and yield potential (e.g., Singh et al., 2012; Lal et al., 2015; Minhas et al., 2015; Elfanssi et al., 2018; Hassena et al., 2018). Similarly, some other investigations reported that irrigation with RCW had no detrimental effects on tree growth and productivity (Parsons et al., 2001; Morgan et al., 2008) nor upon soil physico-chemical properties (e.g., Andrews et al., 2016).

However, the prolonged and indiscriminate use of RCW can result in the accumulation of ions in roots and leaves, potentially reaching toxic levels (Paudel et al., 2016), damage plantations, and decrease the yield (Noshadi et al., 2013). It may further increase soil salinity and SAR, which can lead to the development of sodicity hazards (high exchangeable sodium) in the soils (Bardhan et al., 2016; Assouline et al., 2016; Qian and Lin 2019; Phogat et al., 2020). These conditions can degrade the soil hydraulic properties and thus affect water movement in the soil (e.g., Assouline and Narkis, 2013; Assouline et al., 2016). In particular, high ESP in the soil may cause clay dispersion and swelling (Rengasamy and Olsson, 1993), and overall soil structure degradation (Basile et al., 2012). Therefore, understanding the impacts on soils and crops of long-term irrigation with variable quantity and quality RCW, potentially exacerbated by hotter and drier climate (IPCC, 2014; CSIRO, BoM 2016), is essential to develop guidelines for sustainable irrigation with RCW.

Process-based numerical models are preferred tools to enhance our understanding of the long-term impact of irrigation on soil hydraulic properties (e.g., Valdes-Abellan et al., 2017), salinity (e.g., Phogat et al., 2018a) and sodicity risks (e.g., Phogat et al., 2020). Among these models, the multi-component major ion chemistry module UNSATCHEM, integrated into the HYDRUS-1D software package (Šimůnek et al., 2016), is an advanced numerical tool to predict coupled processes of major ion chemistry, variably-saturated water flow, and solute transport in soils during transient conditions. While the water flow and solute transport components of the standard HYDRUS-1D model have been used widely (e.g., Šimůnek et al., 2016), fewer applications of the major ion chemistry module have been reported, mainly because of a lack of appropriate experimental soil chemical data (e.g., Gonçalves et al., 2006; Ramos et al., 2011). Several of the reported studies focused on assessing the short-term impact of using high SAR water (Suarez et al., 2006), evaluating ways to reclaim sodic soils (Šimůnek and Suarez, 1997; Kaledhonkar et al., 2006; Wang et al., 2014), assessing conditions for a sustainable use of coal seam gas water for crop production (Mallants et al., 2017), and undertaking solute transport simulations of irrigation with saline/degraded water (Ramos et al., 2011; Skaggs et al., 2014). These simulations of the movement of dissolved solutes, while also accounting for precipitation/dissolution reactions of salts in soils, have been a useful complement to field studies (Suarez, 2001). Nevertheless, applications with the major ion chemistry module UNSATCHEM of HYDRUS-1D for assessing long-term risks of irrigation with RCW to horticultural crops and associated environments are limited.

This modeling study aims to evaluate the impact of long-term (2018-2050) irrigation with RCW on (i) crop yield of horticultural crops (almonds and pistachios), viticulture, pasture (mixed), and annual vegetables (carrot, onion, and potato), and (ii) changes in chemical composition in texturally different soils. By applying the actual water usage to different prospective crops considered for expanding irrigated horticulture and agriculture in the NAP region in South Australia, a much-improved understanding of the spatiotemporal soil solution and exchange dynamics allows identifying conditions, including mitigating measures, required for the sustainable use of recycled water for irrigated crops. The outcome of these long-term simulations, accounting for future climate predictions, helps in devising better irrigation guidelines for growing horticultural and vegetable crops.

2. Materials and Methods

2.1. Description of the study site

The Northern Adelaide Plains (NAP), South Australia, will experience a considerable expansion of irrigated agriculture and horticulture, based predominantly on the utilization of increasingly available recycled water (RCW) from the Bolivar treatment plant (The Goyder Institute for Water Research, 2016). The wastewater is treated using the "Dissolved Air Flotation and Filtration" (DAFF) technique through a tertiary process of filtration and disinfection, making it suitable for irrigating horticultural crops. The NAP has a Mediterranean-type climate, which is characterized by hot, dry summers and cool to cold winters. Long-term (1900-2016) average rainfall in the region amounts to 475 mm (Department of Environment, Water and Natural Resources, 2016) and annual evapotranspiration amounts to 1308 mm. With most of the rainfall occurring in the winter months, crop production requires intensive irrigation.

Fourteen representative soil profiles were excavated to determine the relevant physico-chemical properties of the main soil groups (Oliver et al., 2018). Samples consisted of disturbed soil for the particle size analysis and undisturbed cores for measurements of the bulk density, the water content-matric suction relationship, and the saturated hydraulic conductivity. The soil samples were collected from 0-10, 10-30, and 30-60 cm, and selectively also from lower depths (60-90 and 90-120 cm). A detailed description of different soil profiles and their physico-chemical properties can be found in Oliver et al. (2018). Undisturbed soil cores collected from the field were first used to measure the saturated hydraulic conductivity (K_s) using the constant head method of Youngs (2001). Subsequently, the soil water retention characteristic was determined by placing the cores onto saturated ceramic plates connected to either hanging water columns (0.1, 4 and 8 kPa) or subjected to positive gas (nitrogen) pressures (33, 60, and 100 kPa) in sealed chambers. Other soil samples were used to measure the soil water content at 1500 kPa. More details are available from Mallants et al. (2019).

2.2. Model description

We used the UNSATCHEM module of HYDRUS-1D (Šimůnek et al., 2016) for evaluating the long-term dynamics of coupled water flow, solute transport, and major ion geochemistry in the major NAP soil groups, i.e., calcareous (CAL), hard red brown (HRB), sand over clay (SOC), and deep uniform to gradational (DUG) soils under different crops (wine grapes, almond, pistachio, pasture, carrot, onion, and carrot). Initially, the model was warmed up for 48 years from July 1970 to June 2018 using climate parameters from the Bureau of Meteorology (BOM) Station No 023083 at the Edinburgh RAAF site (Latitude -34.7111, Longitude 138.6222, elevation 17 m) to initialize the soil water balance and to attain equilibrium conditions for chemical species for each soil-crop combination.

The future climate (2018-2050) data were taken from the Goyder Institute climate change median climate projections (Charles and Fu, 2015). The median data is based on the downscaled series obtained from the GFDL – ESM2M Global Climate Model (GCM), one of the six better performing GCMs, which are deemed to provide more realistic inputs for impacts and adaptation assessment than those from the six poorer GCMs. Note that the range of a possible future climate change is larger than that obtained from only using the downscaled results from the six better GCMs. A median decrease in annual rainfall by 2050 is 6.8% (relative to the 1986-2005 baseline), the 10th percentile decrease is 8.8%, and the 95th percentile decrease is 3.5% (for the intermediate-emission Representative Concentration Pathway RCP 4.5). RCP 4.5 is a scenario of long-term, global emissions of greenhouse gases, short-lived species, and land-use-land-cover, which stabilizes radiative forcing at 4.5 W/m^2 (approximately 650 ppm CO_2-equivalent) in the year 2100 without ever exceeding that value (Moss et al., 2010). A single climate future is used rather than a range of climate futures to keep the overall number of modeling scenarios manageable. As a result, the simulations present one possible outcome.

A detailed description of the HYDRUS-1D model is available from Šimůnek et al. (2013) and Šimůnek et al. (2016). The one-dimensional Richards equation, which assumes that the air phase plays an insignificant role in liquid flow processes and that water flow due to thermal gradients can be neglected, is solved in HYDRUS-1D using a Galerkin-type linear finite element scheme (Šimůnek et al., 2013). The governing one-dimensional water flow equation is described as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + \cos\alpha\right)\right] - S\left(h, z, t\right) \tag{1}$$

where θ is the soil water content (L^3 L^{-3}); t is the time (T); h is the soil water pressure head (L); z is the vertical coordinate (positive upwards); $K(h)$ is the hydraulic conductivity (LT^{-1}) -pressure head function, α is the angle between the flow direction and the vertical axis (e.g., 1 for vertical flow and 0 for horizontal flow), and $S(h,z,t)$ is a sink term accounting for water uptake by plant roots ($L^3L^{-3}T^{-1}$).

The HYDRUS-1D model will be run with best available soil, crop, climate, and irrigation management parameters. The soil parameters are mostly directly measured on representative soil samples or estimated using auxiliary soil data. Most of the crop parameters are from the literature, although some calibrated parameters were available for wine grapes. Climate data is in part measured on site (for historical climate) and in part derived from downscaled climate projections. Irrigation management parameters were obtained from surveys. These data sets are discussed next. The model was thus not specifically calibrated, as preference was given to use the measured input parameters. Note that estimating model parameters through calibration using an inadequate conceptual model could lead to so-called parameter bias (Enemark et al., 2019).

3. Soil hydraulic characteristics

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

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m} h < 0 \tag{2}$$

$$\theta(h) = \theta_s h \geq 0 \tag{3}$$

$$K(h) = K_s S_e^l [1 - (1 - Se^{1/m})^m]^2 \tag{4}$$

where θ_s is the saturated water content (L^3L^{-3}), θ_r is the residual water content (L^3L^{-3}), K_s is the saturated hydraulic conductivity (LT^{-1}), l is a shape factor, and m, α, and n are empirical shape parameters where $m = 1\text{-}1/n$. S_e is the relative saturation (dimensionless), which is defined as

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{5}$$

The parameters {θ_r, θ_s, K_S, α, and n} for different soils were derived from the measurements on soil cores from 14 soil profiles from the NAP as described in Section 2.1. Mean parameter values were then derived for the 5 most important textural soils groups (Table 1).

Table 1
Estimated average soil hydraulic parameters for different soil groups in the study area (from Mallants et al., 2019).

Soil depth (cm)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (-)	K_s (cm day^{-1})	L (-)
Soil Group 1: Calcareous soils (CAL)						
0-15	0.078	0.48	0.035	1.239	207.36	0.5
15-30	0.096	0.482	0.085	1.208	181.44	0.5
30-60	0.0758	0.485	0.2781	1.1639	146.00	0.5
60-100	0.0001	0.481	0.2305	1.1382	267.79	0.5
100-200	0.0735	0.4087	0.0242	1.298	22.91	0.5
Soil Group 2: Hard red brown soils (HRB)						
0-15	0.073	0.469	0.025	1.217	50.11	0.5
15-30	0.101	0.446	0.059	1.187	40.61	0.5
30-60	0.109	0.465	0.282	1.133	13.98	0.5
60-100	0.1365	0.4588	0.0891	1.1216	13.33	0.5
100-200	0.0807	0.4112	0.0255	1.2196	12.82	0.5
Soil Group 4: Sand over clay soils (SOC)						
0-15	0.0587	0.4127	0.0171	1.7878	311.04	0.5
15-30	0.082	0.4434	0.0371	1.4397	103.68	0.5
30-60	0.1008	0.3866	0.0243	1.4745	71.71	0.5
60-100	0.1097	0.4117	0.025	1.792	190.08	0.5
100-200	0.0695	0.3812	0.0259	1.2511	16.02	0.5
Soil Group 5: Deep uniform to gradational soils (DUG)						
0-15	0.041	0.394	0.0018	1.58	39.05	0.5
15-30	0.126	0.473	0.0014	1.329	27.65	0.5
30-60	0.102	0.442	0.0219	1.1886	171	0.5
60-100	0.1139	0.4545	0.0184	1.1781	233	0.5
100-200	0.0735	0.4007	0.0254	1.2477	17.21	0.5

θ_r is the residual water content; θ_s represents the saturated water content; α represents the inverse of an air entry value; n & l are pore distribution parameters, and K_s is the saturated hydraulic conductivity of soils.

3.1. Solute transport properties for UNSATCHEM

The major ion chemistry module UNSATCHEM enables the simulation of equilibrium geochemical reactions involving Ca, Mg, Na, K, SO_4, Cl, NO_3, H_4SiO_4, HCO_3, and CO_2 (Šimůnek and Suarez, 1997; Šimůnek et al., 2013). The model accounts for equilibrium chemical reactions between these components, such as aqueous complexation, cation exchange, and precipitation-dissolution. For the precipitation-dissolution of calcite and dissolution of dolomite, either equilibrium or multicomponent kinetic expressions are used, which include both forward and back reactions. Other precipitation-dissolution reactions considered involve gypsum ($CaSO_4.2H_2O$), hydromagnesite ($Mg_5(CO_3)_4(OH)_2.4H_2O$), nesquehonite ($MgCO_3.3H_2O$), and sepiolite ($Mg_2Si_3O_7.5(OH).3H_2O$). Since the ionic strength of soil solutions can vary considerably with time and space and often reach high values, both modified Debye-Hückel and Pitzer expressions are incorporated into the model as options to calculate single ion activities.

The geochemical model considered aqueous, gaseous, adsorbed, precipitated, and complexed phases (Šimůnek and Suarez, 1997; Šimůnek et al., 2013). Partitioning of dissolved major ions between the solid and solution phases is described using the Equations (6) to (8) (White and Zelazny, 1986) and Gapon selectivity coefficients (Eqs. 9–11). This requires the definition of the Gapon exchange constants for the exchange of calcium and magnesium, calcium and potassium, and calcium and sodium (Gapon, 1933; Šimůnek and Suarez, 1994) given as:

$$0.5Ca + Na - X \leftrightarrow Na + Ca_{0.5} - X \tag{6}$$

$$0.5Ca + K - X \leftrightarrow K + Ca_{0.5} - X \tag{7}$$

$$0.5Mg + Ca_{0.5} - X \leftrightarrow 0.5Ca + Mg_{0.5} - X \tag{8}$$

The Gapon selectivity or exchange coefficients for reactions (6-8) are defined as (Šimůnek and Suarez, 1994):

$$K_{Ca/Na} = \frac{Ca - XNa}{[Na - X]Ca^{0.5}} \tag{9}$$

$$K_{Ca/K} = \frac{Ca - XK}{[K - X]Ca^{0.5}} \tag{10}$$

$$K_{Mg/Ca} = \frac{Mg - XCa^{0.5}}{[Ca - X]Mg^{0.5}} \tag{11}$$

where [Na], [K], [Mg], and [Ca] are molal activities in the soil solution

Table 2
The estimated initial concentrations of adsorbed cations, Gapon selectivity coefficients (from Mallants et al., 2019), and soil solution compositions in different soil groups in the study area.

Soil Type	Adsorbed cation concentration (meq/kg)				Gapon coefficients		
	Ca-X	Mg-X	Na-X	K-X	$K_{Ca/Na}$	$K_{Ca/K}$	$K_{Mg/Ca}$
CAL	51.87	35.32	13.71	7.74	0.038	0.957	0.009
HRB	53.17	60.61	36.93	15.32	0.033	0.753	0.065
SOC	80.19	21.36	3.00	9.02	0.020	1.880	0.014
DUG	41.14	22.72	22.72	16.79	0.013	1.313	0.025
	Soil solution composition (meq/L)						
	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Alk	Cl-	SO_4^{2-}
CAL	3.82	2.31	9.91	0.05	3.22	0.5	11.3
HRB	2.94	3.58	14.81	0.58	3.78	2.28	15.34
SOC	4.41	1.74	3.0	0.07	1.85	0.44	6.46
DUG	1.76	3.79	11.5	0.26	4.7	0.84	11.5

(dimensionless), and [Na-X], [K-X], [Mg-X], and [Ca-X] are adsorbed concentrations ($mmol_c$/kg soil).

Initial average concentrations of soil solution species, soil exchange cations, and estimated Gapon selectivity coefficients in the soil profiles collected from the NAP area are given in Table 2 (for further details of wet chemistry analyses, see Oliver et al. (2018)). Note that this initial soil solution is brought into equilibrium with the cation exchange complex during the model warming up period (1970-2018).

3.2. Estimation of potential evaporation (E_s) and potential transpiration (T_p)

The HYDRUS-1D/UNSATCHEM (Šimůnek et al., 2016) model requires daily inputs of rainfall as well as potential evaporation (E_s) and potential transpiration (T_p). Therefore, the daily E_s and T_p values for all crops (wine grape, almond, pistachio, pasture, carrot, onion, and potato) for current and future climates were estimated following the FAO-56 dual crop coefficient (DCC) approach (Allen et al., 1998).

The FAO-56 DCC methodology requires a considerable amount of data for crops, soils, and climate. All relevant information and required data for this approach for the NAP soils and crops are included in Mallants et al. (2019) and Phogat et al. (2020). Daily climate data for the historic climate (1970-2018) was obtained from the Bureau of Meteorology (BOM), Edinburg RAAF station, while future climate (2018-2050) data was taken from the Goyder climate change median climate projections for the same station (Charles and Fu, 2015).

Apart from daily E_s and T_p, the irrigation requirements for different crops (almonds, wine grape, pistachios, pasture, carrot, onion, and potato) were also estimated following the FAO-56 dual crop coefficient (DCC) approach (Allen et al., 1998), as discussed in detail by Mallants et al. (2019). For wine grapes, measured LAI values were taken from similar studies (Phogat et al., 2016, 2017) in the study area. Also, values for canopy geometry and fractional cover for wine grape previously calibrated by Phogat et al. (2016) have been used here. The functional relation followed in the FAO dual crop coefficient approach (Allen et al., 1998) is given as:

$$ET_C = (K_{cb} + K_e)\, ET_0 \tag{12}$$

where ET_C is the crop evapotranspiration (LT^{-1}), ET_0 is the reference crop evapotranspiration (LT^{-1}), K_{cb} is the basal crop coefficient, which represents the plant transpiration component, and K_e is the soil evaporation coefficient. Some of the basic information such as *Kcb*, crop duration, plant height, rooting depth, and depletion factor, is available from FAO-56 (Allen et al., 1998). The details on data requirements and other relevant information for each crop, soil, and climate conditions can be found in Mallants et al. (2019). In this approach, standard K_{cb} values (Allen et al., 1998) of the crops were adjusted for the local climate, taking into consideration crop height, wind speed, and minimum relative humidity averages. Estimated K_{cb}*'s* in the current study compares well with previous calibrated values for wine grape (Phogat et al., 2017). Soil specific information (soil texture, field capacity, θfc; permanent wilting point, θwp; readily available water, RAW; total available water, TAW) has been drawn from the soil analyses (Oliver et al., 2018).

The values of daily potential transpiration (T_p) and soil evaporation (E_s) thus obtained were used as time-variable boundary conditions in the HYDRUS model, along with the irrigation schedule for different crops and precipitation received at the site during the simulation period. The amount and timing of irrigation were also imposed as a time-variable flux boundary.

3.3. Root water uptake parameters

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

$$\begin{aligned} S(h, h_s, x, z, t) &= \alpha_1(h, h_s, x, z, t) S_p(x, z, t) \\ &= \alpha_1(h, h_s, x, z, t)\beta(x, z, t) T_p(t) \end{aligned} \tag{13}$$

This model reduces potential plant root water uptake rates according to the local soil water pressure head, h, and osmotic head, h_s, at any point in the root zone. This model defines how potential transpiration (T_p) is reduced when the soil is no longer capable of supplying the amount of water required by plants under prevailing climatic and soil conditions. The multiplicative model for the uptake reduction due to the osmotic stress is considered in this study:

$$\alpha_1(h, h_s) = \alpha_1(h)\alpha_1(h_s) \tag{14}$$

The reduction of root water uptake due to the water stress, $\alpha_1(h)$, is described as:

$$\alpha_1(h) = \begin{cases} 0, & h > h_1 \text{ or } h \le h_4 \\ \dfrac{h - h_1}{h_2 - h_1}, & h_2 < h \le h_1 \\ 1, & h_3 < h \le h_2 \\ \dfrac{h - h_4}{h_3 - h_4}, & h_4 < h \le h_3 \end{cases} \tag{15}$$

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 the pressure head for viticulture and perennial horticulture (e.g., almond) for the study were taken from previous investigations in South Australia (e.g., Phogat et al., 2012, 2013, 2017) and other available literature, e.g., Taylor and

Table 3
The estimated average seasonal composition of recycled water (used for irrigation) and rainwater in the study area.

Water type	Season	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Alk[a]	SO_4^{2-}	Cl-	SAR
		meq/L							
Recycled water (RCW)	Autumn	1.85	2.44	11.25	1.02	1.80	3.77	10.27	7.7
	winter	1.88	2.59	11.72	0.94	1.90	3.73	10.71	7.8
	spring	2.02	3.13	13.62	0.97	2.09	3.76	12.62	8.5
	summer	1.92	2.84	13.12	1.04	2.08	3.77	12.44	8.5
	Average	1.92	2.75	12.43	0.99	1.97	3.76	11.51	8.1
Rainwater		0.17	0.11	0.41	0.01	0.16	0.08	0.51	1.1

[a] Alkalinity.

Ashcroft (1972) and the HYDRUS database.

The threshold model uses two variables to simulate the osmotic stress $\alpha_1(h_s)$: the osmotic head, below which water is extracted at the maximum rate, and the slope, i.e., a fractional reduction of water uptake per a unit increase in the osmotic head above the threshold. These parameters were obtained from Zhang et al. (2002) for wine grapes, Sanden et al. (2004) for pistachios, and Ayers and Westcot (1985) for other crops.

3.4. Irrigation water quality

Average seasonal recycled water (RCW) quality data was obtained from Awad et al. (2019). The mean seasonal composition for RCW was estimated from raw data from 2002-2017. The final values used for the modeling study are given in Table 3. The water quality falls into the medium category for the salinity rating in Australia (ANZECC, ARMCANZ 2000), which means that moderately tolerant crops can be grown using RCW as an irrigation source. The chemical composition of rainwater was obtained from Cresswell et al. (2010) for the Adelaide region (Table 3).

In this study two irrigation systems were identified on the basis of a survey undertaken among the farmers: overhead sprinklers (potato, carrots, cauliflower, broccoli, cabbage. lettuce) and drippers (almonds, wine grapes, tomatoes). For sprinkler irrigation, water application is relatively uniform across the soil surface thus leading to one-dimensional flow and solute migration. The use of the one-dimensional HYDRUS model is thus appropriate. For drip irrigation, flow and solute transport is quasi-three dimensional (in the radial direction away from the dripper), therefore the use of a one-dimensional model may not be entirely correct. The discrepancies in both water content and salinity are likely highest at the edge of the wetting zone surrounding the dripper; how much this impacts crop growth will depend on the spatial distribution of the rooting system relative to the position of the drippers. Previous work by Phogat et al. (2014) with a two-dimensional model with drip irrigation applied to a mandarin tree clearly showed the non-homogeneous salt redistribution surrounding the dripper. Under the dripper, salt levels were the lowest, while highest salinity was observed at the edge of the wetted soil area. Our one-dimensional may capture the water and salt distribution just underneath the dripper, but not at the edges. Estimating the impact of this simplification on crop yield was beyond the scope of this study.

3.5. Modeling domain, initial and boundary conditions

Simulations for all crops were performed for a 200-cm deep soil profile divided into 100 finite elements. The finite element nodes were distributed with a nodal density of 0.5 at the surface and 1 at the bottom to ensure a fine discretization at the soil surface where major water and solute dynamics processes take place. The domain was divided into 5 soil layers (0-15, 15-30, 30-60, 60-100, and 100-200 cm) to accommodate the measured textural heterogeneity in various soil groups (CAL, HRB, SOC and DUG) in the NAP area determined by soil sampling and the particle size analysis. At the soil surface, an atmospheric boundary condition with surface runoff was imposed and a free drainage boundary condition was applied at the bottom boundary. For solute transport, a concentration flux boundary condition was used at the soil surface and a zero concentration gradient boundary condition was imposed at the bottom to allow gravitational outflow with drainage water. A constant pressure head of -100 cm was considered to initiate the model runs. Measured daily rainfall, and calculated daily E_s and E_p for different crops were applied during the warmup period (1970-2018). Measured soil solution and exchange parameters (Table 2) were assumed as initial conditions for the multi-component solute transport module.

While cultivation methods may affect the soil properties over the years, we assume that the measured soil physical and hydraulic properties reflect such tillage effects and remain constant over the simulation period. Furthermore, even though the location of horticultural crops is not static across multiple years, as long as sprinkler irrigation is applied, water is rather uniformly distributed over the cropped area in response to the crop ET demand. This means that salinity distribution is rather uniform in space and therefore assuming the same exposure over many years is justified. Tree crops, however, have a fixed location across the years so the salt distribution is likely less uniform, especially under drip irrigation. The long-term impact of use of RCW will then depend, among others, on the spatial distribution of the root system relative to the location of the drippers. Two-dimensional salinity distribution under drip irrigation was demonstrated by Phogat et al. (2014).

4. Results and Discussion

4.1. Impact of RCW irrigation on pH and salinity (EC_{sw}) dynamics in the soil

Periodic changes in the profile-averaged pH, EC_{sw}, SAR, and ESP in different soils under recycled water (RCW) irrigation of almonds are shown in Fig. 1. Corresponding chemical variables for other crops during selected years are listed in Table 4. The initial profile-averaged pH, which ranged from 7.9 to 8.3 in different soils, gradually converged to a narrow range (8.2-8.3) at the end of the simulation (Fig. 1). Soil pH in CAL and DUG soils decreased during the early years (3-4 years) following the application of RCW irrigation, while it increased slightly in the other two soils (HRB and SOC). The pH remained more or less constant after that and attained a steady-state condition in all soils (Fig. 1). For the other crops, RCW irrigation had a similar impact on soil pH where differences between initial and final values were within a -0.21 to 0.32 range. (data not shown). Quan and Lin (2019) observed a 0.25-0.3 increase in the initial soil pH (7.1-7.5) during 11 years of recycled water irrigation of landscape facilities. However, a soil pH higher than 8 can reduce the micro-nutrient availability to the crops, which in turn can impact the normal growth and development of trees and other crop plants. Previous work in the NAP area by Stevens et al. (2004) also did not observe any significant differences in the soil pH due to RCW irrigation for periods between 10-28 years.

Concentrations of soluble salts in the soil solution (EC_{sw}) increased

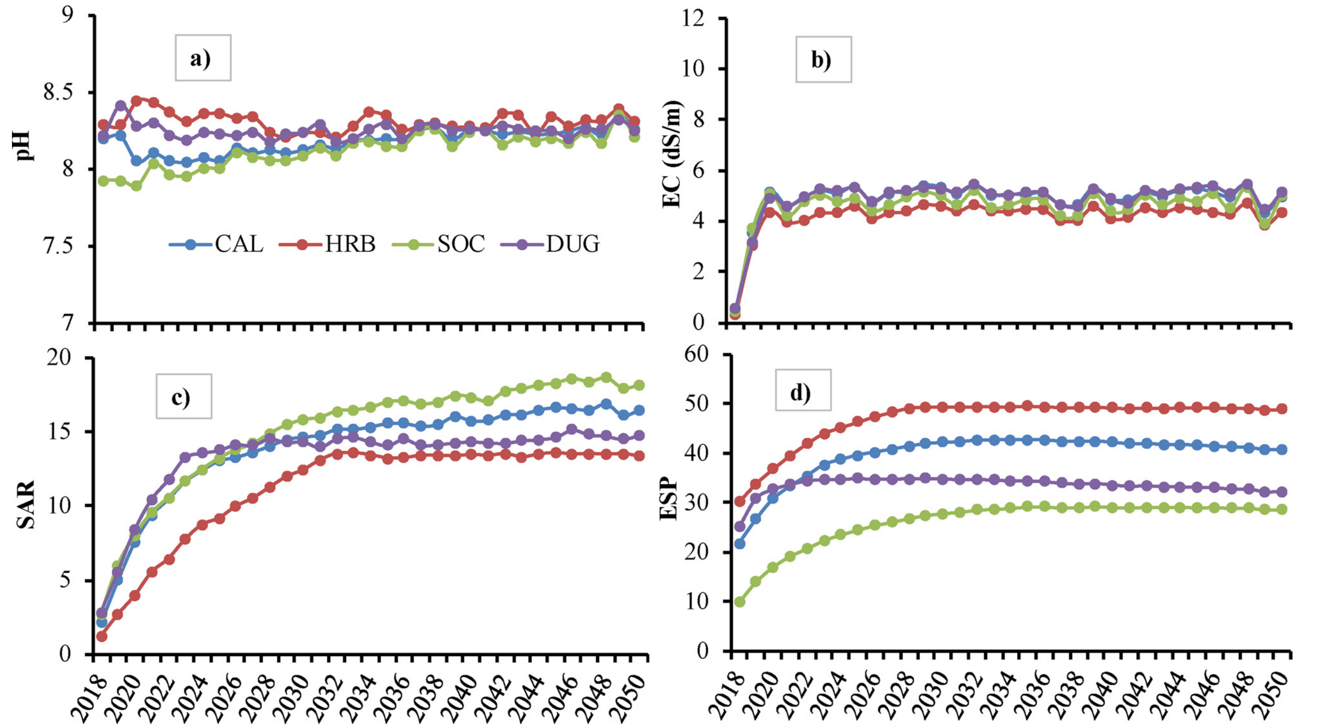

Fig. 1. Temporal changes in the profile-averaged annual values of a) pH, b) EC_{sw}, c) SAR, and d) ESP in different soils (CAL = calcareous soils, HRB = hard red brown, SOC = sand over clay, and DUG = deep uniform to gradational) for almond irrigated with recycled water during 2018-2050.

rapidly as a result of irrigation with RCW of all crops (Fig. 1; Table 4). In almonds, the average profile EC_{sw} in the soil almost attained a steady value within 2-3 years. Final EC_{sw} values (in 2050) varied from 4.33 to 5.15 dS/m across different soils. Similarly, the corresponding values under wine grape, pistachios, pasture (mix), carrot, onion, and potato ranged from 4.0-4.7, 3.8-6.7, 5.5-6.4, 5.8-6.6, 6.1-6.2, and 4.0-9.5 dS/m, respectively (Table 4). These results corroborate well with Stevens et al. (2004), who reported that EC_e values ranged between 2.8 and 6.9 dS/m for 10-28 years of RCW irrigation of different crops in the same region.

However, maximum salinity values, irrespective of the crop, were observed during 2034, which was projected to be a drought year with an annual rainfall of 247 mm. Compared to other crops, the average profile EC_{sw} build up in the soil under potato was higher in CAL and HRB soils (Table 4). This was probably due to a potato-oats (rain-fed) cropping sequence adopted in the study. After 7 years of irrigation (2025), EC_{sw} in these soils was twice as high as in the other two soils under potato and other crops. This pattern continued until the end of the simulation (2050). Overall, the salinity build-up in the CAL and HRB soils in 2050 was double than observed in the other two soils (Table 4). Therefore, the use of RCW irrigation can have a varied and significant impact on the soil salinity build-up under different cropping sequences, which subsequently may have a dramatic impact on crop yields. However, responses of crops to salinity are influenced by several factors, including climate, irrigation, or agronomic management. For example, leaching of soluble salts using low-salinity water is one way to bring the effective rootzone salinity below the crop threshold value to attain optimal yield, and thus to control the harmful impact of salts associated with recycled water irrigation.

On the other hand, EC_{sw} showed an increasing trend from the soil surface to lower depths, irrespective of soil and crop type. For example, in almond, EC_{sw} attained a value larger than 5 dS/m everywhere below a depth of 40 cm after 7 years of irrigation (Fig. 2). At deeper depths (> 80 cm), EC_{sw} increased quickly to a value of more than 5 dS/m in all soils after about 5-7 years of irrigation (see Fig. 2, the first column). Similar patterns of spatiotemporal changes in EC_{sw} were also observed for other crops (Table 4). Interestingly, EC_{sw} was always below 3 dS/m in the surface soil zone (0-30 cm) during the entire simulation period (2018-2050), which is well below the critical threshold salinity for vegetables, almond, and clover (Maas and Hoffmann, 1977). However, the average profile EC_{sw} values are higher than the salinity threshold for vegetables (carrot, potato, and onion; EC_{sw} = 2-3.4 dS/m), mixed pasture clover (3 dS/m), and almonds (3 dS/m), similar to that for wine grapes (4.2 dS/m), but much lower than those for mixed pasture rye grass (11.2 dS/m) and pistachio (18.8 dS/m).

It is generally accepted that soils with EC_e larger than 4 dS/m (≈ EC_{sw} of 8 dS/m) are considered as saline soils (U.S. Salinity Lab. Staff, 1994). The previous work by Stevens et al. (2003) for the NAP soils considered EC_e of 3 dS/m as a salinity threshold for vegetable crops. EC_{sw} higher than the crop salinity threshold can adversely affect the normal growth, development, and yield of horticultural and vegetable crops. Hence, leaching of soluble salts with low-salinity water is essential to bring the effective rootzone salinity below the crop salinity threshold. Among different soils, CAL and HRB displayed high salinity at lower depths, SOC had the lowest EC_{sw}, and DUG had values in between those of the other soils.

Pistachio is a highly salinity tolerant crop that is potentially the most suitable for cultivation in salt-affected soils (Sepaskhah and Maftoun, 1981). Ferguson et al. (2002) and Sanden et al. (2004) showed the viability of using saline water with an EC of 8 dS/m, which showed no impact on the pistachio yield. Notably, the salinity tolerance of pistachio, similarly as of many other woody species, have been associated with a small growth reduction (Sepaskhah and Maftoun, 1988; Picchioni et al., 1990), a small decrease in the photosynthetic activity (including a high chlorophyll index, chlorophyll fluorescence, and chlorophyll content) and the transpiration rate (Walker et al., 1988; Karimi and Maleki Kuhbanani 2015; Momenpour and Imani 2018), smaller amounts of salt ions transported to the leaves (Walker et al., 1987; Picchioni et al., 1990), the ability to maintain relative high K^+/Na^+ and Ca^{2+}/Na^+ ratios needed for osmotic adjustment and enzymatic activities (Chelli-Chaabouni et al., 2010; Hajiboland et al., 2014), and a smaller nut yield reduction (Sanden et al., 2004; Ferguson et al.,

Table 4
Annual values of profile average EC_{sw}, SAR and ESP in different soils (CAL = calcareous, HRB = hard red brown, SOC = sand over clay, and DUG = deep uniform to gradational) under different crops irrigated with recycled water.

Year	ECsw				SAR				ESP			
	CAL	HRB	SOC	DUG	CAL	HRB	SOC	DUG	CAL	HRB	SOC	DUG
Wine grape												
2018	0.5	0.4	0.4	0.4	1.3	0.9	1.5	1.8	19.5	28.1	7.9	24.0
2026	4.6	4.1	3.7	4.1	7.1	5.5	8.8	10.0	31.6	38.2	18.5	34.1
2034	5.3	4.6	4.1	4.5	10.9	9.5	11.2	14.4	37.8	45.1	22.7	35.7
2042	4.6	4.1	4.1	4.0	13.0	12.0	12.0	14.3	40.1	48.1	24.5	34.9
2050	4.7	4.2	4.0	4.1	14.1	14.2	12.9	14.7	41.5	49.7	26.0	34.5
Pistachios												
2018	0.5	0.3	0.4	0.5	1.9	1.3	2.0	2.9	21.4	29.7	8.9	24.5
2026	6.7	4.5	4.5	4.1	13.2	11.4	11.4	12.2	40.9	46.0	23.6	34.5
2034	7.3	4.8	4.9	4.1	17.2	15.2	14.0	13.9	46.2	50.6	28.5	33.8
2042	6.9	4.8	5.2	3.7	18.4	15.4	15.4	13.3	46.8	50.7	30.7	32.7
2050	6.7	4.7	5.4	3.8	19.4	15.8	16.1	13.5	46.4	50.8	31.3	31.6
Pasture												
2018	0.7	0.5	0.5	0.8	2.0	1.3	2.6	3.1	21.8	30.3	9.7	25.5
2026	6.3	5.4	5.4	6.4	13.7	12.4	12.8	16.6	40.7	46.9	25.4	36.9
2034	6.7	5.8	6.1	6.9	16.7	16.0	15.6	18.1	44.5	51.0	29.8	37.6
2042	6.5	5.6	6.0	6.6	17.6	16.3	16.3	18.4	44.2	51.1	30.4	37.1
2050	6.2	5.5	5.6	6.4	18.3	16.8	16.7	18.7	43.3	51.3	30.1	36.4
Carrot												
2018	0.8	0.6	0.7	1.0	2.3	1.4	2.9	3.6	21.9	30.4	10.0	25.8
2026	6.0	5.3	5.6	6.0	13.9	12.6	12.9	16.4	40.9	47.3	25.5	37.0
2034	6.5	5.9	6.9	6.6	16.7	16.1	16.0	18.0	44.3	51.4	30.0	37.6
2042	6.3	5.5	6.5	6.2	17.5	16.1	16.7	18.1	44.0	51.3	30.6	36.8
2050	6.3	5.8	6.6	6.5	18.4	16.9	17.7	18.9	43.0	51.5	30.5	36.1
Onion												
2018	4.7	3.0	1.9	6.6	1.0	0.8	1.5	1.4	20.2	28.6	8.3	23.7
2026	5.9	5.7	5.4	5.8	8.3	6.1	9.5	11.2	34.5	39.7	19.8	37.8
2034	6.6	6.4	6.7	6.5	12.7	10.2	12.4	16.8	40.5	46.3	24.2	39.6
2042	5.9	5.5	5.7	6.0	14.5	13.0	13.3	17.1	42.3	49.6	26.3	39.0
2050	6.2	6.1	6.2	6.2	15.8	15.7	14.8	17.6	43.5	51.5	28.3	38.7
Potato												
2018	2.1	0.8	1.0	2.0	1.3	1.0	1.9	1.8	20.3	28.8	8.5	23.5
2026	8.9	7.3	3.1	4.5	8.8	6.8	9.3	12.8	35.2	40.8	19.1	36.5
2034	10.6	8.7	4.2	5.2	14.1	11.5	10.9	15.5	42.5	47.8	21.9	36.9
2042	9.1	7.5	3.3	4.8	16.9	14.8	11.1	15.3	45.4	51.9	23.0	36.1
2050	9.5	8.2	4.0	5.0	19.2	17.9	12.1	15.6	47.5	53.6	23.9	35.6

2010). Picchioni et al. (1990). The high salt tolerance of pistachio is attributed to the ability to store large amounts of Na in the roots and basal stem. Maintaining normal growth under salinity stress is associated with the ability of plants to reduce water losses and ensure an osmotic adjustment at the cellular level (Munns, 2002). However, other studies (Saandatmand et al., 2007; Karimi et al., 2011) reported that high salinity stress could negatively affect the photosynthesis rate, the morphology of leaves, and the nutrient balance of pistachio trees. The maximum soil salinity value reached during the simulations (EC_{sw} = 13.7 dS/m at 120-200 cm depth in 2047; data not shown), which is still below the crop threshold, suggests that pistachio could be a viable option for RCW irrigation in the NAP area.

4.2. Changes in sodium adsorption ratio (SAR)

The long-term use of recycled water for irrigation resulted in a considerable increase in SAR for all soils and all crops (Figs. 1,2, Table 4). For example, after 7-8 years of irrigation, SAR in all soil (except for HRB) under almond increased to a value larger than 10 (Fig. 1). Similarly, for other crops, SAR increased rapidly and its profile-averaged values ranged between 5.5 and 16.6 (Table 4) during the same time (after 7-8 years of irrigation). Subsequently, SAR continued to increase with the use of RCW irrigation for almost, attaining a constant value after about 15 years of RCW irrigation. Note that SAR at lower depths (> 100 cm) in hard clay and calcareous soils had a delayed response to RCW irrigation (Fig. 2). The profile-averaged SAR values at the end of the simulation were between 10 and 20 in all soils and for all crops (Table 4). SAR values at soil depths larger than 50 cm were greater than 15 in all soils and comparatively higher values in DUG and CAL soils (Fig. 2). Stevens et al. (2003) reported an increase in SAR in the top soil by a factor of three relative to virgin soil, which is similar to our simulations for similar RCW SAR (8.7 for Stevens et al. versus 8.1 for this study).

An increasing soil SAR triggers an exchange of cations between the soil solution and soil cation exchange complex, which increases the soil ESP. SAR values greater than 13 indicate a potential for sodic soil development (US Salinity Lab Staff, 1954). High SAR values suggest that the long-term use of irrigation with recycled water can induce sodicity hazards, which could have a severe impact on the sustainable production of pastures, and perennial and annual horticultural crops. Soil SAR is a dynamic property that depends on the composition of the soil solution when the measurements are made. However, the soil-specific inherent bio-geochemical and ion exchange reactions can have a great impact on the composition of the soil solution and exchange.

Although the profile-averaged SAR varied in a rather narrow range (12.1-19.5) in different soil-crop combinations, these values are much higher than the threshold values reported in Rangasamy et al. (1984), i.e., $SAR_{1:5} > 3$, which may result in adverse soil impacts. Based on the FAO (FAO, 1985) criteria for sodicity, SAR values predicted in our study are in the range of the light to moderate or moderate to high sodicity hazard class. This suggests that the use of recycled water irrigation can lead to the development of high ESP levels in the soil. High ESP causes reductions in the hydraulic conductivity (McNeal, 1968, 1974); for the NAP soils that would be in the range of 20 to 40% (Mallants et al., 2019). The precise extent of any adverse impacts due to high SAR is determined by factors such as concentrations of soluble

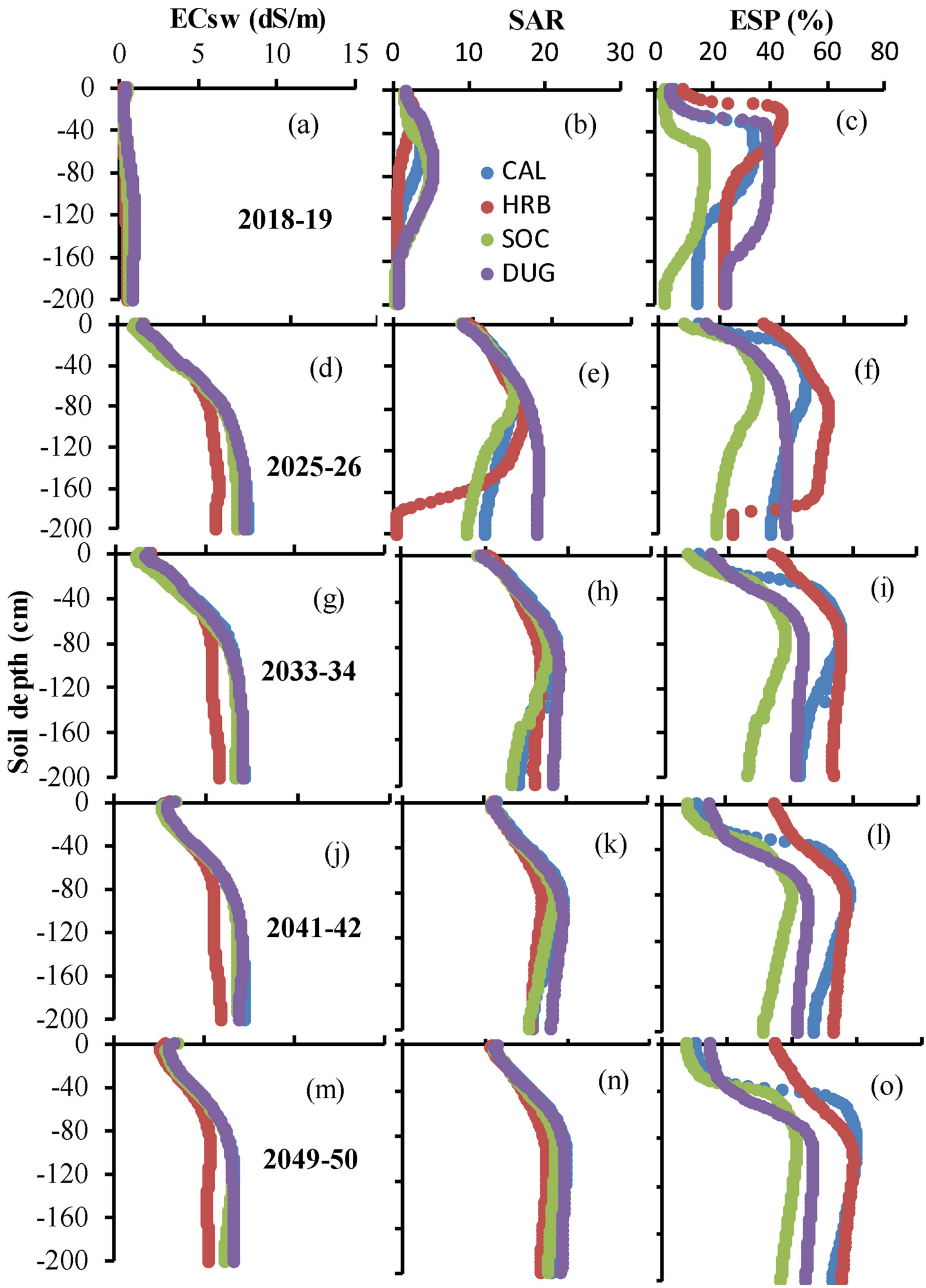

Fig. 2. Predicted changes in EC_{sw} (dS/m), SAR and ESP in different soils (CAL = calcareous soils, HRB = hard red brown, SOC = sand over clay, and DUG = deep uniform to gradational) during 2018-19 (a, b, c), 2025-26 (d, e, f), 2033-34 (g, h i), 2041-42 (j, k, l), and 2049-50 (m, n, o) for almonds irrigated with recycled water.

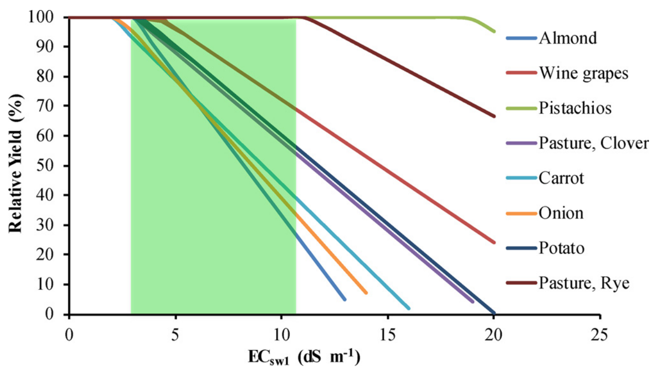

Fig. 3. Relative yield (%) and profile-averaged salinity (EC_{sw1}) relationship (Maas and Hoffman, 1977) for different crops. The green color in the background shows the model-simulated profile-averaged EC_{sw1} in different soils for different crops irrigated with recycled water.

salts, the leaching fraction, rainfall amounts, and the type and content of clay in the soil (ANZECC, ARMCANZ 2000).

4.3. Impact on Exchangeable sodium percentage (ESP)

The initial measured ESP values in the soils ranged between 7.9 and 24% (Oliver et al., 2018) and varied slightly during the warm-up period (1970- 2018) when low-salinity water was used. However, a rapid increase in ESP occurred in response to the use of RCW for irrigation (Figs. 1,2, Table 4). While the profile-averaged ESP (21.8) in the CAL soil doubled, the corresponding ESP in the SOC soil increased roughly 3 times relative to its initial value, reaching 28.7 after 32 years of irrigation (Fig. 1). Such increases in ESP were observed for all soil-crop combinations (Table 4). At the end of the simulation (2050), the corresponding profile-averaged ESP across all crops ranged between 40.7-47.5, 48.9-53.6, 23.9-31.3, and 31.6-38.7% in the CAL, HRB, SOC, and DUG soils, respectively (Table 4). An increase in ESP relative to its initially measured values in response to RCW irrigation varied from 18.8-27.1, 18.6-24.7, 15.4-22.3, and 7.1-15.0% in the CAL, HRB, SOC, and DUG soils, respectively. The maximum ESP ranging between 40 and 60 was observed in the HRB soil at the end of the simulation (Fig. 1). This demonstrates that the use of RCW over the years results in a rapid increase in ESP, which may render the soil unfit for crop production. Calculated ESP values were above their threshold value (<6 is non-sodic) in all soils at all depths.

Normally, shallow depths had lower ESP compared to deeper soil layers (Fig. 2). For example, the average initial ESP in the HRB soil in the surface layer (0-15 cm) under almond was 17.7%, which increased to 56.6% in the 120-200 cm layer at the end of the simulation. ESP at soil depths larger than 40 cm typically was between 40 and 60 in all soils. However, the HRB and CAL soils showed comparatively higher ESP (>35) than other soils. Irrigation with recycled water tends to increase the Na content on the soil exchange complex. An increase in the Na content on the soil exchange complex relative to Ca and Mg may induce soil swelling and dispersion of clay and organic matter, impact soil water movement (water logging), and degrade the soil structure. These conditions may decrease oxygen concentrations and ultimately impact the plant growth. This condition is therefore considered to be a significant barrier to a sustainable irrigation practice. The amount of dispersed clay is also affected by soil mineralogy, soil solution constituents (e.g., salinity), and organic matter (NRMMC EPHC, 2006). Therefore, soil amendments such as gypsum, compost or other organic materials would be required to control ESP below its threshold (ESP <6) and provide a congenial environment for normal crop growth.

The range of SAR and ESP observed in this study can have severe impacts on the clay dispersion, clogging of macropores, and degradation of the soil structure, which ultimately negatively affects crop growth and yield, and long-term sustainability of crops. Therefore, irrigation with recycled water should be supplemented with an adequate amount of soil amendments such as gypsum and organic matter/compost to avoid the harmful impacts on soils and crops.

4.4. Yield-salinity relationship

The modeling results presented in previous sections clearly indicated that irrigation with RCW increased the soil solution salinity (EC_{sw}) for all investigated crops. To estimate the effect of increased salinity on crop yield, the yield-salinity relations were drawn following the Maas and Hoffman (1977) piecewise linear regression. This model is given as:

$$Y_r = 100 - b(EC_{sw1} - EC_t)$$

where Y_r is the relative yield, EC_{sw1} is the profile-average soil salinity at a given time, EC_t is the crop tolerance threshold salinity, and b is a decrease in yield in percent in response to per unit increase in salinity (dS/m) above the threshold value. Calculations based on this model only indicate the impact of soluble salts on the possible reduction in the potential yield. Furthermore, high ESP can lead to an additive or multiplicative effect on the yield reduction due to its adverse impact on soil physical conditions of the soil. The latter effect was not quantified here.

The extent of average profile salinity (EC_{sw1}) in soils under different crops ranged from 2.9 to 10.6 dS/m (the green background in Fig. 3), with an overall mean of 5.5 dS/m across all soils and crops. These salinities developed over 32 years of recycled water irrigation in the NAP soils. These values correspond very well with some of the previous studies in the NAP region, which assessed the impact of the long-term (10-28 years) use of recycled water for irrigation (Stevens et al., 2003, 2004). However, their study focused on analyses of soils (unirrigated virgin soils, RCW irrigated soils, and groundwater irrigated soils) that had received different irrigation waters, while the impact on crop yields was not investigated.

The model-simulated annual profile average salinity (EC_{sw1}) for different crops was used to estimate the reduction in the potential yield (Fig. 3). The yield reduction for the 10th %tile, mean, and 90th %tile profile-averaged salinities for different soils are shown in Table 5. Pistachios and pasture (rye grass) would not experience a significant yield loss because they are tolerant crops. A yield reduction of almonds due to recycled water irrigation varied from 9 to 22%, depending on the soil type. A reduction in wine grapes is comparatively low (0-5.7%) due to a higher tolerance to salinity. A comparison of almond yields grown in the NAP (Pitt et al., 2017) and Riverland regions (Phogat et al., 2013; average yield of 8 years) revealed that the almond yield in the NAP region was only 50% of that in the Riverland region. The major difference between the two sites was the water quality used for irrigation, climate, and the soil type (more sandy in Riverland). In the Riverland, almonds are irrigated with the River Murray water, which has a much lower salinity (0.4 dS/m; Phogat et al., 2018a) than recycled water, groundwater, or blended water (0.8-1.9 dS/m; Phogat et al., 2018b) used in the NAP region. The current hypothesis is that the use of RCW in the NAP region (Pitt et al., 2017) with its high soil salinity (soil profile EC_{Se} = 2-7.5 dS/m) might have contributed greatly to the reduction in the almonds yield.

The yield reduction in clover pasture ranged from 12 to 23.8%. Therefore, under mixed pasture conditions (rye grass and clover), RCW irrigation can potentially impact the clover crop. Similarly, among annual horticulture crops, almost one-third of the potential yield in onion (23.5-34.9%) and potato (23.5-34.9%) could be lost due to salinity stress. The corresponding yield loss for carrot and brassicas ranged from 19.6 to 32.4 and from 5.8 to 14.7%, respectively.

Salinity impacts on crops are influenced by climate, irrigation, and agronomic management (Rhodes and Loveday 1990). Generally, most

Table 5
The reduction in the potential crop yield (%) due to profile-averaged salinity (10^{th} %tile, mean, 90^{th} %tile) in calcareous (CAL), hard red brown (HRB), sand over clay (SOC), and deep uniform to gradational (DUG) soils under recycled water irrigation.

	Soil	Almond	Grape	Pista	Carrot	Onion	Potato	Pasture (Clover)	Pasture (Rye)
10^{th} %tile	Cal	15.1	0.0	0.0	22.9	26.8	23.4	17.2	0.0
	HRD	9.1	0.0	0.0	19.6	24.9	15.2	12.0	0.0
	SoC	11.5	0.0	0.0	22.2	23.5	0.0	13.8	0.0
	DuG	15.0	0.0	0.0	24.4	27.5	5.9	18.7	0.0
Mean	Cal	17.6	1.7	0.0	27.1	30.5	34.5	19.2	0.0
	HRD	11.2	0.0	0.0	23.1	27.5	25.1	13.9	0.0
	SoC	15.1	0.0	0.0	27.7	28.5	0.6	16.1	0.0
	DuG	17.9	0.0	0.0	27.4	30.7	8.0	20.1	0.0
90^{th} %tile	Cal	22.2	5.7	0.0	31.1	33.6	42.9	22.9	0.0
	HRD	15.2	2.5	0.0	26.8	31.4	32.1	17.1	0.0
	SoC	20.0	1.6	0.0	32.4	34.9	3.8	19.9	0.0
	DuG	22.2	2.3	0.0	31.2	33.2	10.5	23.8	0.0

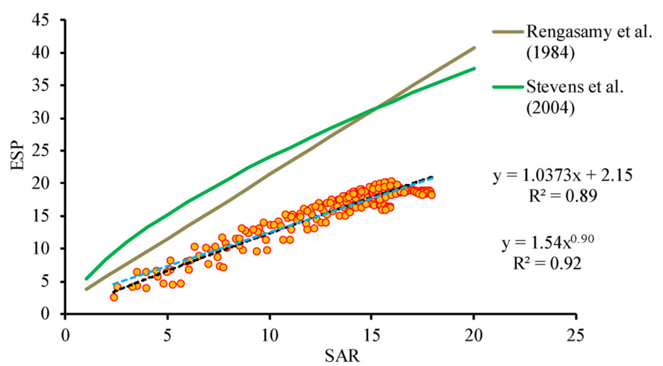

Fig. 4. A comparison of relationships between model-simulated sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) (average data for all soils) with published relations previously developed for the NAP soils.

vegetable crops suffer a 10% yield reduction at an EC_e of 2.7 ± 0.8 dS/m ($EC_{sw1} \approx 2\ EC_e$) (ANZECC, ARMCANZ 2000). Therefore, appropriate management of irrigation induced soil salinity is essential for sustainable crop production in the NAP soils. The effectiveness of mitigation scenarios is reported in Mallants et al. (2019) and will not be discussed here.

4.5. Sodicity development

The NAP soils are inherently sodic with a high Na content in the soil solution and on the exchange complex, especially at deeper depths (Matheson and Lobban 1974). Even the virgin soils have been shown to have SAR as high as 44 at lower depths (Stevens et al., 2003). However, RCW containing SAR_w (SAR of water) of 8-12.2 can have a significant impact on an increase in the soil SAR. The data in the current study showed that a rapid increase in the soil solution SAR occurred due to the use of RCW for irrigation. Overall average increases in the profile-averaged SAR values as a result of RCW irrigation in the CAL, HRB, SOC, and DUG soils were equal to 17.4, 15.8, 13.3, and 13.8, respectively, and corresponding increase ESP values in response to RCW irrigation was 22.7, 21.6, 19.4 and 10.5%, respectively (Table 4).

It is well understood that high SAR of the soil solution can potentially modify the cation dynamics in the soil solution as well as on the soil exchange complex. High SAR ultimately leads to the development of high ESP in the soils. However, there is no universally accepted relationship that can define the intricate dynamics between the soil solution and the soil cation exchange complex. Similarly, there is no universal understanding of the critical ESP value to categorize the sodic soils. In Australia, a sodic soil is defined as the soil, which has an ESP larger than 6 (Northcote and Skene, 1972). However, the American classification of sodic soils has an ESP threshold of 15 (US Salinity Lab Staff, 1954). This difference is attributed to several factors including differences in electrolyte concentrations, pH, organic matter contents, and the clay type and contents, and the way such differences in soil chemistry affect the critical ESP, above which clay dispersion and hydraulic conductivity reduction occur (Rengasamy and Olsson, 1991).

Measuring ESP is complicated and time-consuming, and therefore alternative parameters, which can better characterize sodic soils, have been sought after. Many studies (e.g., Rengasamy et al., 1984) suggested SAR as an alternative indicator for sodic soils, since SAR is highly correlated with the soil ESP and can be more conveniently measured. Numerous studies have attempted to find a relation between SAR_e (SAR of the saturation extract) and ESP of the soils in different parts of the world (US Salinity Lab Staff, 1954; Paliwal and Gandhi, 1976; Shainberg et al., 1980; Evangelou and Marsi, 2003; Seilsepour et al., 2009; Chi et al., 2011). These approximate relationships vary according to site-specific soil parameters, such as the clay content and mineralogy of the soils. Similarly, Rengasamy et al. (1984) extended this relation between $SAR_{1:5}$ and ESP for Australian soils, similar to those in the current study, to facilitate the soil classification (Fig. 5). Similarly, Chi et al. (2011) found that there were non-significant differences in the ESP development from the approximate log relations with SAR_e or $SAR_{1:5}$.

As for the soils of the NAP region, Rengasamy et al. (1984) found a linear relationship (ESP = 1.95*SAR + 1.85, R^2 = 0.82) between $SAR_{1:5}$ and ESP, whereas Stevens et al. (2003) reported a curvilinear (ESP = 5.36*$SAR^{0.65}$, R^2 = 0.83) relationship (Fig. 4). Stevens et al. (2003) hypothesized that the inclusion of the soil analysis of deeper layers (up to 1 m) might change the nature of the relationship as the former study only analyzed samples from surface layers (0-45 cm). We attempted to draw similar relationships to understand the impact of RCW irrigation on sodicity development in the soils. A strong relationship was found between the irrigation-induced SAR and the resulting soil ESP (Fig. 4). Both linear, as well as curvilinear regressions models, showed good agreement, with an R^2 of 0.89 and 0.92, respectively.

Since the simulations provided sufficient SAR/ESP data for all soil types, we have derived separate relationships between SAR and ESP for different NAP soils (Fig. 5). There was a good curvilinear relationship between SAR and ESP with R^2 values of 0.91, 0.93, and 0.94 for the Cal, HRB, and SoC soils, respectively. However, the relation for the DuG soils was poor (R^2 = 0.29). The initially high ESP of these soils may have influenced the rate of Na^+ exchange between the soil solution and the exchange phase, which may, in turn, have resulted in the lower ESP build-up in response to recycled water irrigation. More importantly, the relations in Fig. 5 suggest that different SAR thresholds exist, which could lead to soil ESP exceeding the threshold value of ESP = 6. Indeed,

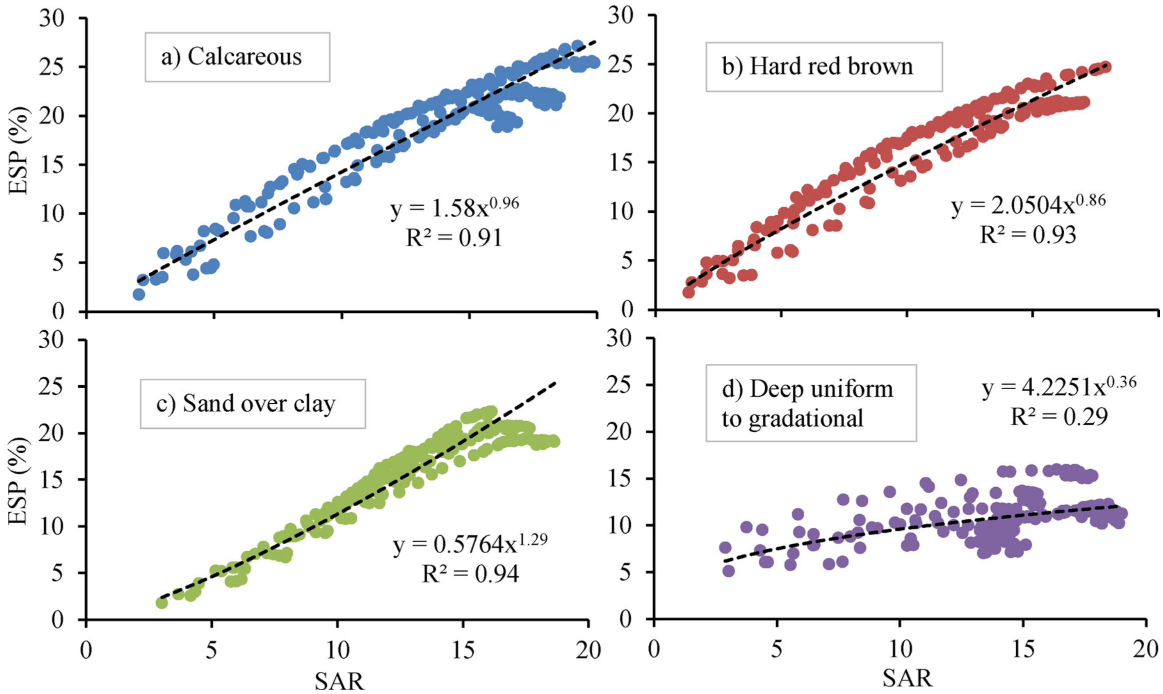

Fig. 5. Relationships between model-simulated sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) for different NAP soils.

the SAR thresholds (SAR_{th}) that would cause ESP to exceed its threshold are as follows: SAR_{th} = 4 for calcareous soils, SAR_{th} = 3.5 for hard red brown soils, SAR_{th} = 6 for sand over clay soils, and SAR_{th} = 3 for deep uniform to gradational soils.

Rengasamy et al. (1984) suggested a common SAR > 3, irrespective of the soil type, associated with clay dispersion, crusting, and reduced porosity in similar soils. However, they found a strong correlation between clay dispersion and both SAR and the total cation concentration (TCC). In another study, Rengasamy and Marchuk (2011) proposed an alternative ratio (CROSS) to SAR. It includes other cations (Mg and K) that induce the dispersive behavior in the soil, which is critical for characterizing the structural stability of the soils. However, we understand that the degree of dispersivity due to different cations (e.g., Na^+, K^+, and Mg^{++}) may not be a basic soil property, but may depend on all inherent soil characteristics, which affect the biogeochemical dynamics of the soil solution and soil exchange. However, our study was not aimed at deriving any such critical thresholds for evaluating the dispersive behavior of different soils. We suggest that further studies are undertaken to thoroughly understand the critical relative concentrations of various cations (i.e., SAR) in different NAP soils that could impact the structural stability, clay dispersion and a reduction in the hydraulic conductivity of the soils. Such information can help devise soil/location-specific guidelines for reducing the harmful impacts of the use of RCW for irrigation.

One of the main concerns with SAR of irrigation water is its effect on modifying the soil cation exchange complex, resulting in high ESP, which, in turn, has a dramatic impact on the structural stability and the hydraulic properties of soil. Excellent hydraulic conductivity needs to be maintained to enable appropriate leaching requirements to move salts below the root zone. Good soil structure also aids root development, improving plant health, and drought resistance. Based on the modeling results, it is suggested that the use of RCW for irrigation may need frequent applications of soil amendments such as gypsum, organic matter/compost, and/or combination of such products, such that soil ESP can be managed to maintain values below the threshold (ESP < 6%) for sustainable crop production. Similarly, low concentrations of soluble salts in the soils need to be maintained by adopting appropriate leaching, preferably, with low-salinity water, such as harvested rainwater, to realize long-term sustainability of RCW irrigation (Mallants et al., 2019). Stevens et al. (2004) suggested a leaching fraction of 20-50% as ideal for RCW water used in the NAP region. Other studies (e.g., Kumar and Kookana, 2006) expressed similar concerns with winery wastewater, containing salinity and SAR problems. Overall, the long-term use of recycled water for irrigation can potentially increase soil salinity and sodicity hazards beyond the threshold, thereby rendering the soil unfit for cultivation. Therefore, adequate management options must be explored to use these waters sustainably for crop production in the NAP region.

The results are broadly applicable to the two irrigation systems: overhead sprinkler and drippers. Note that the modelling itself did not account for differences in irrigation method, as it was a one-dimensional model. A two-dimensional model would be required to incorporate any small-scale spatial effects of different irrigation methods on water and salt distribution in soil (see e.g. Phogat et al. 2014). Extrapolation to other regions where RCW is currently used or may be used in the future is possible, however care should be taken to adjust the findings for local conditions of irrigation water quality, soil types, climate, and crops.

5. Conclusions

This study uses the multicomponent UNSATCHEM module of HYDRUS-1D to evaluate the impact of the long-term (2018-2050) use of RCW for irrigating wine grapes, almonds, pistachios, pasture, carrot, onion, and potato crops in different NAP soils (calcareous, hard red brown, sand over clay and deep uniform to gradational). Simulated data revealed that irrigation with recycled water can potentially increase the soil solution salinity (EC_{sw}), sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP) in the soil. The average end-of-simulation EC_{sw} in the soil profile under different crops in the 10^{th} to 90^{th} %tile range varied from 2.9 to 10.6 dS/m. Usually, the average EC_{sw} in the upper soil layers (< 30 cm) remained lower than 4 dS/m for almonds, wine grapes, pistachios, and pasture, while under annual horticulture (carrot, onion, potato), salinity may rise to between 4.87 and 9.5 dS/m due to upward movement of salts during the cover crop season. Average soil salinity at lower depths (> 30 cm) ranged from 3.6 to 10.8 dS/m for all crops, including pasture, viticulture, and perennial horticulture.

Increased salinity in the soil reduced the potential yield of almond by 12- 20% in different soils, with a higher yield loss in the hard red brown soils, followed by the calcareous soils. However, no yield loss was observed for wine grapes, perennial pastures, and pistachios, as these are relatively salinity tolerant crops. However, annual horticultural crops (carrot, onion, potato) showed yield losses from 4 to 32% due to increased salinity associated with RCW irrigation.

The use of RCW for irrigation also has a strong impact on the soil solution and cation exchange dynamics, which increased the SAR in the soils. After 32 years of irrigation, the simulated profile average values of SAR were 17.4, 15.8, 15.5, and 16.3 in the calcareous, hard red brown, sand over clay, and deep uniform to gradational soils, respectively. These values are higher than the threshold SAR reported in many previous studies, which are associated with an increase in the ESP of the soils. The model predicted profile average ESP in the soil increased in absolute values by 22.7, 21.6, 19.4, and 10.5 respectively, in the calcareous, hard red brown, sand over clay, and deep uniform to gradational soils. These values are much higher than the accepted ESP thresholds (ESP > 6) for Australian soils. Thus, it is suggested that high SAR and ESP build-up in the soils as a result of RCW irrigation to different crops could adversely impact the physical properties of soils including clay dispersion, porosity and hydraulic conductivity, and structural stability of the soil. Therefore, adequate management options must be put in place such that adverse impacts of the use of recycled water can be minimized, realizing a long-term sustainable crop production.

6. Declaration of Competing Interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Acknowledgments

Authors acknowledge the financial support provided by the Goyder Institute for Water Research for this work; under the project "Sustainable Expansion of irrigated Agriculture and Horticulture in Northern Adelaide Corridor (Project Number ED-17-01)."

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106167.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy.
Andrews, D.M., Robb, T., Elliott, H., Watson, J.E., 2016. Impact of long-term wastewater irrigation on the physicochemical properties of humid region soils: "The Living Filter" site case study. Agric. Water Manage 178, 239–247.
ANZECC, ARMCANZ, 2000. National water quality management strategy: Australian and New Zealand guidelines for fresh and marine water quality: volume 1: the guidelines (Chapters 1–7). Australia and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand.
Assouline, S., Narkis, K., 2013. Effects of long-term irrigation with treated wastewater on the root zone environment. Vadose Zone J. 12, 1–10. https://doi.org/10.2136/vzj2012.0216.
Assouline, S.K., Narkis, R., Gherabli Sposito, G., 2016. Combined effect of sodicity and organic matter on soil properties under long-term irrigation with treated wastewater. Vadose Zone J. 15 (4), 1–10.
Awad, J., Vanderzalm, J., Pezzaniti, D., Olubukoa Esu, O.-O., van Leeuwen, J., 2019. Sustainable Expansion of Irrigated Agriculture and Horticulture in Northern Adelaide Corridor: Source water options/water availability, quality and storage consideration. Goyder Institute for Water Research Technical Report Series No. xx/18, Adelaide, South Australia.
Ayers, R.S., Westcot, D.W., 1985. Water Quality for Agriculture. FAO Irrigation and Drainage Paper 29. Food and Agriculture Organization of the United Nations, pp. 174 Rome Babcock, B.A., 2008. Breaking the link between food and biofuels. Iowa Ag. Rev. 14(3), 1–12.
Bardhan, G., Russo, D., Goldstein, D., Levy, G.J., 2016. Changes in the hydraulic properties of a clay soil under long-term irrigation with treated wastewater. Geoderma 264, 1–9.
Basile, A., Buttafuoco, G., Mele, G., Tedeschi, A., 2012. Complementary techniques to assess physical properties of a fine soil irrigated with saline water. Environ. Earth Sci. 66, 1797–1807.
Charles, S.P., Fu, G., 2015. Statistically Downscaled Projections for South Australia – Task 3 CSIRO Final Report. Goyder Institute for Water Research Technical Report Series No. 15/1, Adelaide, South Australia.
Chelli-Chaabouni, A., Ben Mosbah, A., Maalej, M., Gargouri, K., Gargouri-Bouzid, R., Drira, N., 2010. In vitro salinity tolerance of two pistachio rootstocks: *Pistacia vera* L. and *Pistacia atlantica* Desf. Environ. Exp. Bot. 69, 302–312.
Chi, C.M., Zhao, C.W., Sun, X.J., Wang, Z.C., 2011. Estimating exchangeable sodium percentage from sodium adsorption ratio of salt-affected soil in the Songnen Plain of Northeast China. Pedosphere 21 (2), 271–276.
Cresswell, R.G., Dighton, J., Leaney, F., Vleeshouwer, J., Morrow, D., Harris, M., Stenson, M., 2010. Australia-wide network to measure rainfall chemistry and isotopic composition – Final report of project MD311, CSIRO. Water for a Healthy Country National Research Flagship, Australia.
CSIRO, BoM, 2016. State of the Climate (Accessed 28 November 2019). Commonwealth Scientific and Industrial Research Organisation & Bureau of Meteorology. http://www.bom.gov.au/state-of-the-climate/State-of-the-Climate-2016.pdf.
Department of Environment, Water and Natural Resources, 2016. Non-prescribed Surface Water Resources Assessment – Adelaide and Mount Lofty Ranges Natural Resources Management Region, DEWNR Technical report 2016/34. Department of Environment, Water and Natural Resources, Government of South Australia, Adelaide.
Elfanssi, S., Ouazzani, N., Mandi, L., 2018. Soil properties and agro-hysiological responses of alfalfa (*Medicago sativa* L.) irrigated by treated domestic wastewater. Agric. Water Manage 202, 231–240.
Enemark, T., Peeters, L.J.M., Mallants, D., Batelaan, O., 2019. Hydrogeological conceptual model building and testing: A review. Journal of Hydrology 569. https://doi.org/10.1016/j.jhydrol.2018.12.007.
Evangelou, V.P., Marsi, M., 2003. Influence of ionic strength on sodium-calcium exchange of two temperate climate soils. Plant Soil. 250, 307–313.
FAO, 1985. Water Quality for Agriculture. Food and Agriculture Organization, Rome, Italy.
FAO, 2012. Coping with water scarcity. An action framework for agriculture and food security. FAO Water Reports 38. Food and Agriculture Organisation of the United Nations, Rome.
Famiglietti, J.S., 2014. The global groundwater crisis. Nature Climate Change 4 (11), 945–948.
Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc, Wageningen, The Netherlands.
Ferguson, L., Poss, P.A., Grattan, S.R., Grieve, C.M., Want, D., Wilson, C., Donovan, T.J., Chao, C.T., 2002. Pistachio rootstocks influence scion growth and ion relations under salinity and boron stress. J. Amer. Soc. Hort. Sci. 127 (2), 194–1999.
Ferguson, L., Sanden, B., Grattan, S., 2010. Understanding the Effects of Salinity on Pistachios. Fruits and nuts University Research and Information Center, University of California. http://fruitsandnuts.ucdavis.edu/files/74208.pdf.
Gapon, E.N., 1933. Theory of exchange adsorption in soils. J. General Chem. USSR. 3, 144–152.
Gonçalves, M.C., Šimůnek, J., Ramos, T.B., Martins, J.C., Neves, M.J., Pires, F.P., 2006. Multicomponent solute transport in soil lysimeters irrigated with waters of different quality. Water Resour. Res. 42 (8), 1–17.
Grattan, S.R., Díaz, F.J., Pedrero, F., Vivaldi, G.A., 2015. Assessing the suitability of saline wastewaters for irrigation of Citrus spp.: Emphasis on boron and specific-ion interactions. Agric. Water Manage. 157, 48–58.
Hajiboland, R., Noroozi, F., Poschenrieder, C., 2014. Growth physiological, biochemical and ionic responses of pistachio seedlings to mild and high salinity. Trees 28, 1065–1078.
Hamilton, A.J., Stagnitti, F., Xiong, X.Z., Kreidl, S.L., Benke, K.K., Maher, P., 2007. Wastewater irrigation: The state of play. Vadose Zone J. 6 (4), 823–840.
Hanjraa, M.A., Blackwella, J., Carrc, G., Zhangd, F., Jacksona, T.M., 2012. Wastewater irrigation and environmental health: implications for water governance and public policy. Int. J. Hyg. Environ. Health 215, 255–269.
Hassena, A.B., Zouari, M., Trabelsi, L., Khabou, W., Zouari, N., 2018. Physiological improvements of young olive tree (*Olea europaea* L. cv. Chetoui) under short-term irrigation with treated wastewater. Agric. Water Manage 207, 53–58.
IPCC, 2014. Intergovernmental panel on climate change. Climate change 2014: impacts, adaptation, and vulnerability. Accessed 18 Feb 2020. http://www.ipcc.ch/report/ar5/wg2.
Kaledhonkar, M.J., Keshari, A.K., van Der Zee, S.E.A.T.M., 2006. Relative sensitivity of ESP profile to spatial and temporal variability in cation exchange capacity and pore water velocity under simulated field conditions. Agric. Water Manage 83, 58–68.
Karimi, H.R., Ebadi, A., Zamani, Z., Fatahi, R., 2011. Effect of water salinity on growth induces physiological parameters in some pistachio rootstocks. J. Plant Nutr. 34, 935–944.
Karimi, H.R., Maleki Kuhbanani, A., 2015. The evaluation of inter-specific hybrid of P. atlantica × P. vera cv. 'Badami zarand' as a pistachio rootstock to salinity stress. J. Nuts 6 (2), 113–122.
Kumar, A., Kookana, R., 2006. Impact of winery wastewater on ecosystem health - an introductory assessment. Project report to CSIRO Land and Water for Grape and Wine

Research and Development Corporation, Adelaide, Australia.
Lal, K., Minhas, P.S., Yadav, R.K., 2015. Long-term impact of wastewater irrigation and nutrient rates II. Nutrient balance, nitrate leaching and soil properties under peri-urban cropping systems. Agric. Water Manage 156, 110–117.
Maas, E.V., Hoffman, G.J., 1977. Crop salt tolerance- Current assessment. J. Irrig. Drain. Div. 103 (2), 115–134.
Mallants, D., Phogat, V., Oliver, D., Ouzman, J., Beirgadhar, Y., Cox, J., 2019. Sustainable expansion of irrigated Agriculture and Horticulture in Northern Adelaide Corridor: Task 2. Goyder Institute for Water Research Technical Report Series No. 18-02, Adelaide, South Australia.
Mallants, D., Šimůnek, J., Torkzaban, S., 2017. Determining water quality requirements of coal seam gas produced water for sustainable irrigation. Agric. Water. Manage. 189, 52–69.
Matheson, W.E., Lobban, B.L., 1974. Bolivar effluent irrigation project. Progress Report No. S10/74. Department of Agriculture, South Australia, Adelaide.
McNeal, B.L., 1968. Prediction of the effect of mixed-salt solutions on soil hydraulic conductivity. Soil Sci. Soc. Amer. Proc. 32, 190–193.
McNeal, B.L., 1974. Soil salts and their effects on water movement. In: van Schilfgaarde, J. (Ed.), Drainage for Agriculture, Agronomy No 17, Am. Soc. Agr., Madison, WI.
Minhas, P.S., Yadav, R.K., Lal, K., Chaturvedi, R.K., 2015. Effect of long-term irrigation with wastewater on growth, biomass production and water use by Eucalyptus (*Eucalyptus tereticornis* Sm.) planted at variable stocking density. Agric.Water Manage 152, 151–160.
Momenpour, A., Imani, A., 2018. Evaluation of salinity tolerance in fourteen selected pistachio (*Pistacia vera* L.) cultivars. Adv. Hort. Sci. 32 (2), 249–264.
Morgan, K.T., Wheaton, T.A., Parsons, L.R., Castle, W.S., 2008. Effects of reclaimed municipal waste water on horticultural characteristics, fruit quality, and soil and leaf mineral concentration of citrus. Hort. Sci. 43, 459–464.
Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.
Munns, R., 2002. Comparative physiology of salt and water stress. Plant Cell Environ. 25, 239–250.
Northcote, K.H., Skene, J.K.M., 1972. Australian soils with saline and sodic properties. Soil Publication No. 27. Commonwealth Scientific and Industrial Research Organisation, Australia.
Noshadi, I., Salahi, A., Hemmati, M., Rekabdar, F., Mohammadi, T., 2013. Experimental and ANFIS modeling for fouling analysis of oily wastewater treatment using ultra-filtration. Asia-Pac. J. Chem. Eng. 8, 527–538.
NRMMC, EPHC, 2006. Australian Guidelines for Water Recycling. Managing Health and Environmental Risks. Phase 1. National Water Quality Management Strategy 21. In: Natural Resource Management Ministerial Council. Environment Protection and Heritage Council Australian Health Ministers' Conference. Canberra, Australia.
Oliver, D.P., Fruzangohar, M., Johnston, C., Ouzman, J., Barry, K., 2018. Sustainable expansion of irrigated agriculture and horticulture in northern Adelaide corridor. Task 1: Development and optimisation of modelling domain and impact assessment of irrigation expansion on the receiving environment. Goyder Institute for Water Research Technical Report Series No. 18-01, Adelaide, South Australia.
Otoo, M., Drechsler, P., 2018. Resource recovery from Waste. Business models for energy, resource and water reuse in low- and middle-income countries. Routledge, New York.
Paliwal, K.V., Gandhi, A.P., 1976. Effect of salinity, SAR, Ca: Mg ratio in irrigation water and soil texture on the predictability of exchangeable sodium percentage. Soil Sci. 122 (2), 85–90.
Parsons, L.R., Wheaton, T.A., Castle, W.S., 2001. High application rates of reclaimed water benefit citrus tree growth and fruit production. Hort. Sci. 36, 1273–1277.
Paudel, I., Cohen, S., Shaviv, A., Bar-Tal, A., Bernstein, N., Heuer, B., Ephrath, J., 2016. Impact of treated wastewater on growth, respiration and hydraulic conductivity of citrus root systems in light and heavy soils. Tree Physiol. 36, 770–785.
Phogat, V., Mahadevan, M., Skewes, M., Cox, J.W., 2012. Modeling soil water and salt dynamics under pulsed and continuous surface drip irrigation of almond and implications of system design. Irrig. Sci. 30 (4), 315–333.
Phogat, V., Skewes, M.A., Mahadevan, M., Cox, J.W., 2013. Evaluation of soil plant system response to pulsed drip irrigation of an almond tree under sustained stress conditions. Agric. Water Manage. 118, 1–11.
Phogat, V., Skewes, M.A., Cox, J.W., Sanderson, G., Alam, J., Šimůnek, J., 2014. Seasonal simulation of water, salinity and nitrate dynamics under drip irrigated mandarin (Citrus reticulata) and assessing management options for drainage and nitrate leaching. J. Hydrol. 513, 504–516.
Phogat, V., Skewes, M.A., McCarthy, M.G., Cox, J.W., Šimůnek, J., Petrie, P.R., 2017. Evaluation of crop coefficients, water productivity, and water balance components for wine grapes irrigated at different deficit levels by a sub-surface drip. Agric. Water Manage. 180, 22–34.
Phogat, V., Cox, J.W., Šimůnek, J., 2018a. Identifying the future water and salinity risks to irrigated viticulture in the Murray-Darling Basin, South Australia. Agric. Water Manage. 201, 107–117.
Phogat, V., Pitt, T., Cox, J.W., Šimůnek, J., Skewes, M.A., 2018b. Soil water and salinity dynamics under sprinkler irrigated almond exposed to a varied salinity stress at different growth stages. Agric. Water Manage. 201, 70–82.
Phogat, V., Mallants, D., Cox, J.W., Šimůnek, J., Oliver, D.P., Awad, J., 2020. Management of soil chemical changes associated with irrigation of protected crops. Agric. Water Manage. 227. https://doi.org/10.1016/j.agwat.2019.105845.
Picchioni, G.A., Miyamoto, S., Storey, J.B., 1990. Salt effects on growth and ion uptake of pistachio rootstock seedlings. J. Am. Soc. Hort. Sci. 115, 647–653.
Pitt, T., Phogat, V., Fleming, N., Cox, J., 2017. Almond salt sensitivity: avoiding salt stress during critical growth stages. Final report of project SARMS IRSPR1-010. South Australian Research and Development Institute, The State of South Australia.
Qadir, M., Wichelns, D., Sally, L.R., McCornick, P.G., Drechsel, P., Bahri, A., Minhas, P.S., 2010. The challenges of wastewater irrigation in developing countries. Agric. Water Manage. 97, 561–568.
Qian, Y., Lin, Y., 2019. Comparison of soil chemical properties prior to and five to eleven years after recycled water irrigation. J. Environ. Qual. https://doi.org/10.2134/jeq2019.03.0132.
Ramos, T.B., Šimůnek, J., Goncalves, M.C., Martins, J.C., Prazeres, A., Castanheira, N.L., Pereira, L.S., 2011. Field evaluation of a multicomponent solute transport model in soils irrigated with saline waters. J. Hydrol. 407, 129–144.
Rengasamy, P., Greene, R.S.B., Ford, G.W., Mehanni, A.H., 1984. Identification of dispersive behaviour and the management of red-brown earths. Aust. J. Soil Res. 22, 413–431.
Rengasamy, P., Marchuk, A., 2011. Cation ratio of soil structural stability (CROSS). Soil Res. 49, 280–285.
Rengasamy, P., Olsson, K.A., 1991. Sodicity and soil structure. Aust. J. Soil Res. 29, 935–952.
Rengasamy, P., Olsson, K.A., 1993. Irrigation and sodicity. Aust. J. Soil Res. 31, 821–837.
Rhodes, J.D., Loveday, J., 1990. Salinity in irrigated agriculture. In: Stewart, B.A., Nielsen, D.R. (Eds.), Agronomy Monograph No. 30. ASA Publishers, Madison, pp. 1089–1142.
Saandatmand, A.R., Banihashemi, Z., Maftoun, M., Sepaskhah, A.R., 2007. Interactive effects of soil salinity and water stress on growth and chemical compositions of pistachio nut trees. J. Plant Nutr. 30, 2037–2050.
Sanden, B.L., Ferguson, L., Reyes, H.C., Grattan, S.C., 2004. Effect of salinity on evapotranspiration and yield of San Joaquin Valley pistachios. In: Proceedings of the IVth International Symposium on Irrigation of Horticultural Crops. Acta Horti. pp. 583–589 664.
Seilsepour, M., Rashidi, M., Khabbaz, B.G., 2009. Prediction of soil exchangeable sodium percentage based on soil sodium adsorption ratio. Am.-Eurasian J. Agric. Environ. Sci. 5 (1), 1–4.
Sepaskhah, A.R., Maftoun, M., 1981. Growth and chemical composition of pistachio seedlings as influenced by irrigation regimes and salinity levels of irrigation water: I. Growth. J. Am. Soc. Sci. 57, 469–476.
Sepaskhah, A.R., Maftoun, M., 1988. Relative salt tolerance of pistachio cultivars. J. Hort. Sci. 63 (1), 157–162.
Shainberg, I., Oster, J.D., Wood, J.D., 1980. Sodium calcium exchange in montmorillonite and illite suspensions. Soil Sci. Soc. Am. J. 44, 960–964.
Šimůnek, J., Šejna, M., Saito, H., Sakai, M., van Genuchten, M. Th., 2013. The Hydrus-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 4.17, HYDRUS Software Series 3. Department of Environmental Sciences, University of California Riverside, Riverside, California, USA.
Šimůnek, J., Suarez, D.L., 1994. Two-dimensional transport model for variably saturated porous media with major ion chemistry. Water Resour. Res. 30 (4), 1115–1133.
Šimůnek, J., Suarez, D.L., 1997. Sodic soil reclamation using multicomponent transport modeling. ASCE J. Irrig. Drain. Eng. 123 (5), 367–376.
Šimůnek, J., van Genuchten, M.T., Šejna, M., 2016. Recent developments and applications of the HYDRUS computer software packages. Vadose Zone J. 15, 25.
Singh, P.K., Deshbhratar, P.B., Ramteke, D.S., 2012. Effects of sewage waste water irrigation on soil properties, crop yield and environment. Agric. Water Manage. 103, 100–104.
Skaggs, T.H., Suarez, D.L., Corwin, D.L., 2014. Global sensitivity analysis for UNSATCHEM simulations of crop production with degraded waters. Vadose Zone J. 13 (6), 1–13. https://doi.org/10.2136/vzj2013.09.0171.
Stevens, D.P., McLaughlin, M.J., Smart, M., 2003. Effect of long-term irrigation with reclaimed water on soils of the Northern Adelaide Plains. SA. Aust. J. Soil Res. 41, 933–948.
Stevens, D.P., Smart, M., Kelly, J., McLaughlin, M.J., Gerges, N., Ovens, G., van der Wielen, M., Rengasamy, P., Myer, N., 2004. Sustainable use of recycled water for horticultural irrigation on the Northern Adelaide Plains. Final Project Report No. VG 97081. Horticulture Australia Ltd., Sydney, NSW, Australia.
Suarez, D.L., 2001. Sodic soil reclamation: Modelling and field study. Aust. J. Soil Res. 39, 1225–1246.
Suarez, D.L., Wood, J.D., Lesch, S.M., 2006. Effect of SAR on water infiltration under a sequential rain–irrigation management system. Agric. Water Manage. 86, 150–164.
Taylor, S., Ashcroft, A., 1972. Physical Edaphology. Freeman and Co., San Francisco, California, pp. 434–435.
The Goyder Institute for Water Research, 2016. Northern Adelaide Plains Water Stocktake Technical Report. The Goyder Institute for Water Research, Adelaide, South Australia.
UN Environment, 2019. Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. Nairobihttps://doi.org/10.1017/9781108627146. Accessed on 18 Feb, 2020.
US Salinity Lab Staff, 1954. Diagnosis and improvement of saline and alkali soils. Handbook No. 60. United States Department of Agriculture, Washington, DC.
Valdes-Abellan, J., Jiménez-Martínez, J., Candela, L., Jacques, D., Kohfahl, C., Tamoh, K., 2017. Reactive transport modelling to infer changes in soil hydraulic properties induced by non-conventional water irrigation. J. Hydrol. 549, 114–124.
van Genuchten, M.Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.
Walker, R.R., Törökfalvy, E., Behboodian, M.H., 1988. Photosynthetic rates and solute partitioning in relation to growth of salt-treated pistachio plants (P. veracv. Kerman). Aust. J. Plant Physiol. 15, 787–798.
Walker, R.R., Törökfalvy, E., Behboudian, M.H., 1987. Uptake and distribution of chloride: sodium and potassium ions and growth of salt-treated pistachio plants. Aust.

J. Agric. Res. 38, 383–394.
Wang, J., Bai, Z., Yang, P., 2014. Mechanism and numerical simulation of multi-component solute transport in sodic soils reclaimed by calcium sulfate. Environ. Earth Sci. 72, 157–169.
White, N., Zelazny, L.W., 1986. Charge properties in soil colloids. In: Sparks, D.L. (Ed.), Soil Physical Chemistry. CRC Press, BOCA Raten, Florida.
Youngs, E.G., 2001. Hydraulic conductivity of saturated soils. In: Smith, K.A., Mullins, C.E. (Eds.), Soil and Environmental Analysis: Physical Methods, 2nd ed. Marcel Dekker, Inc., New York, NY, pp. 141–181.
Zhang, X., Walker, R.R., Stevens, R.M., Prior, L.P., 2002. Yield-salinity relationships of different grapevine (*Vitis vinifera* L.) scion-rootstock combinations. Aust. J. Grape Wine Res. 8, 150–156.