Sustainable expansion of irrigated agriculture and horticulture in Northern Adelaide Corridor: Task 2 - Modelling nutrient and chemical fate to support the long-term sustainability of the use of recycled water

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Executive summary

The challenge

The Northern Adelaide Plains (NAP) has significant potential for sustainable economic development from the expansion of irrigated agriculture. In 2016, the Goyder Institute for Water Research instigated a stocktake of the water resources, with consideration of both quantity and quality, on the NAP that could be made available for economic development in the region in the short term.

One of the major constraints to expansion of horticulture in the NAP has been an available water supply. The expansion of the use of reclaimed water in the region will aim to address this limitation. In order to monitor and manage the expansion of agriculture in the NAP, it is important to have a good understanding of the baseline status of the receiving environment and constraints and vulnerabilities associated with the use of reclaimed water (including but not limited to salinity, sodicity and soil boron), and the other water sources identified in the NAP Water Stocktake.

Determining which irrigation options to implement is complicated by a number of factors, including: (i) a large number of potential options in relation to agricultural production, such as protected cropping, broadacre agriculture and intensive livestock and the water supply options that are available and best suited to these, (ii) potentially competing uses for available land and (iii) potential environmental and social impacts.

In addition, there are a number of gaps in underlying knowledge that need to be filled in order to enable decisions to be made in an informed manner including: (i) current soil attributes to assist model predictions of the impacts of using recycled water and develop guidelines for the sustainable use of recycled water, (ii) the impact of water from different sources / of different quality on soil biochemical process interactions, (iii) the fate of nutrients from different sources on receiving waters and effects from variable irrigation water quality on the long-term sustainability of the land's ability to grow crops, (iv) the amount of water of different quality that is able to be supplied at different times of the year, v) the depth to shallow (often saline) groundwater which would be affected by increased recharge from expanded irrigation, and vi) the extent of resilient and also vulnerable areas where further irrigation expansion could proceed subject to additional works and management practices being assured (such as interception and removal of shallow, saline groundwater).

To assist with assessing various policy and development options in a holistic, transparent and defensible manner, this project focused on the Greater Study Area of the Goyder Institute for Water Research's Northern Adelaide Plains Water Stocktake, but has broader relevance to irrigation development along the Northern Adelaide Corridor.

The overall aims of the project were to (i) fill a number of gaps in scientific knowledge related to the impact of the application of water from different sources on long-term soil suitability for different types of crops, long-term impacts on soil quality, and the availability of water of different quality at different times of the year, and (ii) integrate this knowledge in a set of guidelines to answer a number of key end-user defined questions. The project was structured into five distinct tasks. This report documents the main findings from Task 2: Modelling nutrient and chemical fate, including salinity/sodicity risk, as the basis for identifying longevity of recycled water utilisation and mitigation strategies under current and future climate. Task 2 was designed to enable the answering of the critical management questions "what water is sustainable to use where, for what crop, and for how long?" The identification of high risk areas for potential loss of soil quality will be available for informing monitoring programs and the implementation of mitigation strategies to minimise adverse environmental outcomes that may arise from the expansion of horticultural activities in the area. Also, areas with poor quality soils may be prioritised for glasshouse expansion.

This task addressed one of the key research challenges identified in the Goyder Institute for Water Research Strategic Research Plan 2015-2019, i.e. to undertake in-depth analysis of coupled processes of variablysaturated water flow, plant water uptake and coupled transport of multiple major ions in soils irrigated with irrigation water featuring different water qualities. By coupling major ion soil chemistry to unsaturated flow and plant water uptake, and by explicitly incorporating effects of salt concentrations on soil hydraulic properties and on root water uptake (the so-called salinity stress), the task has incorporated critical soil processes required for salinity risk assessment associated with irrigation water. In doing so, this task addressed several of the knowledge gaps that are pivotal for an improved salinity/sodicity risk assessment. This task therefore informs optimisation of irrigation practices that will yield minimal long-term effects on soil productivity.

The study

The major ion chemistry module UNSATCHEM, available in the HYDRUS-1D simulator, was used as the primary tool for assessing different water quality scenarios for the current soil status to inform longevity of utilisation of water from a range of sources and of different qualities, including reclaimed water. Simulations with different water qualities provided detailed results regarding soil quality, i.e. pH, salinity (*EC*), sodium adsorption ratio (*SAR*), and exchangeable sodium percentage (*ESP*). This modelling allowed an assessment of the sustainability of the irrigated soils using water with different qualities and allowed the testing of mitigation strategies such as gypsum amendments to prevent soil degradation. The modelling results can be used to inform soil monitoring programs and inform the long-term planning for the development of the region. This task builds upon data collected within Task 1 of the project and, by understanding the baseline soil status, provides a cost effective way to optimise the quality of irrigation water used in the region to ensure the soils are managed sustainably.

The project used best-available data on soil hydrology and chemistry, historic and future climate parameters, water quality of potential irrigation water, and greenhouse horticulture production systems from the NAP area as a basis for the scenario modelling. Key crops considered in the simulations include perennial horticultural crops (represented by almonds and pistachios), viticulture, annual horticultural crops (represented by potatoes, onions, and carrots), and pasture crops. Greenhouse crops included capsicum, cucumber, eggplant, and tomato. Key soils included in the scenarios are calcareous, hard red brown, sand over clay and deep uniform to gradational soils. Simulations of the soil water balance and soil chemical balance were undertaken from 1970-2017 (historic climate) and from 2018-2050 (future climate). The intermediate-emission Representative Concentration Pathway RCP4.5A is used as a single climate future rather than a range of futures, which limits the number of modelling scenarios to a practical level. As a result, the simulations present one possible outcome. However, the tools developed through the project are available to further test additional future climate scenarios.

By considering these two time-series, the effect of one potential future climate on soil water and soil chemistry has been assessed. The reference water source considered was recycled water. All together a total

of 84 scenarios were evaluated. The suitability to grow other crops on the NAP area can be readily inferred from parameters determining water stress and salinity stress and comparing those between simulated crops and other crops of interest.

For a subset of the crops (i.e. potato, wine grapes and almonds), the effect of soil amendment by gypsum application was numerically evaluated. This soil management option was combined with applying higher leaching fractions to leach accumulated salts from the soil profile. A total of 77 additional scenarios were conducted to study the impact of various management options for different NAP soils. Water sources with different salinity were also tested; water qualities ranged from good quality low-salinity (175 mg/L) water, blending water (688 mg/L), to recycled water (1200 mg/L). The effect of cycles of alternatively low-salinity and recycled water was also tested, either using monthly or half yearly cycles.

The project also assessed the effects of long-term irrigation on salt build-up in soil under greenhouse conditions. Blended water (recycled water and harvested rainwater) was used to irrigate soil grown greenhouse vegetables (tomato, cucumber, capsicum, and eggplant). Simulations provided insight into the development of irrigation induced chemical transformations in the soils and which management options provided for a sustainable use of irrigation water. The management scenarios tested included four leaching fractions and four annual levels of gypsum application.

Key model outputs such as depth profiles and time series of salinity and sodicity indicators (*SAR, ESP*) were produced for each soil/crop combination and for each water resource considered. These outputs were compared against threshold values for individual crops and for soils as a whole. In this way the impact of salinity on crop yield can be estimated. Two-dimensional simulations with HYDRUS (2D/3D) were undertaken to optimise the riparian zone widths to control lateral solute migration from irrigated fields to streams. The project further evaluated potential effects of additional boron inputs to the soil profile through the irrigation water; this involved simulations accounting for adsorption-desorption processes and rates of mineral dissolution. Finally, potential impacts of climate change related extreme temperatures, dry spells, and milder winters on crops in the NAP were assessed.

Conclusion and recommendations

This task has delivered an unprecedented set of new site-specific soil hydraulic and chemical parameters to undertake quantitative evaluations of potential impacts of long-term irrigation on soil and plant health. Typical parameters include unsaturated soil hydraulic properties of the key soils at various depths in the soil profile, and interpreted chemical parameters that control the complex interactions between major cations in soil solution (sodium, potassium, calcium, magnesium) and the soil solid phase (e.g. clay particles). A new boron sorption model has been developed to develop better insights into the fate of boron in irrigated soils.

In addition to new soil parameters for quantitative modelling, the project has also delivered a novel capability of the HYDRUS-1D simulator in the form of a gypsum amendment module that allows for the addition, and subsequent dissolution, of an annual amount of solid gypsum to the soil profile. Despite these efforts to use best available information for predictive modelling, the predictions are subject to uncertainties and should therefore be taken as indicative, not absolute futures.

To determine crop water requirements into the future (2018-2050), the dual crop coefficient methodology was implemented using projected climate data that incorporated effects of climate variability and change.

Results showed that irrigation requirements for all crops tested will most likely increase compared to the values calculated for the historic climate (1970-2017).

Predicted increase in crop water requirements are as follows (range indicates variation between soil types):

- Pistachios: +3.0 to 4.5 %
- Wine grapes: +3.5 to 5.8 %
- Almonds: + 6.0 to 7.4 %
- Carrots: +6.2 to 7.4 %
- Pasture: +7.0 to 8.4 %
- Onions: +9.2 to 10.3 %
- Potatoes: +8.8 to 11.0 %

The increase in crop water requirement is dependent on soil type. The ranking of soils from most to least sensitive is as follows: sand over clay > hard red brown > calcareous > deep uniform to gradational.

This task has further delivered information on how to respond to different management and climate scenarios, and identified several mitigation strategies. The main results from the scenario analysis with recycled water are summarised as follows:

- After 32 years of irrigation (at *t* = 2050 y), soil pH was nearly identical for all soil depths across all soils. Overall soil pH was relatively insensitive to the applied water.
- The final (at year 2050) soil profile salinity (*EC*_{sw}) across all soils and crops ranged from 2.9 dS/m at the soil surface to 4.0-9.5 dS/m at 2 m depth. The depth distribution of *EC*_{sw} was different for different crops.
- Potential yield of salt sensitive crops such as annual horticulture and almonds was estimated to be reduced by 4-32% due to the increased soil salinity.
- An increase in the *SAR* across all soils from average initial (year 2018) values (0.8-3.6) to final values in the range 12.1-19.4; *SAR* values at the bottom of the soil profile were about twice as large as values at the soil surface.
- After 32 years of irrigation, the average soil *ESP* increased from 21 to 43.7% for calcareous soil, from 29.4 to 51.0% for hard red brown soil, from 9 to 28.4% for sand over clay soil, and from 24.5 to 35.0% for deep uniform to gradational soil. Different crops developed different *ESP* depth distributions.
- High SAR and ESP build up in the soils could adversely affect soil structural stability and water movement in the soil, which can lead to water logging below or in the root zone, and which can severely impact optimal crop production.
- New relationships between soil solution SAR and ESP for each soil were developed from which threshold SAR values can be derived that exceed threshold ESP values. In Australia, a soil is defined sodic when the ESP > 6%. These relationships revealed that a SAR of 4, 4, 6 and 3 for calcareous, hard red brown, sand over clay and deep uniform to gradational soils, respectively, would be able

to develop a critical *ESP* (>6%) which can lead to adverse impacts such as poor soil structure.

Table 1. Reduction in the potential yield (%) of different crops with profile average salinity build up in different soils (Calcareous (Cal), Hard red brown (HRB), Sand over clay (SoC), Deep uniform to gradational (DuG)) in relation to recycled water use. Coloured cells indicate the risk level to reduction in crop yield: green = low risk; amber = medium risk; red = high risk.

SOIL	REDUCTION IN POTENTIAL YIELD (%) FOR VARIOUS CROPS								
	ALMOND	WINE	PISTA-	CARROT	ONION	ΡΟΤΑΤΟ	BRASSICAS	PASTURE	
		GRAPE	CHIOS					CLOVER	RYE
Cal	17.6	1.7	0.0	27.1	30.5	34.5	11.0	19.2	0.0
HrB	11.2	0.0	0.0	23.1	27.5	25.1	8.3	13.9	0.0
SoC	15.1	0.0	0.0	27.7	28.5	0.6	11.4	16.1	0.0
DuG	17.9	0.0	0.0	27.4	30.7	8.0	11.2	20.1	0.0

The increased soil salinity and sodicity can be mitigated by adopting a combination of management options: soil amendments with gypsum, increased leaching rates, and use of low-salinity irrigation water (continuously or as part of a cyclic approach).

In sandy soils (sand over clay), the use of less saline irrigation water (low-salinity sources, blended) and adoption of cyclic water use decreased the salinity and sodicity to levels close to or below the thresholds. The difference in impacts between the different water sources was relatively small; the use of blended water was equally successful in reducing *SAR* and *ESP* as use of monthly or half-yearly cycles. While low-salinity water produced optimal growing conditions, differences with blended water and cyclic irrigation was small. Adoption of an annual dose of gypsum at 4.3 t/ha combined with a 20% leaching fraction was found suitable to manage the salinity and sodicity hazards associated with the use of recycled water at all depths, except for the shallow depth (0-15 cm). At the shallow depth, *SAR* and *ESP* were fluctuating around the threshold value, mainly driven by year to year variability in climate.

Calcareous soils contained high amounts of calcium carbonate in variable soluble forms as well as in variable shapes and sizes of calcrete rocks. Long-term use of recycled water on calcareous soils combined with annual gypsum amendment of 8.6 t/ha and a leaching fraction of at least 20% yielded *EC* values similar to the threshold value for wine grapes at the 0-15 cm soil depth. The sodicity indicators *SAR* and *ESP* at the same depth were similar or slightly larger than the soil threshold, respectively. At intermediate soil depth (30-60 cm), the same irrigation conditions resulted in acceptable *EC* and *SAR* values; *ESP* was about two times the soil threshold value. At the 60-90 cm soil depth, the *EC* and *SAR* values were marginally higher than the wine grape threshold; more salt tolerant crops such as pistachios could be grown very well under such conditions. The relatively high *ESP* at this deeper depth could cause water logging, especially if high leaching fractions are used.

For hard red brown soils, all water qualities tested gave above-threshold *EC* values at all soil depths (based on almonds), even when gypsum was added at an annual rate of 8.6 t/ha. Only the low-salinity water was able to keep *EC* below or at the threshold level. *SAR* values were acceptable at the shallow and intermediate soil depth for all water qualities tested, except for the recycled water. At the 60-90 cm depth, only the low-salinity water was able to keep *SAR* values below the soil threshold. The *ESP* exceeds the threshold value for

all water qualities at all depths, except for the low-salinity water. The combination of annual gypsum amendment at 8.6 t/ha and a leaching fraction of 20% was not able to keep the *ESP* below threshold when recycled water was used. With blended water, gypsum and 20% leaching fraction, both *EC* and *SAR* were acceptable for the 0-15 and 30-60 cm soil depth.

Blended water (recycled water and harvested rainwater) was used to irrigate soil grown greenhouse vegetables (tomato, cucumber, capsicum, and eggplant). Results showed that temperature based irrigation scheduling for greenhouse crops (with a zero leaching fraction) could lead to the emergence of salinity and sodicity hazards in the soil. Analysis of further management scenarios suggested that a 15-20% higher irrigation amount coupled with an annual gypsum application of 10 meq/kg soil (1.7 t/ha), kept the salinity and sodicity (*SAR, ESP*) below critical thresholds. This scenario created a favourable soil environment for long-term sustainable vegetable production under glasshouse condition.

The results suggest that irrigation induced salinity and sodicity will continue to impact agriculture in arid and semi-arid areas for the foreseeable future if adequate mitigation options are not put in place. The sustainable use of recycled water for irrigation requires designing and implementing effective farm-scale and regional-scale solutions. Therefore, a comprehensive strategy for a long-term monitoring, auditing and reporting framework could help streamline the use of recycled water for irrigation.

Based on two-dimensional simulations with HYDRUS (2D/3D), riparian zone widths to control lateral solute migration from irrigated fields to streams were optimised. Simulations showed the likely average annual water flow from almond and annual horticulture irrigated area to the stream was nearly twice as much than under wine grapes. The study showed that buffer widths of 20, 60, and 40 m for irrigated wine grapes, almond, and annual horticulture, respectively, are needed to restrict the migration of salts to the stream.

A sensitivity analysis of boron leaching involved several key sources of variability (and thus uncertainty) and demonstrated that the leaching model is least sensitive to the natural soil variability (sorbed boron concentration and sorption models) and most sensitive to the variation in boron concentration in the irrigation water. Importantly, the higher the initial boron concentration (i.e., prior to adding boron containing irrigation water) in the pore water and on the solid phases, the smaller the relative effect on the long-term boron concentrations. This means that soils with an already high boron concentration will be at a lesser risk relative to soils with a much lower boron concentration.

An analysis of the chosen warming scenario showed that the NAP region will be subjected to greater daily temperature indices and frequency of hot days relative to historic climate. There will be also a higher frequency for dry days (with rainfall less than 1 mm) and dry spells compared with historic data. The NAP region, following global climate change predictions, will be subjected to milder winters based on smaller frequencies of frost and chill days. The following consequences are anticipated for the crops in the NAP region, as the result of these climatic shifts, without mitigation and adaption of management practices:

- Potatoes will likely see a yield decrease and a higher risk to being invaded by pests.
- The growth and yield in carrots may be stimulated due to increased frequency of hot and dry days. Nevertheless, extreme heat events may reduce the quality of carrots and mid-season drought stress can depress the yield in carrots.
- Warmer climate may reduce the duration of crop growth, yield, and seed production for onions; low rainfall conditions can reduce the risk of infection by pests.

- The projected drought and extremely hot weather in the NAP region is expected to negatively impact vines, which may result in poor budburst, leaf loss, bunch damage, and consequently low yield and production or even crop loss.
- For almonds and pistachios, it is expected that their yield and production may be impacted by drought in the NAP region if not properly managed. While the current NAP climate hardly accommodates chill requirements for these fruits, the projected climate shows there would be some years that this requirement cannot be met at all.
- As the NAP region will likely be subjected to an increased number of hot days, a decline in pasture production is anticipated for this region, unless irrigation amounts are increased.

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Abbreviations

Abbreviation	Full name
AHD	Australian Height Datum
ASR	Aquifer storage and recovery
ASRIS	Australian Soil Resource Information System
BD	Bulk density
BOM	Bureau of Meteorology
CAL	Calcareous soil
CDF	Cumulative distribution function
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CV	Coefficient of variation
DAFF	Dissolved Air Flotation and Filtration
DEWNR	Department of Environment, Water and Natural Resources, South Australia
DCC	Dual crop coefficient
DUG	Deep uniform to gradational soil
EC	Electrical conductivity
EV	Estimated value
GCM	Global Climate Model
GFDL-ESM	Geophysical Fluid Dynamics Laboratory-Earth System Model
GIS	Geographical Information System
IR	Irrigation requirement
HRB	Hard red brown soil
MAR	Managed aquifer recharge
MAE	Mean absolute error
ME	Mean error
MIR	Mid-infrared
MWHC	Mean water holding capacity
NAP	Northern Adelaide Plains
ОМ	Organic matter
PTF	Pedotransfer function
RAW	Readily available water
Rw	Recycled water
SD	Standard deviation
SOC	Sand over clay soil

Symbols

Parameter	Definition
α	Air entry value of the van Genuchten water retention curve (cm $^{-1}$)
CEC	Cation exchange capacity: Total capacity of a soil to hold exchangeable cations (mmol _c kg ⁻¹); typically the sum of [Na ⁺], [K ⁺], [Ca ²⁺] and [Mg ²⁺]
ESP	Exchangeable sodium percentage: 100×[Na ⁺]/CEC, where [Na ⁺] is sodium concentration (mmol _c kg ⁻¹)
EC _{SW}	Electrical conductivity of the soil pore-water at measured or predicted maximum field water content (dS/m)
<i>EC</i> _{Se}	Electrical conductivity of the soil saturation extract (dS/m)
ECw	Electrical conductivity of the irrigation water (dS/m)
Es	Soil evaporation (mm day ⁻¹)
ET ₀	Reference crop evapotranspiration (mm day ⁻¹)
ET _C	Crop evapotranspiration under standard conditions (mm day-1)
Kc	Crop coefficient (-)
Ксв	Basal crop coefficient (-)
Ke	Soil evaporation coefficient (-)
Ks	Saturated hydraulic conductivity (m/day)
Ι	Pore-connectivity parameter (-)
LF	Leaching fraction (-)
n	Shape parameter of the van Genuchten water retention curve (-)
SAR	Sodium adsorption ratio: $[Na^+/(Ca^{2+}+Mg^{2+})^{0.5}]$ (mmol ^{0.5} l ^{-0.5})
T _P	Crop transpiration (mm yr ⁻¹)
$ heta_{ m r}$	Residual water content (cm ³ cm ⁻³)
$ heta_{\sf s}$	Saturated water content (cm ³ cm ⁻³)

1 Introduction

Irrigation, regardless of water source, intrinsically carries a risk to soils and landscapes. This is the result of an inevitable modification in the water, salt and nutrient balance that affect processes including deep drainage, runoff, and groundwater recharge. The timeframe in which the risk can be expressed is governed by fundamental landscape attributes including landform, the depth of the variably-saturated or vadose zone and soil properties, and management considerations (water application rate and crop water use). For example, some irrigation waters are typically high in sodium but relatively low in calcium and magnesium, and therefore yield a high sodium absorption ratio (*SAR*). If such water is used for irrigation, it leads to sodium displacing calcium and magnesium in the soil and salt accumulation in the soil profile. This will cause a decrease in the ability of the soil to form stable aggregates and results in a loss of soil structure. This in turn will result in a decrease in infiltration leading to problems with crop production. Therefore, prior to any use of variable quality water for irrigation purposes, an in-depth assessment has to be undertaken of the long-term effects of dissolved ions on soil and plant productivity to ensure irrigation is managed sustainably.

The overall aims of the project were to (i) fill a number of gaps in scientific knowledge related to the impact of the application of water from different sources on long-term soil suitability for different types of crops, long-term impacts on soil quality, and the availability of water of different quality at different times of the year, and (ii) integrate this knowledge in a set of guidelines to answer a number of key end-user defined questions. The project was structured into five distinct tasks. This report documents the main findings from Task 2: Modelling nutrient and chemical fate to support the long-term sustainability of the use of recycled water.

This task addressed one of the key research challenges identified in the Goyder Institute for Water Research Strategic Research Plan 2015-2019, i.e. to undertake in-depth analysis of coupled processes of variably-saturated water flow, plant water uptake and coupled transport of multiple major ions in soils irrigated with irrigation water featuring different water qualities. This is consistent with Biggs et al. (2012), who identified the description of the unsaturated zone as the key knowledge and data gap when conducting salinity risk assessments. By coupling major ion soil chemistry to unsaturated flow and plant water uptake, and by explicitly incorporating effects of salt concentrations on soil hydraulic properties and on root water uptake (the so-called salinity stress), the task has incorporated critical soil processes required for salinity risk assessment associated with irrigation water. In doing so, this task addressed several of the knowledge gaps that are pivotal for an improved salinity/sodicity risk assessment. This task therefore informs optimisation of irrigation practices that will yield minimal long-term effects on soil productivity.

Although the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC 2000) provide background information on quality of irrigation water for different soil types, including permissible levels of chloride, sodium and *SAR*, and concentrations of metals and metalloids in irrigation, these are general values that do not take into account site-specific conditions that govern effects on soil productivity. Therefore, site-specific assessments are the recommended approach to develop sustainable irrigation practices where irrigation water quality is optimised for specific soil-crop-groundwater conditions and linked to localised management and infrastructure needs.

2 Soil water and soil chemistry models

2.1 Introduction

To quantitatively assess salinity risks associated with long-term irrigation using recycled water requires effective numerical tools that couple major ion soil chemistry to unsaturated flow and plant water uptake. Such models should be able to explicitly incorporate effects of salt concentrations on soil hydraulic properties and on root water uptake (so-called salinity stress) (Figure 1). The state-of-the-science HYDRUS-1D simulator (Šimůnek et al., 2008, 2013, 2016) has been used to model the water and salt balance for a range of different water sources, each with their specific chemical composition. HYDRUS-1D is a public domain Windows-based modelling environment for analysis of coupled variably-saturated water flow and transport of multiple solutes.

In doing so, the current Task 2 addressed several of the knowledge gaps identified in the Introduction Section that are pivotal for an improved salinity/sodicity risk assessment. This task therefore informs optimisation of water quality scenarios that will yield minimal long-term effects on soil productivity. This task has a critical dependency on Task 1, 3 and 4, where input parameters are generated for water source and receiving environment. These tasks together will enable the answering of critical question "what water is sustainable to use where and for how long?"



Figure 1. Conceptual representation of the coupled water and chemical processes acting on a soil profile subject to boundary conditions (rainfall, irrigation, transpiration, evaporation, capillary rise). These coupled processes are represented in the HYDRUS-1D UNSATCHEM simulator which is used in this study (modified from Šimůnek and van Genuchten, 2006).

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The major ion chemistry module UNSATCHEM (Šimůnek and Suarez 1994, 1997; Šimůnek et al., 2008; 2013), available in the HYDRUS simulator, has been used as a tool for assessing different water quality scenarios for current soil status to inform longevity of utilisation of water from a range of sources and of different qualities, including reclaimed water. Simulations with different water qualities will provide detailed results regarding soil quality, i.e., salinity, *SAR*, and exchangeable sodium percentage (*ESP*). This modelling allowed an assessment of the longevity of the irrigation using water with different qualities and allowed testing of implementing mitigation strategies to prevent soil degradation. This modelling can also be used to inform soil monitoring programs and inform the long term planning for the development of the region. This task links with Task 1 and, by understanding the baseline soil status, provides a cost effective way to optimise the quality of irrigation water used in the region to ensure the soils are managed sustainably.

One of the unquantified benefits of using recycled water is the provision of nutrients that support crop growth. Modelling of nutrient fate and behaviour will also determine risk of contamination of the groundwater and nearby waterways by nutrients, such as nitrate and other agrochemicals that may potentially be transported through the soil or off-site. The identification of high risk areas for potential contamination will also be available to inform monitoring programs and the implementation of mitigation strategies such as maintaining buffers zones next to streams to minimise adverse environmental outcomes that may arise from the expansion of horticultural activities in the area.

2.2 Soil hydrological model

Simulation of variably saturated flow in soil requires a mathematical relationship between i) the soil water content (θ) and the soil pressure head (h), i.e. the soil water retention curve $\theta(h)$, and ii) either the water content or the pressure head and the unsaturated hydraulic conductivity, $K(\theta)$ and K(h), respectively. We applied the analytical model of van Genuchten (1980) to describe the soil water retention curve, $\theta(h)$, since it permits a relatively good description of $\theta(h)$ for many soils using only a limited number of parameters. We assumed the non-hysteretic form of the soil water retention curve. The van Genuchten (1980) soil moisture retention characteristic is defined as:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |ah|^n)^m}$$
(1)

where θ_r is the residual water content [cm³/cm³], θ_s is the saturated water content [cm³/cm³], and α [1/m], *n* [-] and *m* (= 1 – 1/n) [-] are the retention curve shape parameters. The van Genuchten (1980) θ (*h*) equation has the additional advantage that when coupled with the unsaturated hydraulic conductivity *K*(*h*) model of Mualem (1976), it produces the following closed-form expression:

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

where K_s is saturated hydraulic conductivity [cm/day], $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$ is the effective saturation [-], m=1-1/n, and n>1. The pore-connectivity parameter (*I*) was estimated by Mualem (1976) to be about 0.5 as an average for many soils. In this study, we used Equation (2) with the *I* parameter fixed at 0.5, while K_s was derived either by direct measurement on undisturbed soil samples or indirectly estimated using a variety of approaches (for details, see Appendix 1). Equation (1) was fitted to measured soil water retention data for undisturbed soil samples from key soils in the NAP region, where samples were available, or indirect estimation methods were adopted (see Chapter 3 and Appendix 1 for details).

2.3 Soil geochemical model

Migration of chemicals in soil is primarily by advection and dispersion (ignoring gaseous transport) when advection (i.e. mass transport by flowing water) is greater than the rate of diffusion (i.e. mass transport by a concentration gradient). For the transport of contaminants during transient water flow, HYDRUS implements the advection-dispersion equation which couples mass transport by flowing water, mechanical dispersion and molecular diffusion (Šimůnek et al., 2008, 2013). In this study, a dispersivity of 0.1 m was taken, or one twentieth of the total travel distance from top to bottom of the 2 m deep soil profile. This dispersivity is based on the best estimate mean value for 0.8 - 2 m deep fine-textured soil profiles derived from a major literature review (Vanderborght and Vereecken, 2007).

The solute transport module of HYDRUS-1D as described above is limited to single ions, or ions subject to relatively simple first-order consecutive decay or transformation reactions (e.g., nitrification-denitrification chains, or radionuclide decay chains). As an extension to this approach, HYDRUS-1D implements a major ion chemistry module based on the UNSATCHEM model (Šimůnek and Suarez 1994, 1997; Šimůnek et al., 2008, 2013). The UNSATCHEM module of HYDRUS-1D enables quantitative predictions of processes involving major ions, such as simulations of the effects of salinity on plant growth and estimating the amount of water and amendments required to reclaim soil profiles to desired levels of salinity and *ESP* (Šimůnek et al., 2006) or to optimise water quality for sustainable irrigation (Mallants et al., 2017).

The UNSATCHEM module (Šimůnek and Suarez, 1994) considers the transport of major ions and carbon dioxide in soils. The major variables of the chemical system are Ca, Mg, Na, K, SO₄, Cl, NO₃, H₄SiO₄, alkalinity, and CO₂ (Table 2). The model accounts for equilibrium chemical reactions between these components such as complexation, cation exchange, and precipitation-dissolution. For the precipitation-dissolution of calcite and the dissolution of dolomite, either equilibrium or multicomponent kinetic expressions are used, including both forward and backward reactions. Other precipitation-dissolution reactions considered involve gypsum (CaSO₄.2H₂O), hydromagnesite (Mg₅(CO₃)₄(OH)₂.4H₂O), nesquehonite (MgCO₃.3H₂O) (Mg), and sepiolite (Mg₂Si₃O_{7.5}(OH).3H₂O). Since the ionic strength of soil solutions can vary considerably in time and space and often reach high values, both the modified Debye-Hückel and Pitzer expressions were incorporated into the model, thus providing options for calculating single-ion activities (Šimůnek et al., 2013).

CHEMICAL SPECIES GROUP	#	CHEMICAL SPECIES		
Aqueous components		Ca ²⁺ , Mg ²⁺ , Na ⁺ , K ⁺ , SO ₄ ²⁻ , Cl ⁻ , NO ₃ ⁻		
Complexed species	10	CaCO ₃ ⁰ , CaHCO ₃ ⁺ , CaSO ₄ ⁰ , MgCO ₃ ⁰ , MgHCO ₃ ⁺ , MgSO ₄ ⁰ , NaCO ₃ ⁻ , NaHCO ₃ ⁰ , NaSO ₄ ⁻ , KSO ₄ ⁻		
Precipitated species	6	$\label{eq:2.1} \begin{array}{llllllllllllllllllllllllllllllllllll$		
Sorbed (exchangeable) species	4	Ca, Mg, Na, K		
CO ₂ -H ₂ O species	7	<i>P_{CO₂}</i> , H ₂ CO ₃ , CO ₃ ²⁻ , HCO ₃ ⁻ , H ⁺ , OH ⁻ , H ₂ O		
Silica species	3	H ₄ SiO ₄ , H ₃ SiO ₄ ⁻ , H ₂ SiO ₄ ²⁻		

Table 2. Chemical species included in the	UNSATCHEM major ion module of	HYDRUS-1D (Šimůnek et al., 2008).
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Partitioning of dissolved major ions between the solid and solution phases is described with the Gapon equation (White and Zelazny, 1986) provided in the HYDRUS-1D Major Ion Chemistry module. This requires the definition of the Gapon Exchange Constants for exchange of calcium and magnesium,

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calcium and potassium, and calcium and sodium. The Gapon Exchange Constants are described in Appendix 2.

UNSATCHEM also considers the effects of solution composition on the unsaturated soil hydraulic properties. The accumulation of monovalent cations, such as sodium and potassium, often leads to clay dispersion, swelling, flocculation and overall poor soil physico-mechanical properties. These processes have an adverse effect on the soil hydraulic properties including hydraulic conductivity, K(h), infiltration rates and soil water retention as a result of swelling and clay dispersion. These negative effects are usually explained based on the diffuse double layer theory.

The effect of solution chemistry on the hydraulic conductivity K(h) in the major ion chemistry module is calculated as:

$$K(h, pH, SAR, C_0) = r(pH, SAR, C_0)K(h)$$
(3)

where *SAR* is the sodium adsorption ratio, C_0 is the total salt concentration of the ambient solution (meq/L), and *r* is a scaling factor which represents the effect of the solution composition on the final hydraulic conductivity [-], and which is related to pH, *SAR*, and salinity (Šimůnek et al., 2008). Conceptually, this effect is related to clay swelling as a result of changes in ion composition here expressed via the parameters *SAR* and C_0 (McNeal, 1968, 1974). Although soil water retention curves may also be affected by *SAR* and electrolyte concentrations (e.g., Lenhard and Brooks, 1986), this is not being considered in the current simulations. The parameter *r*(pH, *SAR*, *C*₀) in Equation (3) is calculated internally in the UNSATCHEM module based on calculated values for pH, *SAR*, and *C*₀. The *K*(*h*) parameter was determined as described previously (see Equation (2)).

We note that other effects of solution chemistry on hydraulic properties, such as mineral precipitation resulting in a decrease of pore space and hence a decrease in hydraulic conductivity, may be equally important to determine a soil's water balance under irrigation in arid and semi-arid regions. Examples of a more general approach to couple major ion chemistry with porous media hydraulic and solute transport parameters are available from Jacques et al. (2013a, b).

2.4 Root water and solute uptake model

The volume of water removed from a unit volume of soil per unit time due to plant water uptake, *S*(*h*) [day⁻¹], is defined as (Šimůnek et al., 2008):

$$S(h) = \alpha(h)b(z)T_p \tag{4}$$

where $\alpha(h)$ is the plant-water stress response function (between 0 and 1, see Figure 2), b(z) is the normalised water uptake distribution $[\text{cm}^{-1}]$ (here assumed linearly decreasing with depth), and T_p is potential transpiration [cm/day]. The parameters for the plant-water response function $\alpha(h)$ (Feddes et al., 1978) are defined in Table 3. The parameter b(z) is defined by the rooting depth of the various crops (see Appendix 3). Plant transpiration T_p was calculated in Section 4.2.

When salinity stress is considered in HYDRUS, a selection must be made whether the effect of salinity stress is additive or multiplicative to water stress. Here the multiplicative Threshold Model according to Maas (1990) was selected. The Threshold Model has two parameters, the threshold parameter and the slope parameter. The first parameter represents the value of the minimum osmotic head (the salinity threshold) above which root water uptake occurs without any reduction. The second parameter is the slope of the curve determining the fractional root water uptake decline per unit

increase in salinity below the threshold. Salinity stress parameters for selected crops were used to investigate combined water and salinity stress (see Appendix 3 for further details).



Figure 2. Plant water stress response function for pasture as applied in this study (based on Feddes et al. (1978)). For definition of parameters, see Table 3.

Table 3. Parameters for the stress response functions due to water stress (based on Wesseling et al., 1991).Example is for pasture.

PARAMETERS OF THE WATER STRESS RESPONSE FUNCTION (FEDDES' PARAMETERS)				
PARAMETER	PASTURE	PARAMETER DEFINITION		
h1 (cm)	-10	Value of the pressure head below which roots start to extract water from the soil		
h2 (cm)	-25	Value of the pressure head below which roots extract water at the maximum possible rate		
h3 (cm)	-200	Value of the limiting pressure head, below which roots cannot longer extract water at the maximum rate (assuming a potential transpiration rate of 0.5 cm/day)		
h4 (cm)	-800	Value of the limiting pressure head, below which roots cannot longer extract water at the maximum rate (assuming a potential transpiration rate of 0.1 cm/day)		
h5 (cm)	-8000	Value of the pressure head, below which root water uptake ceases (usually taken at the wilting point)		

A summary of threshold models for crops of the NAP is shown in Figure 3; also included are the range of safe soil water salinities EC_{SW} (green band) and the range of soil water salinities as calculated in this study (red band). This graph also shows which are the most salt tolerant crops (Pistachios, Rye grass) and which are the least salt tolerant crops (carrot, onion, almond, etc.).

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The sensitivity of other crops that were not explicitly simulated can be readily inferred from parameters determining water stress and salinity stress and comparing those between simulated crops and other crops of interest. Relevant water and salinity stress parameters are available in Appendix 3. For example, for water stress, broccoli and cabbage behave similar to carrots (nearly identical root water uptake parameters). These crops (cabbage, broccoli, carrots) also have identical crop coefficients (K_c) to calculate crop evapotranspiration (ET_c). Hence, from a water stress calculation point of view, these crops are interchangeable. Regarding salinity stress, carrots (threshold EC = 1.0 dS/m) and onions (threshold EC = 1.2 dS/m) are more sensitive than cabbage (threshold EC = 1.8 dS/m) and broccoli (threshold EC = 2.8 dS/m). In other words, the more sensitive crops were studied in detail here; results for the less sensitive crops would be at least as good as for the sensitive crops.



Figure 3. Threshold model indicating degree of salinity stress for various crops. *EC*_{sw} is simulated soil water electrical conductivity.

3 Data collection for modelling

3.1 Soil physical properties

Soil physical properties required for our study included particle size distribution and bulk density of all soil horizons of the key soil types considered, as these were used to indirectly estimate hydraulic properties (see further Section 3.2). Although a large number of soil samples were collected in this study to obtain site-specific measurements of these parameters (see Task 1 report, Oliver et al., 2019), it would not be possible to cover the full spatial variability of these soil properties. Also, not all soil horizons could be accessed during the soil sampling, usually because the layers were too deep for hand auguring or too hard to penetrate with manual sampling tools. For this purpose the new field-based data will be supplemented with data from existing databases.

Particle size and bulk density data was used to generate soil hydraulic properties for each soil horizon using pedotransfer functions based on the existing tool ROSETTA that is implemented in HYDRUS-1D (Šimůnek et al., 2016).

3.1.1 Properties from database

The study area lies between Gawler River, Light River, and Kapunda Road, South Australia, hence, the use of this boundary to create the soil groups map and generate summary statistics that describe the distribution of soil groups in the area (Figure 4). Table 4 shows the soil group distribution in the wider NAP region based on the soil group classification for South Australian soils. The six main soil groups are hard red brown (39%), calcareous (17%), gradational soils (13%), deep uniform to gradational (6%), sand over clay soils (6%), and cracking clay soils (5%). All remaining five soil groups represented each less than 5% of the study area.

SOIL GROUP DESCRIPTION	% OF STUDY AREA
Hard red-brown texture contrast soils with alkaline subsoil	39%
Calcareous soils	17%
Gradational soils with highly calcareous lower subsoil	13%
Deep uniform to gradational soils	6%
Sand over clay soils	6%
Cracking clay soils	5%
Deep loamy texture contrast soil with brown or dark subsoil	4%
Wet soils	4%
Shallow soils on calcrete or limestone	3%
Shallow soils on rock	1%
Deep sands	1%

Table 4. Soil group distribution of 15 generalised soil groups (only soils with > 1% of study area are shown)

When the focus area was limited to the priority primary production area (SA Government, 2017), the major soil groups and their areal distribution were: hard red brown (52%), deep uniform to gradational

(13%), calcareous (12%) and sand over clay (10%). The remaining area (about 12%) was occupied by gradational soils with highly calcareous lower subsoil (6%), deep loamy texture contrast soil with brown or dark subsoil (4%), and shallow soils on calcrete or limestone (2%). For details of the focus area, see Report Task 1 (Oliver et al., 2019).

On the basis of the Interactive NatureMaps¹ database, a total of fourteen soil profile sites were identified inside the wider study area. The sampling points from the NatureMaps were overlain onto the GIS database to generate the soil attribute maps and to extract the soil type classification of the sampling points. Based on the dominant soil group within each cluster, five soil groups were identified (Table 5). For each of these fourteen soil profiles, physical and chemical attributes were derived from the GIS database Land and Soil Spatial Data for Southern Australia (Liddicoat et al., 2014).

SOIL GROUP	DEWNR SITE	MEAN DISTRIBUTION OF DOMINANT SOIL (%)	DESCRIPTION		
Group 1 C	CL015		Calcareous soils		
	CL029	55			
	CL030				
	CL053				
Group 2	CL027		Hard red-brown texture		
	CL028	65	contrast soils with alkaline		
	CL058		subsoil		
Group 3	CL007	50	Cracking clay soils		
Group 4	CL008		Sand over clay soils		
	CL014	86			
	CL050				
	CL051				
Group 5	CL033	00	Deep uniform to gradational soils		
	CL049	00			

Table 5. Soil group cluster and description.

The soil attribute maps generated through this process include the toxicity of aluminium and boron, salinity, depth to water table, deep drainage, and potential root zone depths for different crop types (see Appendix 4). These maps provide useful background information for the further planning of expansion of irrigated agriculture in the Northern Adelaide Plains, and in the area north of the current study area between Gawler and Light River.

Similarly, particle size data were generated from the ASRIS database (Australian Soil Resource Information System²) to determine sand, silt, and clay content for the soils based on the 14 sampling

¹ https://data.environment.sa.gov.au/NatureMaps/Pages/default.aspx

² <u>http://www.asris.csiro.au/</u>

points. The data were available for the following six soil depths: 0-5, 5-15, 15-30, 30-60, 60-100, and 100-200 cm. The data were provided in three confidence levels, i.e. 5th percentile, Estimated Value (EV), and 95th percentile. The EV represents the predicted central value of the distribution and was calculated as the weighted mean soil property value (Odgers et al., 2015). Details of how the 5th and 95th percentiles were calculated are available from Odgers et al. (2015). For this study, use was made of the EV as this would provide representative average values for each soil property. Bulk density data were generated using the same method; together with particle size data, bulk density was subsequently used to generate hydraulic properties using pedotransfer functions (see Section 3.2 and Appendix 1).

Based on the 14 different sites across five soil groups, statistical profiles of soil physical parameters were derived for each soil group. For each statistical profile we calculated the minimum, mean, and maximum value of % sand, silt, clay, and bulk density. There are thus three data sets for each soil group that will be subsequently used to generate the soil hydraulic functions (section 3.2). Example statistical profiles of particle size are shown for calcareous soils (Figure 5); a complete description for all others soils can be found in Appendix 5.

Soil Group 1 describes calcareous soils which has been classified into eight soil types from A1 to A8 (Hall et al. 2009). The soils of this group are generally calcareous throughout, with gradational to uniform texture profiles and surface textures of loamy sand to light clay. Statistical profiles of particle size shown in Figure 5 highlight the decreasing sand content with increasing depth and the increasing clay content with increasing depth. The silt content is fairly constant across the entire profile.



Figure 4. Soil groups within the study area for the Goyder NAP project (green boundary) with indication of soil profile locations within the focus area (green circles) and outside the focus area (black circles).



Figure 5. Statistical profiles of particle size (% sand, silt, clay) for Soil Group 1 (calcareous soil).

3.1.2 Properties from field investigations

Particle size and bulk density were also obtained through direct measurement on soil samples collected from 10 sites that were visited during this project (sampling sites are described in Task 1 Report, Oliver et al., 2019). Samples consisted of disturbed material for particle size analysis and undisturbed cores for measurement of bulk density (this section) and hydraulic properties (section 3.2). Soil profiles were distributed across four soil groups: calcareous soils (3), hard red brown soils (6), sand over clay soils (3), and deep uniform to gradational soils (1). Soil samples could generally be collected only for shallow soil depths, usually up to 30 or 60 cm and exceptionally up to 90 cm (see Appendix 1 for details).

3.2 Soil hydraulic properties

3.2.1 Developing and testing predictive models of hydraulic properties

Soil hydraulic properties are key input parameters for modelling the soil water and salt balance of irrigated soil. To generate sufficient hydraulic properties for the Northern Adelaide Plains irrigation project in a cost-effective manner, pedotransfer functions (PTF) have been used that utilise existing gridded basic soil properties such as particle size and bulk density (Figure 6). The predictive capacity of PTF generally increases when more input data is provided. Therefore, this study explored different approaches that use different type of data when generating soil hydraulic properties through PTFs. The predictive capacity of the approaches was tested using a limited set of independent soil hydraulic property data (water retention curve and saturated hydraulic conductivity, *Ks*). Because of the inherent limitations in pedotransfer function

generated hydraulic properties (Espino et al., 1995), they have only been considered as input data to HYDRUS-1D where no other data was available.

Pedotran	sfer Functions: Rosetta Lite			
Hierarchical Models	Select Model Textural classes % Sand, Silt and Clay (SSC) % Sand, Silt Clay and Bulk Density (BD) % Sand, Silt Clay and Bulk Density (BD)			
Input Data	Input Output Textural Class Unknown Sand [%] 30 Sitt [%] 20 Clay [%] 50 BD [gr/cm3] 1.3 TH33 [cm3/cm3] 1.3 TH1500 [cm3/cm3] Height			
	Predicted Parameters			

Figure 6. Prediction of soil hydraulic properties using ROSETTA (Schaap et al., 2001). In this study the %Sand, Silt, Clay and Bulk Density (BD) model was applied.

Hydraulic properties are required for all soil layers as input for the HYDRUS-1D model. Because we did not have the resources to measure hydraulic properties for all soils at all depths, and because only shallow soil depths were accessible for undisturbed core sampling, we used different approaches to generate soil hydraulic properties.

The first approach used pedotransfer functions based on the existing ROSETTA tool (Schaap et al., 2001) that was implemented in HYDRUS-1D (Figure 6). The data to feed ROSETTA included particle size, bulk density and water content at specific pressure head (if available). Some of those data (particle size and bulk density) were available in gridded form from the CSIRO database (Soil and Landscape Grid Digital Soil Property Maps for South Australia [3" resolution - approx. 100m cell size]) (Liddicoat et al., 2014). This data has been used here and is the first approach to generate soil hydraulic properties. Because these particle size and bulk density data are predictions themselves, there is likely a considerable uncertainty around them.

The ability of the PTFs of Schaap et al. (2001) to reliably predict soil water retention parameters was tested by comparing the predicted values with direct measurements. For this purpose we used cores on which both input parameters for the pedotransfer function were known (particle size and bulk density) and direct measurements of hydraulic properties were available. Two data sets were used for this purpose: i) a database from Green (2010) involving two Soil Groups (sand over clay soils and hard red brown soils), and ii) the database obtained in the current project encompassing four Soil Groups (sand over clay soils, hard red brown soils, deep uniform to gradational soils, and calcareous soils). Cross plots for the four van Genuchten parameters are shown in Figure 7. Pearson correlation coefficients for all parameters are listed in Table 6. The general trend is that, based on Table 6, the van Genuchten α parameter has the poorest predictions while the remaining parameters are reasonably well predicted.



Figure 7. Validation of PTF using CSIRO's laboratory data (this study) and Green's field data (Green, 2010). Soil group A = calcareous soils; soil group D = hard red brown soils; soil group G = sand over clay soils; soil group M = deep gradational soils. Parameter shown are van Genuchten's shape parameters *n* and α , saturated water content (θ_s) and residual water content (θ_s).

PARAMETER	PEARSON CORRELATION COEFFICIENT			
	ALL SOIL GROUPS COMBINED	HARD RED BROWN SOILS	SAND OVER CLAY SOILS	CALCAREOUS SOILS
α (PTF) - α (lab)	0.324	0.412	0.429	0.270
<i>n</i> (PTF) - <i>n</i> (lab)	0.706	0.417	0.598	0.359
θ_r (PTF) - θ_r (lab)	0.744	0.822	0.910	0.708
θ_s (PTF) - θ_s (lab)	0.517	0.010	0.910	0.715

Table 6. Pearson correlation coefficient between estimated (pedotransfer function - PTF) and measured (laboratory) van Genuchten parameters (α , n, θ_r , θ_s).

The second approach was to use the measured particle size and bulk density from the soil sampling (Section 3.2.2) and use those data as input to the PTFs. While these estimates will still have a considerable degree of uncertainty, they will be more representative of the local soil properties than the first approach which only used gridded data.

The third approach used mid-infrared (MIR) spectroscopy to estimate basic soil properties (Soriano-Disla et al., 2014). Spectroscopic methods such as MIR provide reflectance spectra that are characteristic of the soil type and its chemical/molecular composition, therefore are suitable for the analysis of physical, chemical, and hydraulic soil properties. This method required calibration models between IR spectra (i.e. predictor variables) and reference soil property values (i.e. response variables). The response variables were available from shallow soils depths as discussed in section 3.1.2. The MIR method was used to predict water content at different soil pressure heads (0.01, 4, 8, 33, 60, 100, and 1500 kpa) and saturated hydraulic conductivity $(K_{\rm s})$. These water content – pressure head data were then used to fit the van Genuchten soil water retention model (Appendix 1). The reliability of the MIR predictions can be asserted from the cross plot in Figure 8; water contents are very well predicted for soil suction of 8 KPa and higher, while the water contents at low suction have inferior predictions. This is not a surprise: at the 0.01 and 4 kPa soil suction the soil structure is the dominant factor determining soil water content. Because soil structure (i.e., spatial arrangement of soil particles into larger aggregates) is relatively difficult to measure with MIR, the soil water content predictions are somewhat less reliable. At the higher suctions (8 kPa and higher), soil texture (particle size distribution) is the dominant factor in determining soil water content. Because soil texture is relatively easily predicted with MIR, the water content is too.

3.2.2 Direct measurement on undisturbed soil cores

Undisturbed 0.05 m diameter and 0.05 m high soil cores collected from the field were allowed to gradually saturate from the base upward over approximately 7 days. When samples were deemed to be fully saturated, the hydraulic conductivity was measured using the constant head method of Youngs (2001).

When all measurements of saturated hydraulic conductivity were completed, the soil cores were disconnected from their hydraulic extensions and weighed to obtain their saturated weights. The cores were then placed onto saturated ceramic plates connected to either hanging columns of water, or exposed to positive gas (nitrogen) pressures in sealed chambers. The cores were exposed to a series of sequentially increasing hydrostatic pressures ranging from saturation (nominated to be 0.1 kPa) to 4, 8, 33, 60 and 100 kPa (1kPa equals 10 cm of water column). When equilibrium was deemed to have occurred (based upon experience and measurement) each soil core was weighed, re-saturated and placed back onto a ceramic plate for the next pressure. After weighing the samples at 100 kPa, they were dried to constant weight in an oven at 105 °C, then re-weighed (and the tare weight of the stainless steel ring, mesh and elastic band recorded). Separate pieces of soil (saved from trimming each core) were used to measure the water content of the soil

at 1500 kPa. To achieve this, small duplicate samples were placed directly onto the surface of saturated ceramic plates (capacity 15 bar) and exposed to 1500 kPa of nitrogen gas pressure in reinforced steel chambers for 6 weeks. Full details of the fitted moisture retention curves using the RETC (van Genuchten et al., 1991) code are available in Appendix 1. Example measured and fitted moisture retention curves are shown in Figure 9.





3.2.3 Combined data sets for field soils

Three datasets were combined to have the best available soil hydraulic parameters for use in the HYDRUS-1D simulations across the different soil groups and soil depths. For the shallowest depths, the directly measured values were used: these provide the highest reliability as they do not depend on some prediction method using related prediction variables. Where such data were not available, the MIR predictions were used as second-best option as they provide site specific estimates using site-specific auxiliary data. Finally, if neither direct measurements nor MIR predictions were available, the pedotransfer function predictions based on the regional data set were used. An example summary dataset for calcareous soil is shown in Table 7.



Figure 9. Fitted retention curve using the van Genuchten model. Saturated (θ_s) and residual (θ_r) water content were fixed during the optimisation with RETC (van Genuchten et al., 1991). Values for θ_r were fixed to 50% of the measured water content at 1500 kpa. Soil profile NAP11 – sand over clay (left column); soil profile NAP8 – deep uniform to gradational (right column).

Table 7. Summary of van Genuchten soil hydraulic parameters (α , n, θ_r , θ_s), saturated hydraulic conductivity (K_s) and pore connectivity parameter *I*. Direct measurements on site specific soil cores (0 - 30 cm); predicted with MIR using site specific core material (30 - 100 cm); PTF predictions (100 - 200 cm).

SOIL	SOIL GROUP 1: CALCAREOUS SOILS					
DEPTH (CM)	Θ _R (CM³/CM³)	O₅ (CM³/CM³)	α (CM ⁻¹)	N (-)	K _s (CM/DAY)	L (-)
0-15	0.078	0.480	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	0.5
60-100	0.0001	0.4810	0.2305	1.1382	267.79	0.5
100-200	0.0735	0.4087	0.0242	1.298	22.91	0.5

3.2.4 Data for greenhouse soils

Soil hydraulic properties for greenhouse soils were obtained in a two-step approach: step one involved generating soil water retention data (θ , h) by means of MIR, step two used the RETC code to fit the van Genuchten parameters to the water retention data (Figure 10). The data from Figure 10 are from one and the same greenhouse, showing a very similar behaviour likely due to the top soil becoming homogenised after several years of soil management (further details in Appendix 1).



Figure 10. Measured and fitted water retention curves for greenhouse soil. All 3 sampling locations from one farm.

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3.3 Soil chemical data

Soil chemical parameters required for the UNSATCHEM module included the Gapon Exchange Constants, the initial concentrations of soil exchangeable cations (K^+ , Na^+ , Ca^{2+} , Mg^{2+}), and the initial solution composition (K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Mg^{2+} , Alkalinity, SO_4^{2-} , Cl^-) in the soil profile. The latter was defined using the composition of rainwater measured in the Adelaide region (Cresswell et al., 2010). Note that this initial solution will be automatically brought into equilibrium with the cation exchange complex. The soil exchangeable cations were taken from the Task 1 Report (Oliver et al., 2019).

Partitioning of dissolved major ions between the solid and solution phases is described with the Gapon equation (White and Zelazny, 1986) provided in the major ion chemistry module. This requires the definition of the Gapon Exchange Constants for exchange of calcium and magnesium, calcium and potassium, and calcium and sodium (Gapon, 1933; Šimůnek and Suarez, 1994):

$$0.5Ca + Na - X \leftrightarrow Na + Ca_{0.5} - X \tag{5}$$

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

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

where Ca, Mg, Na, and K are solution concentrations, and all other species (e.g. Na-X) are adsorbed onto the exchange sites -X. The Gapon selectivity or exchange coefficients for reactions (5-7) are defined as (Šimůnek and Suarez, 1994):

$$K_{Ca/Na} = \frac{[Ca-X] [Na]}{[Na-X][Ca]^{0.5}}$$
(8)

$$K_{Ca/K} = \frac{[Ca-X] [K]}{[K-X][Ca]^{0.5}}$$
(9)

$$K_{Mg/Ca} = \frac{[Mg-X] \ [Ca]^{0.5}}{[Ca-X][Mg]^{0.5}}$$
(10)

where [Na], [K], [Mg], and [Ca] are molal activities in solution (dimensionless), and [Na-X], [K-X], [Mg-X], and [Ca-X] are adsorbed concentrations (mmolc/kg soil). All calculated mean Gapon coefficients are listed in Table 8. Source data for the calculations were obtained from wet chemistry analysis (Task 1 Report, Oliver et al., 2019), including all solution concentrations and adsorbed concentrations on the exchange sites. For details about the calculation procedure, see Appendix 2.

Table 8. Mean values of Gapon selectivity or exchange coefficients K_{Ca/Na}, K_{Ca/K}, and K_{Mg/Ca}.

SOIL GROUP	K _{Ca/Na}	Кса/к	K _{Mg/Ca}
Hard red brown	0.753	0.065	0.033
Deep uniform to gradational	1.313	0.025	0.013
Sand over clay	1.880	0.014	0.020
Calcareous	0.957	0.009	0.038

3.4 Crop data for water balance modelling

3.4.1 Root water uptake parameters

To simulate the effect of both water and salinity stress on root water uptake, the suction-dependent plantwater stress response function or Feddes' model (Feddes et al., 1978) was implemented, together with the threshold-slope salinity stress model by Maas (1990). The database for the threshold model provides suggested values based on the electric conductivity of the saturation extract EC_{Se} in dS/m (Appendix 3). These values are converted internally in the HYDRUS-1D GUI into the electric conductivity of soil water (at the field capacity) as follows: $EC_{SW} \approx ke \times EC_{Se}$, where ke is approximately 2 (Skaggs et al., 2006). Crop tolerance to salinity and threshold EC_{Se} values used in this study are available from Table 9. Note that we used the same relationship $EC_{SW} = 2 \times EC_{Se}$, to relate the electrical conductivity of the soil saturation extract EC_{Se} (as expressed in Table 9) to the electrical conductivity of the soil at measured or predicted maximum field water content EC_{SW} (assumed to represent the simulated electrical conductivity).

Table 9. Salinity thresholds for crops considered in the calculations. Threshold = maximum soil salinity without yieldloss.

CROP	TOLERANCE	THRESHOLD <i>EC</i> se (dS/M)	YIELD REDUCTION (IN % PER dS/M)
Almonds	Sensitive**	1.5**	19**
Pistachios	Moderately tolerant#	9.4#	8.4#
Wine grapes	Moderately sensitive [@]	1.5 [@]	9.6 [@]
Carrots	Sensitive*	1.0*	14*
Onions	Sensitive*	1.2*	15*
Potato	Moderately sensitive*	1.7*	12*
Pasture crops	Moderately tolerant*	5.6*	7.6*

Data source: *Maas and Hoffman (1977); **Maas and Grattan (1999); @Francois and Maas (1999); #Sanden et al. (2004).

3.4.2 Rooting depth

The rooting depth value characterises the depth distribution of root water uptake, b(x) [L⁻¹], in the soil root zone. Adopted rooting depths are listed in Table 10.

Table 10. Rooting depths for crops used in HYDRUS-1D simulations.

CROP	ROOTING DEPTH (CM)	REFERENCE
Wine grapes	100	Phogat et al., 2017b
Almonds	100	Phogat et al., 2018b
Pistachios	100	Allen et al., 1998
Pasture	100	Allen et al., 1998
Onions	60	Allen et al., 1998
Carrots	60	Allen et al., 1998
Potatoes	60	Allen et al., 1998

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3.4.3 Grouping of cropping systems for soil water and salinity balance calculations

Seven crops account for over three-quarters of the irrigated horticulture area in the Northern Adelaide Plains, namely potatoes (25%), olives (12%), winegrapes (12%), almonds (9%), carrots (9%) and lettuce (8%), onions (4%) (City of Playford, 2013). Pastures cover 21% of the area (ABS, 2012).

There are a wide range of potential crops that have been identified which could potentially be grown with recycled water. For the purpose of analysing their respective water demand, all potential crops and cropping systems were grouped into perennial horticulture (pistachios, almonds), viticulture, pastures (mixes), and annual horticulture (carrots, onions, potatoes) crops. The breakdown of cropping systems is provided in Table 11 (based on Arris, 2015). For each cropping system, parameters for the root water uptake water stress response function for the Feddes model (Figure 2) are provided in Table 11 (based on data in Appendix 3). Within each cropping system, crops with similar (though not necessarily identical) water stress response parameters are combined for the purpose of modelling. Crops that have not been explicitly modelled will have similar water uptake than the explicitly modelled crops (underlined), provided they have a similar transpiration.

Table 11. Root water uptake parameters for common crops based on Feddes model (Feddes et al., 1978). h₁: no water extraction at higher pressure heads; h₂: h below which optimum water uptake starts; h₃: h below which water uptake reduction starts at high Tpot; h₄: h below which water uptake reduction starts at low Tpot; h₅: wilting point, no water uptake at lower pressure heads. Crops analysed in this study are underlined. Crops are grouped according to similar root water uptake parameters (for details, see source reference).

CROPPING SYSTEM	CROP	ROOT WATER UPTAKE PARAMETERS (h ₁ , h ₂ , h ₃ , h ₄ , h ₅)	REFERENCE
Tree-fruit or top- fruit/perennial horticulture	<u>Almonds</u>	-10; -25; -500; -800; -8,000	Phogat et al., 2012
	Apples/pears, cherries, lemons <u>, viticulture</u>	-15; -30; -500; -800; -8,000	Taylor and Ashcroft, 1972
	Olives	0; 0; -4,000; -4,000; -20,000	Rallo and Provenzano, 2013
Annual horticultural crops/broadacre vegetables	Broccoli, <u>carrots,</u> parsnips*, <u>onions,</u> celery, lettuce, cabbage, melons	-15; -30; -450; -550; -8,000	Taylor and Ashcroft, 1972
	<u>Potatoes</u>	-10; -25; -320; -600; -8,000	Wesseling et al., 1991
Shrub nuts, fruits and berries	Strawberries	-15; -30; -1,000; -1,000; -8,000	Taylor and Ashcroft, 1972
	<u>Pistachio nuts</u> , Quandong or native peach (<i>Santalum</i> acuminatum)	-10; -25; -500; -800; -8000	Phogat et al., 2012
Greenhouse and protected cropping	Tomatoes, capsicums, cucumber, eggplant	-15; -30; -800; -1,500; -8,000	Taylor and Ashcroft, 1972
Field and Fodder	Cereals	0; -1; -500; -900; -16,000	Wesseling et al., 1991
Crops/pastures	<u>Legumes</u> , lucerne (alfalfa)	-15; -30; -1,500; -1,500; -8,000	Taylor and Ashcroft, 1972
	<u>Rye grass</u>	-10; -25; -200; -800; -8000	Taylor and Ashcroft, 1972

3.4.4 Boundary conditions

The lower boundary condition of the model domain was assigned a free drainage or zero-gradient boundary condition. A zero-gradient boundary condition is typically used to simulate a freely draining soil profile. Such a situation often occurs in field studies of water flow and drainage in the vadose zone. This lower boundary condition is most appropriate for situations where the water table lies far below the domain of interest (Šimůnek et al., 2008). In the current study the bottom of the model domain is at 2 m below surface. This assumes the groundwater table is at least at 2 m depth or deeper. This situation is true for many parts of the study area, as is shown in Figure 11 (derived by Task 4). Only soils closer to the coast would have a relatively shallow groundwater table, possibly within 2 m from the surface. In these soils water could move by capillary rise from the shallow groundwater table to the root zone and transport salts to the surface (e.g., Abliz et al., 2016). The water evaporates leaving the salt in the surface layers of the soil. These soils are therefore at higher risk of becoming saline and require dedicated soil water management if put in production. It is worth noting that effects of shallow groundwater table are unique to each location and crops grown; in Tunesia, for instance, a saline groundwater table as shallow as 0.75 m did not have any negative effects on date palm transpiration, even when the irrigation water had a salinity of 4 dS/m (Askri et al., 2014). Note that the salinity of the Dissolved Air Flotation and Filtration (DAFF) recycled water ranges from 1.59 (autumn) to 1.85 dS/m (summer) (Task 3 Report, Awad et al., 2019).



Figure 11. Depth to groundwater as derived by Task 4 (Batelaan et al., 2019).

The upper boundary of the HYDRUS-1D model was assigned an atmospheric boundary condition with daily inputs for rainfall as well as the 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 historic and future climate were estimated following the FAO-56 dual crop coefficient approach (Allen et al., 1998). Subsequently, this approach was used to estimate annual irrigation requirements of different crops. All relevant information for this approach and results obtained for the NAP soils-climate conditions are summarised in Appendix 6.

Climate parameters were obtained from Bureau of Meteorology (BOM) Station No 023083 at Edinburgh RAAF site (Latitude -34.7111, Longitude 138.6222) for historical data (1970-2017) and from the Goyder climate projection data for this station (2018-2050). Initially, the model was warmed up for 48 years (from July 1970 to June 2018) using the BOM climate data to stabilise the input parameters and attain equilibrium conditions for chemical species in the soil. Subsequently, the model was run using the median future climate data generated by the Goyder Institute for Water Research for South Australia (Charles and Fu, 2015) on the agreed set of downscaled projections.

4 Scenario modelling

4.1 Overview of scenarios

The assessment of potential impact of the use of different water qualities for long-term irrigation involved the definition of several scenarios. The modelling scenarios were grouped in several themes (Table 12); a brief description of the modelling scenarios is given here, and more details are provided in the respective modelling sections (4.2 - 4.8) and their Appendices.

Table 12. Scenarios considered for impact modelling.

THEME	EXPLANATION
Reference simulation (outdoor soil-based cropping)	 Recycled water with DAFF Water Quality is used as a reference. 4 soil types (HRB, CAL, SOC, DUG) covering cover 70% of NAP area. 7 crop types (almonds, vines, pistachios, pasture (rotational grazing with a mix of rye grass and white clover), potatoes, carrots, onions) Estimation of irrigation requirements (20% leaching)
Water quality alternatives	Following water qualities are explicitly simulated: mains water from SA Water (SAW); blended water (in proportion DAFF:SAW = 1:1); alternative water applications with monthly cycles (DAFF/SAW) or half-year cycles (DAFF/SAW) Not explicitly simulated water qualities, however impacts can be derived: groundwater (T1/T2 aquifer; Managed Aquifer Recharge (MAR)); surface water with chemical composition similar to DAFF water; urban storm water and farm dams with chemical composition similar to SAW.
Management options (outdoor soil-based cropping)	Gypsum application to manage soil sodicity (4 levels) Increased leaching fractions: 30%, 40%, 50%
Glass house cropping	Cucumber, tomatoes, capsicums, egg plant Estimation of irrigation requirements
Management options (glass house cropping)	Gypsum application with 4 levels; leaching fraction: 20%, 30%.
Management of solute load to streams	Optimising riparian zone widths to control lateral solute migration
Other toxicity	Boron toxicity
Climate extremes	Impact on crop production from extremely hot days (>35°C), hot spells, dry days (<1 mm rain), dry spells, and chilling days. Effect of a drier and hotter climate on annual irrigation requirements.

The reference scenario theme was developed for outdoor soil-based cropping and considered four soil types and seven crops (Table 12). In the reference scenario the DAFF recycled water was used for irrigation. Two sets of scenarios were run with HYDRUS-1D: one set determined the annual irrigation requirement (includes a 20% leaching fraction), while the second set evaluated the effect of recycled water on soil chemical parameters (*EC*_{sw}, *SAR*, *ESP*). Note that simulations with HYDRUS-1D did not assume any particular form of irrigation, e.g. drip, subsurface or sensor-triggered irrigation. The irrigation water is assumed to be applied at the soil surface in the same way as rain water is applied at the soil surface. Only when HYDRUS-2D was

applied (see Section 4.6) did we use the so-called "trigger option", in which case irrigation is triggered when the predefined suction level in the soil profile is reached.

In this study a 20% leaching fraction was chosen as part of the reference scenario. Exact estimation of the leaching fraction depends on several factors, including irrigation water quality (EC_w), rootzone salinity (EC_{se}), soil texture, rainfall and crop to be grown. As per different leaching estimation models (Letey et al., 2011), maintaining an EC_{se}/EC_w ratio equal to 1 (for salt sensitive crops) requires a *LF* of 0.3 (Letey et al., 2011). However, the salinity management hand book (DERM, 2011) and the Australian and New Zealand irrigation water quality guidelines (ANZECC, ARMCANZ, 2000) adopt a common 0.15 *LF* for categorising irrigation water for crop production irrespective of soil type. Therefore, our reference scenario uses a *LF* of 0.2 as a minimum *LF* requirement to address the irrigation induced salinity issue.

Note that each scenario was run for historic climate (1970-2017) and future climate (2018-2050). The intermediate-emission Representative Concentration Pathway RCP4.5A was used as a single climate future rather than a range of futures to keep the overall number of modelling scenarios to a practical number. For this region, the median decrease in annual rainfall by 2050 is 6.8% (relative to the 1986-2005 baseline), while the median increase in annual maximum daily temperature is 1.3°C.

A second group of scenarios considered different water qualities, with four modelling scenarios: low salinity water using mains water (SA Water), blending of mains and recycled water (1:1 ratio), alternating monthly cycles of mains/recycled water, and alternating 6-monthly cycles of mains/recycled water. Other water sources such as groundwater (possibly following an Aquifer Storage and Recovery (ASR) scheme) and surface water or urban storm water and farm dams were not explicitly included in the simulations as their water quality is similar to that of recycled water and mains water, respectively.

In the third theme specific management scenarios for outdoor cropping were evaluated, i.e. addition of gypsum to soil to ameliorate sodicity of soils (four levels were tested) and application of increased leaching fractions (three fractions were tested) to remove excess salt from the soil profile. No specific criteria were used to determine the gypsum application rate, other than testing whether or not threshold values for electrical conductivity, *SAR* and *ESP* had not been exceeded.

Theme four involved greenhouse crops, an assessment of the irrigation requirements of greenhouse crops, and the long-term impact of irrigation on soil salinity and sodicity. Management options tested for greenhouse cropping included gypsum amendment (four levels) and increased leaching fractions (two levels).

Theme five addressed lateral solute migration from irrigated fields to streams and how to optimise riparian/buffer zone widths to control such solute loads.

The sixth theme explored effect of recycled water on boron toxicity.

The final theme discussed effects of climate extremes on crop productivity.

In the subsequent sections, summary information is provided for each of these themes; a detailed discussion is available in a series of Appendices. The remainder of this chapter is organised as follows:

- Section 4.2 Estimation of irrigation water requirements for selected crops.
- Section 4.3 Impact of recycled water on crop yield and soil salinity and sodicity.
- Section 4.4 Management options associated with long-term irrigation.
- Section 4.5 Management of greenhouse crops.
- Section 4.6 Optimising riparian zone widths to control lateral solute migration.
- Section 4.7 Boron impact associated with use of recycled water.
- Section 4.8 Climate extremes and their impact.

4.2 Estimation of irrigation water requirements for selected crops

4.2.1 Introduction

Different crops have wide-ranging water requirements to complete their life cycle. For example, annual crops need frequent water application for their initial vigorous growth while large horticultural trees may need more water due to their large canopy transpiring large amounts of water. Therefore, development of an irrigation schedule for a particular crop involves an assessment of the seasonal water requirements as influenced by soil, crop and climate conditions. There are various methods and techniques for estimating crop water requirements, with each having their pros and cons (e.g. Jones, 2004). Among them are plant and soil based methods that are generally adopted to estimate real time crop water requirements. Simulation models are commonly used for estimating seasonal irrigation needs of crops, utilising local crop, weather and soil based measurements. Modelling of current irrigation water requirements provides a baseline for estimating the future impact of climate change on water requirements, as well as on demographic, socioeconomic, and technological changes (Döll and Siebert, 2002).

Among various modelling approaches, FAO-56 (Allen et al., 1998) has been extensively used to derive crop evapotranspiration (ET_c) and irrigation requirements for different crops across the globe. FAO-56 outlines two approaches to estimate crop evapotranspiration, i.e. the single and the dual crop coefficient approach. In the single crop coefficient approach, the effect of both crop transpiration and soil evaporation are integrated into a single crop coefficient (K_c). The FAO-56 dual crop coefficient (DCC) approach (Allen et al., 1998), describes the relationship between maximal $ET_{\rm C}$ and reference evapotranspiration (ET_0) by separating the single $K_{\rm C}$ into the basal (transpiration) crop coefficient ($K_{\rm CB}$), responsible for transpiration, and the soil evaporation coefficient (K_e), i.e., $K_c = K_{CB} + K_e$. The effects of characteristics that distinguish field crops from grass are integrated into the basal crop coefficient (K_{CB}). The basal crop coefficient (K_{CB}) is defined as the ratio of the crop evapotranspiration over the reference evapotranspiration (ET_c/ET_0) , when the soil surface is dry but transpiration is occurring at a potential rate, i.e., water is not limiting transpiration (Allen et al., 1998). This approach (DCC) requires numerous climate, soil and crop parameters to estimate the daily crop transpiration (T_P) and evaporation (E_s), as part of developing a seasonal or long-term irrigation schedule for different crops. Therefore, the FAO-56 DCC approach is a more advanced method which can be used to manage scarce water adequately in water limited environments. This method is particularly suitable for crops having incomplete ground cover or where a fraction of the soil surface is wetted by irrigation and exposed to radiation (Allen et al., 2005), such as under drip irrigation.

The present investigation used the FAO-56 dual coefficient approach for the estimation of irrigation requirements of different crops (almond, wine grapes, pistachio, pasture, carrot, onion, potato) for key soil groups (calcareous, hard red brown, sand over clay, deep uniform to gradational) in the NAP region, South Australia. We used local climate, soil and crop parameters for assessing seasonal water requirements of the different crops. The annual irrigation requirements were estimated for the historical (1970-2017) and future (2018-2050) climate data for the NAP region.

4.2.2 Methods and materials

The FAO-56 procedure (Allen et al., 1998) is a widely used methodology to estimate the crop evapotranspiration (ET_c), i.e. the composite of crop transpiration (T_P) and soil evaporation (E_s). The daily output of calculated T_P and E_s for different crops serves as input for the HYDRUS-1D simulator (Šimůnek et al., 2016). Key equations used in this method are available from Appendix 6; readers are referred to the main publication (Allen et al., 1998) for full details of the procedure.

The FAO-56 DCC methodology requires a considerable amount of data for crop, soil and climate. Some of the basic information such as crop duration, plant height, rooting depth, and depletion factor is available from FAO-56 (Allen et al., 1998), which has been reproduced for Australian conditions (Appendix 6). Soil specific information (soil texture, field capacity, permanent wilting point, readily available water, and total available water) has been drawn from the soil analyses of this report.

Daily climate data for the historic climate (1970-2017) were obtained from the BOM, Edinburgh RAAF climate station (34.71°S, 138.62°E, elevation 17 m), while 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)³, 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 possible future climate change is larger than that obtained from only using the downscaled results from the six better GCMs. The median decrease in annual rainfall predicted for the study area by GCM 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 RCP4.5⁴). A single climate future is used rather than a range of futures to keep the overall number of modelling scenarios to a practical number. As a result, the simulations present one possible outcome. In addition, a number of other uncertainties are not captured in the soil model. However, the tools developed through the project are available to further test additional future climate scenarios.

Analysis of historic and future rainfall and reference evapotranspiration data (from the median downscaled projection) shows that the average annual rainfall for the future climate (2018-2050) is expected to reduce by 7.7 % as compared to the historic (1970- 2017) climate (Figure 12). The 95th percentile annual rainfall for future climate in the study area shows a decrease of 19% relative to the historic climate. In contrast, there was a 3.5% increase in the projected average total annual ET_0 compared to the historic climate. Note that the rainfall distribution function captures the variability between years within the ensemble mean, but does not take into account the uncertainty between climate prediction models.

³ NOAA Geophysical Fluid Dynamics Laboratory, USA

⁴ RCP4.5 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 CO₂-equivalent) in the year 2100 without ever exceeding that value (Moss et al., 2010).



Figure 12. Cumulative distribution functions for annual rainfall under historical and future climate (for the intermediate-emission Representative Concentration Pathway RCP4.5).

4.2.3 Results and discussion

Typical results for calculated irrigation requirements (IR) are illustrated for almonds. The reader is referred to Appendix 6 for a complete overview of results. For historical climate, seasonal IR values for almond varied from 960-1022 mm in different NAP soils depending on soil texture and climatic conditions (Figure 13). Different soils had different annual IR, with smaller variation for almonds as compared to wine grapes (367-461 mm, see Appendix 6). With each soil having a different and unique set of hydraulic properties (water retention curve and unsaturated hydraulic conductivity function), the water holding capacity or plant available water will be different too. Indeed, the total available water for plant uptake was 74, 93, 135 and 144 mm/m for sand over clay, hard red brown, calcareous, and deep uniform soils, respectively (see Appendix 6 for details).

Highest IR values were recorded for sand over clay soil (1022 mm), with average IR values for other soils smaller by 4.8, 1.6 and 5.6% in calcareous (Cal), hard red brown (HRB) and uniform to deep gradational (DuG) soils, respectively. On the other hand, the average percent increase in mean annual IR for almonds under future climate (2018-2050) is 7.2, 6.3, 6.0 and 7.4% in calcareous, hard red brown, sand over clay and deep uniform to gradational soils, respectively (Appendix 6). The deep rooted system of almonds (up to 2 m;

Phogat et al., 2013) could possibly mine water from much larger depths resulting in a lower sensitivity to soil texture and climate change as compared to shallower rooted annual horticulture crops.

Other studies (Pitt et al., 2017; Phogat et al., 2017) in the NAP have recorded similar amounts of seasonal irrigation (889-960 mm) applied to mature almonds in a hard red brown soil. Phogat et al. (2013) calibrated and validated a numerical model for the more inland Riverland conditions (sandy soil and drier climate) and found that seasonal "deficit" irrigation of 1104 mm (35% less than full irrigation) was adequate for enhancing water productivity by 37% as compared to full irrigation (1686 mm). Moreover, the latter irrigation schedule increased the leaching losses by 18%; unless such leaching is required to remove excess salts from the soil profile, it is considered a loss of water and an unnecessary water (and solute) flux to the groundwater table. Other studies have also shown promising results with deficit irrigation of almonds (Goldhamer and Viveros, 2000; Romero et al., 2004; Girona et al., 2005; Egea et al., 2012; Monks et al., 2017). These results confirm almond is a drought resistant crop which is able to withstand frequent periods of low soil moisture accompanied by high evaporation rate and high temperature during the growing season (De Herralde et al., 2003; Rouhi et al., 2007). The results also underscore the importance of continued optimisation of irrigation scheduling for site-specific and often unique combinations of soil, climate, groundwater depth, and fruit tree variety.



Figure 13. Long-term (1970-2050) annual rainfall and seasonal irrigation schedule for almonds estimated by the FAO-56 dual crop coefficient approach in different soils (Cal-Calcareous, HRB-Hard Red Brown, SoC-Sand over clay, DuG-Deep uniform to gradational). Solid black line represents the long-term average annual trend for irrigation requirement.

The main findings around irrigation requirements considering all crops and soils are summarised as follows (also see Figure 14):

- The estimated overall average annual IR during the historical and future climate was, respectively:
 - \circ $\,$ 407 and 427 mm for wine grapes,
 - o 989 and 1055 mm for almonds,

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- o 798 and 828 mm for pistachios,
- o 1041 and 1120 mm for pastures (mixed),
- o 1017 and 1085 mm for carrots (winter and summer),
- o 655 and 718 mm for onions, and
- 573 and 628 mm for potatoes.
- Accounting for future climate change for the NAP region resulted in a 3.5-11.0% increase in the annual IR of different crops.
- Irrigation requirements in sand over clay soils for different crops was 3.1-21.3, 1.2-7.8, and 3.7-24.3%, higher than in calcareous, hard red brown and deep uniform to gradational soil, respectively.

A detailed discussion of the findings for different crops is available from Appendix 6.



Figure 14. Summary of irrigation requirements for all crops and soils considered in this study. Historic climate (1970-2017) and future climate (2018-2050). Increase in irrigation requirement for future climate is indicated on green panels. Error bars represent year-to-year variability in climate. Soils shown are: Cal-Calcareous, HRB-Hard Red Brown, SoC-Sand over clay, DuG-Deep uniform to gradational.

4.2.4 Conclusion

The estimated average annual irrigation requirement (IR) for both historic and future climate was highly dependent on crop and soil type (Table 13). Variation between crops for the same soil was higher than

variation between soils for the same crop. In other words, for the soils investigated, the crop type is the more important factor in determining irrigation requirements. Therefore, in estimating irrigation requirements one should put sufficient effort on characterising crop factors such as K_c and its evolution throughout the year, rooting depth and root distribution.

Results further revealed that for all crop types, sand over clay soils had the overall largest irrigation requirement compared to all other soils. Compared to sand over clay, the annual average IR values in calcareous, hard red brown and deep uniform to gradational soil were smaller by 3.0-17.6, 1.2-7.3, and 3.5-19.6%, respectively. Deep uniform to gradational soil had the lowest irrigation requirement; this was true for all crops. Pasture was the crop with the highest average annual IR, irrespective of soil type. Wine grapes required the least amount of irrigation (Table 13).

Projected future climate data for the NAP region showed a significant influence on the annual IR for different crops. The average percent increase in IR in different soils was 3.5-5.8 (grapes), 6.0-7.2 (almonds), 3.0-4.5 (pistachios), 7.0-8.4 (pasture), 6.2-7.4 (carrots), 9.2-10.3 (onions), and 8.8-11.0% (potatoes), depending on the soil textures and crop stress tolerance (Table 13). The results suggest that annual horticultural crops could face more irrigation related risks under the future climate as compared to deep rooted perennial horticultural crops.

Table 13. Summary of irrigation requirements (mm) for current and future climate. Soils shown are: Cal-Calcareous,HRB-Hard Red Brown, SoC-Sand over clay, DuG-Deep uniform to gradational.

CROPS		CURRENT CLIM	ATE (1970-201	7)	F	UTURE CLIMAT	E (2018-2050)	
	CAL	HRB	SOC	DUG	CAL	HRB	SOC	DUG
Grapes	376	425	461	367	398	446	477	388
Almonds	968	1004	1022	960	1038	1068	1083	1031
Pistachios	784	810	820	776	819	837	845	810
Pasture	1022	1061	1089	993	1103	1137	1165	1074
Carrot	1005	1027	1040	998	1077	1091	1104	1073
Onion	641	663	686	631	705	723	750	696
Potato	547	592	619	532	604	646	674	591

4.3 Impact of recycled water on crop yield, soil salinity and sodicity

4.3.1 Introduction

The finite element, multicomponent major ion geochemistry module UNSATCHEM implemented in the soil model HYDRUS-1D (Šimůnek et al., 2016) was used to evaluate the impact of long-term (2018-2050) use of recycled water (R_W) for irrigating perennial horticulture (almonds, pistachios), viticulture (wine grapes), annual horticulture (carrot, onion and potato), and pasture crops in different NAP soils (calcareous, hard red brown, sand over clay and deep uniform to gradational). Related soil hydraulic, soil solution and exchange data were determined from 20 soil profiles sampled from the NAP region (Appendix 1, 2). The long-term (1970- 2050) daily potential transpiration (T_P), evaporation (E_S), and the seasonal irrigation schedule for different crops were developed following the FAO-56 dual crop coefficient approach (Allen et al., 1998) utilising historic and climate change data for the NAP region and using local crop specific information (Appendix 6). An initial warming up period used historic climate data for 48 years (from July 1970- June 2018) with rainwater chemical composition used for both rain events and scheduled irrigation (as per Appendix 6). For the subsequent period (July 2018-June 2050), the statistically downscaled climate projections for South Australia (Charles and Fu, 2015) were used together with irrigation applied to different crops based on R_W . The model predicted the impact of long-term use of R_W for irrigation on soil health using the following soil chemical metrics: pH, *EC*_{SW}, *SAR*, and *ESP*.

4.3.2 Methods and materials

The HYDRUS-1D simulator is the most advanced vadose zone model which appropriately couples unsaturated water, heat transport, major ion chemistry, and solute transport (Šimůnek et al., 2016). Simulations for all crops were performed in a 200 cm-deep domain divided into 100 nodes. The nodes were distributed to ensure smaller discretization at the surface where major water and solute dynamics processes take place. The domain was divided into 5 depth layers (0-15, 15-30, 30-60, 60-100 and 100-200 cm) to accommodate measured textural heterogeneity in the key soil groups (calcareous, hard red brown, sand over clay, and deep uniform to gradational) in the NAP area.

At the soil surface an atmospheric boundary with surface run off was imposed – allowing no ponding on the surface - and free drainage was applied at the bottom boundary. For solute transport, a concentration flux boundary was assumed at the surface and a zero concentration boundary was imposed at the bottom to allow normal solute mass transfer with drainage water. With daily input values for rainfall, E_S , and E_P for different crops, the soil water balance was initialised during the warming up period. Measured soil solution and exchange parameters were assumed as initial condition for the multi component solute transport module UNSATCHEM (for details of parameters see Appendix 2).

Water quality data for different available water resources in the NAP region including recycled water (R_W) from the Bolivar water treatment plant were obtained from Awad et al. (2019). Mean seasonal composition of recycled water was estimated from raw data from 2002-2017. The values for Ca, Mg, Na, K, Alk(alinity), SO₄, and Cl used for the modelling study are given in Table 14. Based on the chloride concentration, the DAFF/ R_W quality falls in the medium category for salinity rating in Australia (ANZECC and ARMCANZ, 2000) which means that moderately tolerant crops could be grown using DAFF water as an irrigation source. Also based on the sodium concentration, moderately tolerant crops can be grown. Rainwater composition was obtained from Cresswell et al. (2010) for the Adelaide region (Table 14). Among all the water types shown in Table 14, mains water represents the best water quality. Blended water represents mixing of DAFF and SA Water (mains water) in a 1:1 proportion.

SEASON	Са	Mg	Na	К	ALK	SO ₄	Cl
			DAFF/R _w WATE	R (Meq/L)			
Autumn	1.85	2.44	11.25	1.02	1.80	3.77	10.27
Winter	1.88	2.59	11.72	0.94	1.90	3.73	10.71
Spring	2.02	3.13	13.62	0.97	2.09	3.76	12.62
Summer	1.92	2.84	13.12	1.04	2.08	3.77	12.44
Average	1.92	2.75	12.43	0.99	1.97	3.76	11.51
OTHER WATER S	OURCES (MEQ/L)						
Rain water	0.17	0.11	0.41	0.01	0.16	0.08	0.51
SA Water	0.73	0.61	2.3	0.10	0.03	0.29	2.32
1:1 blend	1.32	1.68	7.36	0.55	1.00	2.02	6.92

Table 14. Quality of irrigation waters used in the modelling simulations (based on Awad, 2019).

4.3.3 Results and discussion

Typical results for calculated effects of irrigation on soil chemical parameters and crop response are illustrated on the basis of almonds (Figure 15). The reader is referred to Appendix 6 for a complete overview of results. Periodic changes in pH, EC_{sw}, SAR and ESP in the soil profile following long-term use of recycled water in almonds is shown in Figure 16. The pH of all soil profiles remained in the alkaline range and showed little impact in response to the use of recycled water irrigation. Profile average pH at the end of the simulation (year 2050) varied in a narrow range (8.2-8.3) in all the soils (Figure 15, first column). A soil pH higher than 8 can reduce the micro-nutrient availability to the crop, which in turn can impact the normal growth and development of almonds. The extent of soluble salts (ECsw) in the soils gradually increased as a result of recycled water irrigation use (Figure 15, second column). Soil solution salinity in the upper soil layer (0-15 cm) remained below the almond tolerance threshold (EC_{sw} = 3.3 dS/m) for the initial 15 years of irrigation. At deeper depths (> 80 cm), the EC_{sw} increases quickly and always remained >5 dS/m in all the soils after 7 years of irrigation (Figure 15f, j, n, r). The annual profile average EC_{sw} remained almost constant and varied in a narrow range of 4-5 dS/m in all the soils (Figure 16). The salinity build up in the profile was slightly lower in hard red brown (hrb) as compared to other soils. Almonds are known to be sensitive to salinity and EC_{sw} values > 3.3 dS/cm can affect the normal growth and development, and therefore yield. Therefore, leaching of soluble salts with good water quality is essential to maintain the effective root zone salinity below the crop threshold for an optimal yield.

The low initial *SAR* of the soil solution (Figure 16) for all the soils increased rapidly with the application of recycled water. The *SAR* values were within 10 to 20 in all the soils at the end of the simulation showing slightly higher values for deep uniform to gradational soils (dug) than others. High *SAR* values suggest that the long-term use of recycled water irrigation can induce a sodicity hazard which could have severe impact on the sustainable almond production.

Contrary to EC_{SW} and SAR, the initial ESP in the soils was much higher than the threshold (> 6%) which could adversely affect the water movement in the soils (Figure 16). Hard red brown (hrb) and calcareous soils (cal) showed comparatively higher ESP (>35%) than others. Normally, shallow depths had lower ESP as compared to deeper layers. For example, the average initial ESP in hard red brown soils (hrb, Figure 15) in the surface layer (0-15 cm) was 17.7% which increased to 56.6% in the 120-200 cm layer at the end of the simulation showing a significant response to the use of recycled water. Similarly, the initial profile average ESP (21.8%) in calcareous soils (cal) doubled whereas corresponding *ESP* in sandy soils (soc) increased roughly 3 times (28.7%) due to the use of recycled water irrigation for 32 years (Figure 16). Similarly, the initial profile average *ESP* (29.6%) in hard red brown soil increased to 56.6% while deep uniform to gradation soil showed an increase of 2.5 times (from 12.8 to 32.3%) in the *ESP* (Figure 16).

These results show that recycled water has a tendency of increasing Na content on the soil exchanger. The increased Na contents on the soil exchanger, compared to Ca and Mg, may induce swelling and dispersion of clay and organic matter, thus, impacting the hydraulic movement of the water in the soil and degrade the soil structure. High *ESP* may induce waterlogging conditions in the soil which restrict the water movement in the soil, decrease the oxygen level and ultimately impact the plant growth. Therefore, soil amendments such as gypsum, compost or other organic sources would be required to bring down the *ESP* and providing a suitable environment for normal crop growth.

The main findings around impacts from irrigation considering all crops and soils are summarised as follows:

- Soil pH by 2050 was nearly identical for all soil depths across all soils.
- The terminal (at year 2050) soil profile salinity (*EC*_{sw}) as a result of *R*_w irrigation ranged from 2.9 at the soil surface to 3.95- 9.45 dS/m at 2 m depth across all soils and crops. The depth distribution of *EC*_{sw} was different for different crop types.
- Potential yield of salt sensitive crops such as annual horticulture and almonds was estimated to be reduced by 4-32% due to the increased salinity level in the soil.
- The model predicted an increase in the SAR as a result of R_w irrigation to different crops. Average initial (2018) profile SAR values (0.8-3.6) were increased to 12.1-19.4 in different soils at year 2050 and SAR in the soil solution was depth dependent.
- After 32 years of irrigation with *R*_w, the average soil *ESP* also increased to 43.7, 51.0, 28.4, and 35.0% in calcareous, hard red brown, sand over clay and deep uniform to gradational soils, respectively. Different crops developed different *ESP* depth distributions.
- Threshold relationships between *SAR* and *ESP* for each soil were developed. These relationships revealed that a *SAR* of 4, 3.5, 6 and 3 for calcareous, hard red brown, sand over clay and deep uniform to gradational soils, respectively, would be able develop a critical *ESP* (>6) which can lead to adverse impacts in the soils affecting normal crop growth.
- High SAR (12.1-19.4) and ESP (23.9-51.5%) build up in the soils could adversely affect soil structural stability and hydraulic movement in the soil which can severely impact the sustainable crop production.

The simulated annual profile average salinity (EC_{SW}) for different crops was used to estimate the reduction in the potential yield (Table 15). The salinity impact for Brassicas (cauliflower and cabbage) was estimated based on the calculated salinity for carrots since the water use in Brassicas and winter carrots is almost similar. The yield reductions for the 10th %tile, mean and 90th %tile profile average salinity for different soils are summarised in Table 15. It can be seen that pistachios and pasture (rye grass) had no impact of increased soil salinity because they are salt tolerant crops. These crops could be potential viable options for future cultivation in the NAP area. Yield reduction in almonds due to recycled water use varied from 9-22% in different soils; the yield reduction in wine grapes is comparatively low (0-5.7%) due to the higher salt tolerance for the latter crop (Appendix 3).



Figure 15. Model predicted average pH, soil water electrical conductivity EC_{SW} (dS/m), sodium adsorption rate (*SAR*) and exchangeable sodium percentage (*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, d), 2025-26 (e, f, g, h), 2033-34 (i, j, k, l), 2041-42 (m, n, o, p), and 2049-50 (q, r, s, t) under almond cultivation.

The discussion around yield here compares the reduction vis-à-vis overall mean salinity. However, detailed reduction in the relative yield of tests crops over the years is included in Appendix 7 (Table 5, Figure 24). The yield reduction varied from 6-35% in various crops depending on their salinity tolerance level and the salinity build up in the soils. Notably, such extent of yield loss is not a limited effect. Additionally, increased salts in

the soils would need more water to leach them out of the crop rootzone, thus incurring increased financial burden for buying more water. On top of that the main objectives of this study were to assess the extent of loss in the potential yield due to the use of recycled water and not aimed at assessing the economic implications of such interventions.



Figure 16. Model simulated annual profile average a) pH, b) soil water electrical conductivity *EC*_{SW} (dS/m), c) sodium adsorption ratio (*SAR*), and d) exchangeable sodium percentage (*ESP*) in different soils (cal = calcareous soils, hrb = hard red brown, soc = sand over clay, and dug = deep uniform to gradational) for DAFF water irrigated almond during 2018-2050.

Comparing almond yield obtained in the NAP region (Pitt et al., 2017) and the Riverland region in South Australia (Phogat et al., 2013; average yield of 8 years), revealed that the almond yield at the NAP site was only 50% of that in the Riverland. The major difference at the two sites was the water quality used for irrigation, climate (rainfall, *ET*) and type of soils (more sandy in Riverland). In the Riverland, almonds are irrigated with River Murray water which has a much lower salinity (0.4 dS/m; Phogat et al., 2018a) than the 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 $R_{\rm W}$ at the NAP site (Pitt et al., 2017) with its high soil salinity (soil profile $EC_{\rm Se}$ = 2-7.5 dS/m) might have contributed greatly to the reduction in the almonds yield.

The potential yield reduction in clover pasture crop was observed to range from 12 to 23.8%. Therefore, under mixed pasture conditions (rye grass and clover), R_W irrigation potential can impact the clover crop. Similarly, among annual horticultural crops, almost one-third of the potential yield for onion (23.5-34.9%) and potato (23.5- 34.9%) could be lost due to the high soil salinity. Corresponding numbers for carrot and brassicas ranged from 19.6-32.4 and 5.8-14.7%, respectively.

More importantly, crop salinity impacts are influenced by climate, irrigation and agronomic management (Rhoades and Loveday, 1990). Generally, most vegetable crops suffer a 10% yield reduction at an EC_{Se} of 2.7 \pm 0.8 dS/m ($EC_{SW} \approx 2 EC_{Se}$) (ANZECC and ARMCANZ, 2000). Therefore, appropriate management of irrigation induced soil salinity is essential for sustainable crop production in the NAP soils.

Table 15. Reduction in the potential yield (%) of different crops with profile average salinity (10th %tile, mean, 90th %tile) build up in different soils (Calcareous (Cal), Hard red brown [HRD), Sand over clay (SoC), Deep uniform to gradational (DuG)] in relation to recycled water use for irrigation (future climate). Coloured cells indicate the risk level to reduction in crop yield: green = low risk; amber = medium risk; red = high risk.

PERCENTILE	SOIL	ALMOND	WINE	PISTA-	CARROT	ONION	ΡΟΤΑΤΟ	BRASSICAS	PASTURE	
			GRAPE	CHIOS					CLOVER	RYE
10 th %	Cal	15.1	0.0	0.0	22.9	26.8	23.4	8.1	17.2	0.0
	HrB	9.1	0.0	0.0	19.6	24.9	15.2	5.8	12.0	0.0
	SoC	11.5	0.0	0.0	22.2	23.5	0.0	7.6	13.8	0.0
	DuG	15.0	0.0	0.0	24.4	27.5	5.9	9.2	18.7	0.0
Mean	Cal	17.6	1.7	0.0	27.1	30.5	34.5	11.0	19.2	0.0
	HrB	11.2	0.0	0.0	23.1	27.5	25.1	8.3	13.9	0.0
	SoC	15.1	0.0	0.0	27.7	28.5	0.6	11.4	16.1	0.0
	DuG	17.9	0.0	0.0	27.4	30.7	8.0	11.2	20.1	0.0
90 th %	Cal	22.2	5.7	0.0	31.1	33.6	42.9	13.8	22.9	0.0
	HrB	15.2	2.5	0.0	26.8	31.4	32.1	10.8	17.1	0.0
	SoC	20.0	1.6	0.0	32.4	34.9	3.8	14.7	19.9	0.0
	DuG	22.2	2.3	0.0	31.2	33.2	10.5	13.8	23.8	0.0

4.3.4 Conclusion

This study used the multicomponent UNSATCHEM module of HYDRUS-1D to evaluate the impact of longterm (2018-2050) use of recycled water (R_W) for irrigating wine grapes, almonds, pistachios, pasture, carrot, onion and potato crops in key NAP soils. The simulations revealed that irrigation with recycled water can potentially increase the soil solution salinity (EC_{SW}), *SAR* and *ESP* in the soil. The average terminal EC_{SW} in the soil profile under different crops in the 10th to 90th %tile range varied from 2.9-10.5 dS/m. Usually, the average EC in the upper soil layers (<30 cm) remained roughly below 4 dS/m for almonds, wine grapes, pistachios and pasture while under annual horticulture (carrot, onion, potato), salinity rose between 4.87 and 9.5 dS/m due to upward movement of salts during the cover crop season. Average profile soil salinity at lower depths (> 30 cm) ranged from 3.6-10.8 dS/m under all crops including pasture, viticulture and perennial horticulture.

Increased salinity in the soil reduces the potential yield in almond by 12-20% in different soils, with higher yield loss in hard red brown soils, followed by calcareous soils. No yield loss was observed in wine grapes, perennial pastures and pistachios as they are relatively salinity tolerant crops. Annual horticulture crops (carrots, onions, potatoes, brassicas) showed yield losses from 4-32% due the increased salinity.

Use of R_w for irrigation also has a strong impact on the soil solution and exchange dynamics, exemplified by an increase in the soil *SAR*. After 32 years of irrigation, the simulated profile average values of *SAR* were 17.4, 15.8, 15.5, and 16.3 for 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 by 22.7, 21.6, 19.4, and 10.5% in calcareous, hard red brown, sand over clay and deep uniform to gradational soils, respectively. 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 R_w irrigation to different crops could adversely impact the physical properties of soils. This could lead to clay dispersion, porosity and hydraulic conductivity reduction, and overall loss of structural stability of the soils which can severely impact the sustainable crop production. Therefore, adequate management options must be put in place so that adverse impacts of use of recycled water can be reduced realising long-term sustainable crop production.

4.4 Management options associated with long-term irrigation

4.4.1 Introduction

Long-term use of recycled water for irrigation in arid and semiarid regions usually changes the soil solution composition and soil exchange characteristics which in turn enhances the risk for salinity and sodicity hazards in soils. We focused on developing alternative management options which can reduce the potentially harmful impact of use of recycled water for long-term irrigation in the NAP region. The HYDRUS-1D multi-component module UNSATCHEM was used to evaluate the impact of long-term (2018- 2050) use of irrigation waters with different chemical composition: good quality low salinity (175 mg/L) water (G_W), recycled DAFF water with 1200 mg/L salinity (R_W), blending G_W and R_W in 1:1 proportions (B), and alternate use of G_W and R_W for monthly (Alt1) and half yearly (Alt6) cycles. Further management options considered include different levels of annual gypsum application (0, 1.7, 4.3, and 8.6 t/ha soil) in sand over clay (SoC), calcareous (Cal) and hard red brown (HRB) soils. Crops considered in the simulations include annual horticultural crops (potato), wine grapes and perennial horticultural crops (almonds). A further management option involves applying an increased leaching fraction (LF) (0.3, 0.4, and 0.5) in Cal and HRB soils for R_W and B irrigation water types. A very high gypsum application rate of 12.9 t/ha was also run in HRB soils to evaluate its ability to reduce impact in clay soils. A total of 77 scenarios were undertaken to study the impact of various management options for different NAP soils.

4.4.2 Methods and materials

The model was executed for different water quality scenarios listed in Table 16, for sand over clay (SoC), calcareous (Cal), and hard red brown (HRB) soils. In these soils, an annual horticultural crop (potato), viticulture and almonds were taken as the test crops for evaluating the impacts on a range of crops grown in the NAP region. Detailed information on the individual scenarios is given in Appendix 8.

In calcareous soils, additional scenarios were tested to evaluate the impact of different leaching fractions (*LF*) (0.3, 0.4, 0.5), particularly for recycled water and blending irrigation options. In hard red brown soils, additional scenarios were tested involving a much higher annual gypsum application (12.9 t/ha). Also in hard red brown soils, additional scenarios were run to address the occurrence of high subsoil sodicity in the collected soil profiles from the NAP. These scenarios were carried out to evaluate the impact of different leaching fractions (*LF*) (0.3, 0.4, 0.5), particularly for recycled water and blending irrigation options.

Most of the input parameters required for executing the management scenarios using HYDRUS-1D with the UNSATCHEM module have been described in Appendix 7. We tested a new software module implemented in HYDRUS-1D specifically for this study, i.e. yearly application of gypsum in long-term modelling scenarios. If the soil is sodic, gypsum is commonly added as a cheap source of calcium which replaces sodium with calcium on the solid phase (e.g. clays) and therefore reverses the sodicity or structure breakdown. In the model, the gypsum is allowed to dissolve over time according to its solubility and the chemical composition of the pore water. Therefore, simulations were conducted with annual additions of different levels of gypsum to optimise the application rate in different NAP soils.

Table 16. Different water quality and gypsum application scenarios performed in various soil-crop combinations. R_W = recycled DAFF water, G_W = good quality low salinity water, LF = leaching fraction, B = blended G_W and R_W in 1:1 proportion.

	WATER QUALITY	SOIL TYPE	CROP	
SAND OVER C	LAY (SOC) SOILS UNDER POTATO CULTIVATIO	л		APPLICATION (T/HA)
1	DAFF water, <i>R</i> w	Sand over clay	potato	0
2	DAFF water, R _W	Sand over clay	potato	1.7
3	DAFF water, <i>R</i> w	Sand over clay	potato	4.3
4	DAFF water, R _w	Sand over clay	potato	8.6
5	Good/SA water, G _w	Sand over clay	potato	0
6	Good/SA water, G _w	Sand over clay	potato	1.7
7	Good/SA water, G _w	Sand over clay	potato	4.3
8	Good/SA water, G _w	Sand over clay	potato	8.6
9	Blend R _w and G _w in 1:1, B	Sand over clay	potato	0
10	Blend R _w and G _w in 1:1, B	Sand over clay	potato	1.7
11	Blend R _w and G _w in 1:1, B	Sand over clay	potato	4.3
12	Blend R _w and G _w in 1:1, B	Sand over clay	potato	8.6
13	<i>R</i> _w & <i>G</i> _w in monthly cycles	Sand over clay	potato	0
14	$R_{\rm W}$ & $G_{\rm W}$ in monthly cycles	Sand over clay	potato	1.7
15	$R_{\rm W}$ & $G_{\rm W}$ in monthly cycles	Sand over clay	potato	4.3
16	<i>R</i> _w & <i>G</i> _w in monthly cycles	Sand over clay	potato	8.6
17	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	Sand over clay	potato	0
18	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	Sand over clay	potato	1.7
19	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	Sand over clay	potato	4.3
20	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	Sand over clay	potato	8.6
CALCAREOUS	SOILS (CAL) UNDER VITICULTURE CULTIVATIO	ON		
21	DAFF water, R _w	Calcareous	wine grapes	0
22	DAFF water, R _W	Calcareous	wine grapes	1.7
23	DAFF water, R _w	Calcareous	wine grapes	4.3
24	DAFF water, R _w	Calcareous	wine grapes	8.6
25	Good/SA water, G _w	Calcareous	wine grapes	0
26	Good/SA water, G _w	Calcareous	wine grapes	1.7
27	Good/SA water, G _W	Calcareous	wine grapes	4.3
28	Good/SA water, G _w	Calcareous	wine grapes	8.6
29	Blend $R_{\rm W}$ and $G_{\rm W}$ in 1:1, B	Calcareous	wine grapes	0
30	Blend R_W and G_W in 1:1, B	Calcareous	wine grapes	1.7
31	Blend R_W and G_W in 1:1, B	Calcareous	wine grapes	4.3
32	Blend $R_{\rm W}$ and $G_{\rm W}$ in 1:1, B	Calcareous	wine grapes	8.6

	WATER QUALITY	SOIL TYPE	CROP	GYPSUM
SAND OVER C	LAY (SOC) SOILS UNDER POTATO CULTIVATIO	NC		APPLICATION (1/HA)
33	<i>R</i> _w & <i>G</i> _w in monthly cycles	Calcareous	wine grapes	0
34	<i>R</i> _W & <i>G</i> _W in monthly cycles	Calcareous	wine grapes	1.7
35	<i>R</i> _w & <i>G</i> _w in monthly cycles	Calcareous	wine grapes	4.3
36	<i>R</i> _w & <i>G</i> _w in monthly cycles	Calcareous	wine grapes	8.6
37	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	Calcareous	wine grapes	0
38	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	Calcareous	wine grapes	1.7
39	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	Calcareous	wine grapes	4.3
40	R _w & G _w in half yr cycles	Calcareous	wine grapes	8.6
41	<i>R</i> _W + 0.3 <i>LF</i>	Calcareous	wine grapes	8.6
42	<i>R</i> _W + 0.4 <i>LF</i>	Calcareous	wine grapes	8.6
43	<i>R</i> _W + 0.5 <i>LF</i>	Calcareous	wine grapes	8.6
44	B + 0.3LF	Calcareous	wine grapes	8.6
45	B + 0.4LF	Calcareous	wine grapes	8.6
46	B + 0.5 <i>LF</i>	Calcareous	wine grapes	8.6
HARD RED BR	OWN (HRB) SOILS UNDER ALMOND CULTIVA	TION		
47	DAFF water, R _w	HRB	almond	0
48	DAFF water, R _w	HRB	almond	1.7
49	DAFF water, R _w	HRB	almond	4.3
50	DAFF water, R _w	HRB	almond	8.6
51	DAFF water, R _w	HRB	almond	12.9
52	Good/SA water, G _w	HRB	almond	0
53	Good/SA water, G _w	HRB	almond	1.7
54	Good/SA water, G _w	HRB	almond	4.3
55	Good/SA water, G _W	HRB	almond	8.6
56	Good/SA water, G _w	HRB	almond	12.9
57	Blend $R_{\rm W}$ and $G_{\rm W}$ in 1:1, B	HRB	almond	0
58	Blend R_W and G_W in 1:1, B	HRB	almond	1.7
59	Blend $R_{\rm W}$ and $G_{\rm W}$ in 1:1, B	HRB	almond	4.3
60	Blend $R_{\rm W}$ and $G_{\rm W}$ in 1:1, B	HRB	almond	8.6
61	Blend $R_{\rm W}$ and $G_{\rm W}$ in 1:1, B	HRB	almond	12.9
62	<i>R</i> _w & <i>G</i> _w in monthly cycles	HRB	almond	0
63	<i>R</i> _w & <i>G</i> _w in monthly cycles	HRB	almond	1.7
64	<i>R</i> _w & <i>G</i> _w in monthly cycles	HRB	almond	4.3
65	<i>R</i> _w & <i>G</i> _w in monthly cycles	HRB	almond	8.6
66	<i>R</i> _w & <i>G</i> _w in monthly cycles	HRB	almond	12.9
67	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	HRB	almond	0

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SCENARIO NUMBER SAND OVER C	WATER QUALITY LAY (SOC) SOILS UNDER POTATO CULTIVATIO	SOIL TYPE DN	CROP	GYPSUM APPLICATION (T/HA)
68	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	HRB	almond	1.7
69	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	HRB	almond	4.3
70	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	HRB	almond	8.6
71	$R_{\rm W}$ & $G_{\rm W}$ in half yr cycles	HRB	almond	12.9
72	<i>R</i> _W + 0.3 <i>LF</i>	HRB	almond	8.6
73	<i>R</i> _W + 0.4 <i>LF</i>	HRB	almond	8.6
74	<i>R</i> _W + 0.5 <i>LF</i>	HRB	almond	8.6
75	B + 0.3LF	HRB	almond	8.6
76	B + 0.4LF	HRB	almond	8.6
77	<i>B</i> + 0.5 <i>LF</i>	HRB	almond	8.6

4.4.3 Results and discussion

Typical results for calculated effects of management options on soil chemical parameters are illustrated for sand over clay soils. The reader is referred to Appendix 8 for a complete overview of results, including those for calcareous soils and hard red brown soils. In sand over clay soils, the average pH values at different soil depths without gypsum amendment were usually around 7.64 to 8.10 for different water quality scenarios (Figure 17). Simulated pH values were comparable with the measured values using a 0.01M CaCl₂ solution (6.25-8.32), based on different soil depths. Irrigation with R_W resulted in relatively higher pH values at all depths as compared to G_W , blending and cyclic water use scenarios. The pH decreased with annual addition of gypsum: application rates of 1.7, 4.3 and 8.6 t/ha soil reduced the pH by 2.03, 3.95, and 4.23%, respectively. These are, albeit, very small changes. The pH values in the gypsum amended soils may not have any adverse impact on the crop nutrition as these values fall in the adequate pH range for optimal bioavailability (Roques et al. 2013).

The average annual EC_{sw} values without gypsum amendment were lower than the potato threshold (EC_{sw} = 3.7 dS/m) in almost all depths under different irrigation water quality scenarios (Figure 17). Hence, R_w irrigation including its blending (B) and cyclic options (Alt1 and Alt6) can be effectively used for potato production without any adverse salinity build up in the soils. However, the annual gypsum application at a rate of 1.7, 4.3 and 8.6 t/ha soil across different water quality scenarios has increased the concentration of soluble salts in the soil by 53-77, 40-60, and 31-54%, respectively, as compared to the zero gypsum scenario. As gypsum is a moderately soluble salt, increased amounts of salt will occur in the soil on account of gypsum application. These salts could be leached below the root zone later in the season, and thus would not contribute to the overall salinity increase. These observations justify the use of higher leaching fractions (i.e. higher than the reference 20% *LF*), although this was not tested here.

The time series of annual values of EC_{SW} in the 0-15, 30-60, and 90-120 cm soil depth for different irrigation qualities and their blending and cyclic use options with 4.3 t/ha annual gypsum application are shown in Figure 18. The EC_{SW} values at the 0-15 cm soil depth were higher than the potato threshold ($EC_{SW} = 3.4 \text{ dS/m}$, based on a threshold $EC_{Se} = 1.7 \text{ dS/m}$) under all qualities of irrigation water. The EC_{SW} was much higher under R_W irrigation when the overall average values ranged from 4.1-6.6 dS/m. Note that this is still lower than the tolerance thresholds for moderately tolerant and tolerant crops thresholds (ANZECC and ARMCANZ, 2000). Irrigation with good water, blending and cyclic use yielded lower soil solution salinity than irrigation with R_W water. At 30-60 cm depths, though the annual EC_{sw} was still higher than the potato threshold, its annual fluctuations were much lower as compared to the upper soil depth. Similarly, the annual EC_{sw} reduced at 90-120 cm and remained close to the potato threshold. Stevens et al. (2003) also showed a similar EC ($EC_{se} = 2.8 \approx EC_{sw}$ of 5.6 dS/m) in the upper soil (20 cm) with recycled water irrigation in the NAP region. Most vegetable crops (except zucchini) suffer around 10% yield reduction at an EC_{se} of 2.7± 0.8 dS/m (ANZECC and ARMCANZ, 2000). This indicates that the extent of salinity development with R_w may have a limited impact on the crop yield. Stevens et al. (2003) proposed an EC_{se} of 3 dS/m as a critical value for vegetable cultivation in NAP soils. These results further suggests that a leaching fraction (20%) adopted in the present study as a reference, is able to keep the root zone salinity near the potato crop threshold in SoC soil. Rhoades and Loveday (1990) suggested a leaching fraction of 20-50% as an ideal fraction under recycled water irrigation. While higher leaching fractions can further reduce the EC_{sw} from the crop root zone, it can also increase the total salt load to groundwater.



Figure 17. Simulated spatiotemporal average values of pH, soil water electrical conductivity EC_{SW} (dS/m), sodium adsorption ratio (*SAR*) and exchangeable sodium percentage (*ESP*) in sand over clay soils at 0-15 cm, 30-60 cm, and 90-120 cm soil depths under long-term (2018-2050) irrigation of potato with different water qualities (recycled water, R_W ; Good/SA water, G_W ; blending R_W and G_W in 1:1 proportion, B; R_W and G_W used in monthly cycles, Alt1; R_W and G_W used half yearly cycles, Alt6) along with annual gypsum application of 0 (G0), 1.7(G1), 4.3 (G2), and 8.6 (G3) t/ha soil. Threshold values for EC_{SW} , *SAR* and *ESP* are shown as blue lines.

The average *SAR* values in 0-15 cm soil without gypsum amendment ranged from 5.6-11.8, which is highest for R_W irrigation and lowest for G_W irrigation (Figure 17). Overall, these values increased at 30-60 cm by 3.2% but decreased at 90-120 cm by 1.9%. Average *SAR* values were higher than the sand over clay soil threshold (*SAR* threshold = 6, see Appendix 7⁵). The *SAR* values decreased sharply with the addition of gypsum at 1.7 t/ha (10 meq/kg soil) annually. This resulted in a 30% reduction in the original *SAR* values. However, *SAR* values in some treatments and depths were still maintained at higher levels than the threshold. Further increase in the gypsum application to 4.3 t/ha soil resulted in more than 50% reduction in the *SAR*, which were comparable to sensitive crop thresholds (ANZECC and ARMCANZ, 2000) in light textured soils. Further increase in the gypsum application to 8.6 t/ha only reduced the *SAR* values by another 2.35% compared to the 4.3 t/ha application. Therefore, an application of 8.6 t/ha in light textured soils may not be an economical proposition as compared to 4.3 t/ha soil in the NAP region, in addition to increasing the salt load to shallow groundwater and connected surface waters.



Figure 18. Impact of long-term (2018-2050) use of different qualities of irrigation waters (recycled water, R_W ; Good/SA water, G_W ; blending R_W and G_W in 1:1 proportion, B; R_W and G_W used in monthly cycles, Alt1; R_W and G_W used half yearly cycles, Alt6) along with annual gypsum application of 4.3 t/ha (G2) on the annual soil water electrical conductivity EC_{SW} (dS/m) build up at a) 0-15, 30-60, and c) 90-120 cm depth in sand over clay soil (S4) under potato cultivation. Threshold values for EC_{SW} are shown as green lines.

Annual *SAR* values with 4.3 t/ha gypsum amendment varied between 2.57 to 9.76 in the 0-15 cm soil depths (Figure 19). The mean value (6.8) was comparable to the threshold value for SoC soils (*SAR* threshold = 6, see

⁵ The soil specific *SAR* threshold was derived from the soil specific *SAR*-ESP relationship, by assuming the same ESP threshold for all soils, i.e. 6%, to indicate a sodic soil consistent with Northcote and Skene (1972).

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Appendix 7). Irrigation with other water qualities (blending and cyclic use) coupled with 4.3 t/ha gypsum application showed much lower annual *SAR* values than the threshold. Similarly, the annual *SAR* at 30-60 and 90-120 cm depths were much lower than the critical threshold for sand over clay soils. Therefore, it is inferred that annual gypsum application at a rate of 4.3 t/ha is potentially able to keep the *SAR* lower than the critical value.



Figure 19. Impact of long-term (2018-2050) use of different qualities of irrigation waters (recycled water, R_W ; Good/SA water, G_W ; blending R_W and G_W in 1:1 proportion, B; R_W and G_W used in monthly cycles, Alt1; R_W and G_W used half yearly cycles, Alt6) along with annual gypsum application of 4.3 t/ha (G2) on the annual sodium adsorption ratio (*SAR*) build up at a) 0-15, 30-60, and c) 90-120 cm depth in sand over clay soil (S4) under potato cultivation. Threshold values for *SAR* are shown as green lines.

The average *ESP* values without gypsum amendments varied from 9.8-20.5% in different treatments at various depths (Figure 17). It should be noted that the measured *ESP* in the sandy soils ranged from 0.1- 27% (Task 1 Report, Oliver et al., 2019), while the average *ESP* values in 0-15, 15-30, 30-60, 60-90 and 90-120 cm soil depths were 7.4, 8.3, 7.5, 15.4, and 17.2%, respectively. This indicates there is an appreciable amount of inherent *ESP* in these soils, especially at lower depths (Task 1 report, Oliver et al., 2019). Simulated data showed gypsum application at 1.7 t/ha had a good response and decreased the *ESP* by 30%. However, the *ESP* values were still higher than the SoC threshold of 6 (Appendix 7). Further increase in the annual gypsum application to 4.3 t/ha soil reduced the *ESP* by another 50% which brought the values almost below the soil threshold (*ESP* <6%; Northcote and Skene, 1972) at all soil depths. The exception exists at deeper depths when *R*_w is used, producing a slightly higher *ESP* than the critical value; this may not have a drastic impact on the hydraulic and structural properties in the sandy texture soils. A further increase in gypsum application of 4.3 t/ha (G2) with *R*_w will likely offer an effective control to the harmful impact of *R*_w to all depths for sustainable potato cultivation in the NAP region.

The extent of annual *ESP* build-up at different depths with 4.3 t/ha gypsum application is shown in Figure 20. Although the *ESP* build-up decreased with depth, the values were higher than the threshold, especially under R_W irrigation. In most cases, the annual *ESP* falls under the sodic class (*ESP*= 6-15%), except with G_W irrigation where *ESP* was maintained below the critical (<6%) value throughout the soil profile.



Figure 20. Impact of long-term (2018- 2050) use of different qualities of irrigation waters (recycled water, R_W ; Good/SA water, G_W ; blending R_W and G_W in 1:1 proportion, B; R_W and G_W used in monthly cycles, Alt1; R_W and G_W used half yearly cycles, Alt6) along with annual gypsum application of 4.3 t/ha (G2) on the annual exchangeable sodium percentage (*ESP*) build up at a) 0-15, 30-60, and c) 90-120 cm depth in sand over clay soil (S4) under potato cultivation. Threshold values for *ESP* are shown as green lines.

Overall, the annual gypsum application at a rate of 4.3 t/ha in the SoC soils was observed to manage the negative impact of use of R_W and other combinations adequately. Apart from the test crop (potato), other crops can also be grown with R_W water along with 4.3 t/ha gypsum application while maintaining a 0.2 leaching fraction (*LF*) with each irrigation.

For calcareous and hard red brown soils, a leaching fraction of 0.5 would at least solve the salinity issue, and reduce *SAR* to acceptable limits for most water types (recycled water excluded). The *ESP* values for both soils is still above the threshold value of 6%.

The slightly higher *ESP* values in the surface depth under R_w irrigation can be further controlled with additional application of organic manure or compost along with the annual gypsum application. Organic manure not only helps reduce the sodicity impact (i.e. improve soil structure), but also adds nutritional value to sandy soils which are traditionally deficient in many essential nutrients required for sustainable crop production.

4.4.4 Conclusion

Irrigation induced salinity and sodicity will likely impact agriculture in areas such as the NAP for the foreseeable future if adequate management options are not put in place. The sustainable use of recycled water for irrigation requires designing and implementing effective farm-scale and regional-scale solutions. A comprehensive strategy for long-term monitoring, auditing and reporting framework can help streamline the use of recycled water for irrigation. This modelling study evaluated the impact of long-term (2018-2050) management options when using recycled water (R_W), and included the use of good quality (G_W), blending R_W and G_W (B), and alternate use of R_W and G_W . Management options tested further include the annual application of varied rates of gypsum (0, 1.7, 4.3, 8.6, and 12.9 t/ha) to reduce sodicity hazards (*SAR* and *ESP*). Finally, simulations were also conducted to evaluate the impact of different leaching fractions (0.2, 0.3, 0.4, and 0.5) for reducing salinity and sodicity problems.

In sandy soils, use of various irrigation water qualities had relatively little negative impact on salinity and sodicity. However, continuous use of R_w over the long-term can increase *SAR* and *ESP* of the soils to a level which could reduce the hydraulic conductivity and lead to other structural problems in the soil profile. Adoption of annual use of gypsum at 4.3 t/ha with 0.2 *LF* were found suitable to manage the hazards associated with the use of recycled water irrigation.

In contrast, the degree of salinity and sodicity problems increased many fold in calcareous soils, particularly with the continuous use of R_W . Gypsum application decreased *SAR* and *ESP*, and increased the level of soluble salts; to avoid problematic salinity levels, applying a 50% higher irrigation amount (LF 0.5) would effectively reduce the salinity levels below crop thresholds. Annual gypsum applications of 8.6 t/ha decreased the *SAR* below its threshold (< 3), especially for the *B* water type and the blending combinations, but not under R_W . While the *ESP* reduced four fold with gypsum application (8.6 t/ha) and *LF* (0.5), the *ESP* is still higher than the threshold value (< 6%) for Australian soils, under all water quality combinations. While gypsum improves soil structure, this salt can become counterproductive to crop growth under excessive application rates. Reliance on regular soil amendment with gypsum should be tempered by a better understanding of soil water interactions, clay mineralogy and the fate of salts as well as the effectiveness of drainage in the NAP soils.

Out of the three soils studied, hard red brown (HRB) soils developed the overall highest salinity and sodicity levels, regardless of water types used. The EC_{SW} values at surface depths (0-15 cm) were below sensitive crop thresholds for almonds (3 dS/m) under all water quality scenarios. At the 30-60 and 90-120 cm depths, EC_{SW} attained an average value of 4.2 and 5.4 dS/m, respectively, using R_W . Gypsum application at 8.6t/ha further increased the EC_{SW} in the soil; increasing *LF* from 0.2 to 0.5 decreased the EC_{SW} to become close to the threshold for almonds. The 8.6 t/ha gypsum application resulted in *ESP* values that were still higher than the critical threshold value of 6% for Australian soils for all irrigation scenarios and at all soil depths.

4.5 Impact of irrigation under greenhouse cropping conditions

4.5.1 Introduction

Long-term evaluation of irrigation induced transformations in the soil is essential for optimal water management and devising effective irrigation scheduling for crops, including protected crops. In this study, the multi-component numerical model HYDRUS-1D UNSATCHEM was used to assess the effects of long-term (2018-2050) irrigation on salt build-up in soil under greenhouse conditions. Blended water (recycled water and harvested rainwater) was used to irrigate soil grown greenhouse vegetables (tomato, cucumber, capsicum, and eggplant). Simulations provided insight into the development of irrigation induced chemical transformations in the soils and which management options provide for a sustainable use of irrigation water. The management scenarios include 4 leaching fractions (*LF*), i.e. *LF*0, *LF*0.15, *LF*0.2, and *LF*0.3, accounting for 0, 15, 20, and 30% excess water applied, respectively. We also considered four annual levels of gypsum application, i.e. 0 (G0), 10 (G10), 15 (G15) and 20 (G20) meq/kg soil, respectively. The model simulated annual root water uptake by cucumber, tomato, capsicum and eggplant was 303, 476, 642 and 649 mm, respectively, in response to a temperature based irrigation schedule that did not account for a leaching fraction.

4.5.2 Methods and materials

Soil samples from two greenhouses were collected from the NAP region from 3 locations at two depths (0-20 and 20-30 cm) (Awad et al., 2019). These samples were analysed for their physico-chemical properties (Oliver et al., 2019) to generate soil hydraulic and chemical properties for the HYDRUS-1D - UNSATCHEM model. Because a 200 cm-deep domain was adopted for the simulations, soil hydraulic parameters obtained in 20-30 cm layer of the greenhouse soils were extended to the bottom of the 200 cm-deep domain.

A survey of the existing greenhouses conducted in the NAP region (Awad et al. 2019) indicated four crops are commonly grown under greenhouse conditions (tomato, capsicum, cucumber and eggplant). Therefore, these crops were considered for the long-term simulations. The water quality parameters and irrigation schedules for the test crops were obtained from the IQ-QC2 model developed by Awad et al. (2019). This model generates daily crop water requirements for crops and the associated water quality parameters based on a user-defined mixing of available waters for irrigation, such as recycled water, harvested rain water and storm water. Monthly averaged irrigation water quality data for multiple years was used as shown in Table 14. Other crop specific inputs such as root water uptake parameters (Feddes et al., 1978) and salinity threshold-slope functions (Maas and Hoffman, 1977) are given in Appendix 3 of this report.

The IQ-QC2 model adopted a temporally uniform factor of 0.6 to the open field crop evapotranspiration (ET_c) to derive the crop water requirement of the glasshouse crops. The calculated ET_c matches the temperature based irrigation schedule adopted by the local growers, therefore, we used these values as daily potential crop transpiration in the HYDRUS-1D-UNSATCHEM simulations. Rainfall and soil evaporation were not considered in the simulations as these are supposed to be controlled by the presence of closed growing structures (greenhouse). The daily ET_c of all the crops was estimated from the reference crop evapotranspiration (ET_0) and the crop coefficient (K_c) approach (Allen et al., 1998) used for open field crops. Monthly K_c values for tomato, cucumber, capsicum and eggplant are provided in the IQ-QC2 mixing model as described by Awad et al. (2019). Climate parameters for the ET_c estimation were obtained from the Bureau of Meteorology station at Edinburgh RAAF site (34.71°S, 138.62°E; BOM station number 023083) for the historical climate (1970-2018) and from the Goyder Institute climate change projections for the future climate (2018-2050) (Charles and Fu, 2015).

More details on the crops, their irrigation schedule, mixing strategy, and quality of blended water are given in Awad et al. (2019). A schematic representation of the temperature based irrigation schedule for greenhouse cultivation is shown in Figure 21.





4.5.3 Results and discussion

Results from the simulations are illustrated for one of the two soils. Further details are available in Appendix 9. The simulated annual values of pH, *EC*_{SW}, *SAR* and *ESP* under different crops are shown in Figure 22. The pH values decreased gradually, although the magnitude of reduction was very small. At the end of the simulation at year 2050, the average pH values in the soils varied in a narrow range (8.2-8.5) for all the crops. The pH values were relatively higher in cucumber as compared to other crops. These changes in soil pH might be related to a low pH of the irrigation water as compared to the soil solution, which gradually decreased the pH to achieve a quasi-equilibrium.

Profile average EC_{SW} values showed a sharp increase for all crops. The EC_{SW} build up was the lowest in cucumber, followed by tomato; these results are consistent with the lower amount of seasonal irrigation applied to those two crops. Meanwhile, the highest annual EC_{SW} was observed for capsicum and eggplant; this is the result of the higher irrigation application for these crops and a longer cropping season (Jan to Oct-Nov) as compared to cucumber (Jan-May) and tomato (Jan-Sept). The profile average EC_{SW} at year 2050 rose to 6.5, 7.6, 8.7 and 9.3 dS/m for cucumber, tomato, capsicum and eggplant, respectively. These values are above the salinity tolerance threshold EC_{SW} (EC_{SW} was derived from published EC_{Se} values as $EC_{SW} = 2 \times EC_{Se}$) for these crops, i.e. 5, 5, 3.4 and 2 dS/m (Maas and Hoffman, 1977; Sonneveld and Vogt, 2009).



Figure 22. Simulated annual average values of a) pH, b) soil water electrical conductivity *EC*_{sw} (dS/m), c) sodium adsorption ratio (*SAR*), and d) exchangeable sodium percentage (*ESP*) in the sandy clay loam soil (S1) under tomato (t), cucumber (cu), capsicum, and eggplant crops irrigated with a blend of recycled water and rain water following a temperature based irrigation schedule.

Similarly, annual average *SAR* and *ESP* values in the soil also showed an increasing trend for all crops. The *ESP* values at the end of simulation (year 2050) were 30.8, 27.1, 33.2, and 31.4 % under tomato, capsicum, eggplant and cucumber, respectively. The initial *ESP* values (13-18 %) in the soil were also high, which had increased over the model warming up period (1970-2018) and varied for different crops in response to the amount of irrigation water applied. Undoubtedly, the final *ESP* values are much higher than the critical *ESP* (>6%), which leads to the development of sodic soil conditions. Therefore, an annual addition of gypsum is essential to reclaim the soil from the high *ESP* values. Alternatively, a soluble Ca application as part of the irrigation above the crop requirement also helps in keeping the *ESP* under control. Note that rapid leaching of soluble Ca or likely precipitation in the soil as calcite at high pH may reduce the effectiveness of added soluble Ca.

An annual comparison of profile average pH, EC_{SW} , SAR and ESP values obtained with and without 0.2 LF along with different annual gypsum applications (0, 10, 15 meq/kg soil) for tomato cultivation is shown in Figure 23. The G10 with 0.2 LF scenario initially had average profile SAR and ESP values higher than the threshold (6%). These reduced gradually to the values similar to those obtained with 15 meq/kg soil (G15) gypsum at the end of the simulation at year 2050. Similarly, the average SAR values were also reduced below the threshold, the pH reduced by 8.7% with average values around 7.7, and EC_{SW} was much lower than the tomato tolerance threshold.



Figure 23. Effect of leaching fraction (*LF*0 and *LF*0.2) and gypsum application [0 (G0), 10 (G10), and 15 (G15) meq/kg soil] on the changes in annual profile average a) pH, b) soil water electrical conductivity *EC*_{sw} (dS/m), c) sodium adsorption ratio (*SAR*), and d) exchangeable sodium percentage (*ESP*) in the sandy clay loam soil (S1) during 2018-2050 under tomato cultivation in greenhouse condition.

4.5.4 Conclusion

This study used the multi-component major ion chemistry module UNSATCHEM of the HYDRUS-1D model to evaluate the effects of long-term (2018-2050) irrigation with blended water for soil grown tomato, cucumber, capsicum and eggplant under unheated greenhouse conditions. The results revealed that irrigation schedules that do not apply a significant leaching fraction may lead to high salt build up and *ESP* development in the soil while accounting for future climate projections. The soil solution salinity (*EC*_{SW}) can increase to 6.5-9 dS/m at year 2050 and *ESP* can rise to 27-33% for all crops considered. These conditions could render the soil unfit for crop production and could potentially degrade the associated environment. Therefore, appropriate management options should be implemented to keep the irrigation induced harmful impacts under control.

The study evaluated the efficacy of increased leaching and gypsum application to control salinity and sodicity. Management scenarios with different leaching fractions for salinity control showed that 15-20% more water per irrigation would be required to keep the salinity under control for soil grown greenhouse vegetables. Results obtained in various scenarios for amelioration of soil with high *ESP* suggest that annual gypsum application at a rate of 1.7 t/ha was adequate for managing this hazard. Ideally, both management options (i.e. leaching fraction and gypsum use) need to be implemented simultaneously. Finally, long-term monitoring of highly efficient greenhouse production systems is essential for early identification of irrigation induced soil issues.

4.6 Optimising riparian zone widths to control lateral solute migration⁶

4.6.1 Introduction

Riparian zones are essential to preserve water quality of rivers adjacent to large areas of irrigated agriculture. We used HYDRUS (2D/3D) to quantify the influence of crops (almonds, wine grapes and potato-carrot) irrigated with recycled water (R_w) (from 1st July, 2009 to 30th June, 2017) on water and solute exchange at the Gawler River interface in relation to vegetation buffer widths from 10-110 m.

The study involves complex heterogeneous geological formations involving real-time climatic, vegetative (crop and buffer), and stream flow conditions (see Appendix 10 for details). The key objectives of this investigation were: i) to calibrate and validate a numerical model (HYDRUS 2D/3D) for water table dynamics in an area adjacent to a seasonal river (Gawler River) by incorporating daily water level fluctuations in the river, groundwater dynamics, crop evapotranspiration, riparian zone vegetation evapotranspiration, and soil heterogeneities; ii) to estimate the impact of different buffer zone widths on the flux exchange at the river-buffer interface under different cropping systems, iii) to optimise the riparian width to control the irrigation-induced solute movement to the river for different irrigated crops; and iv) to estimate the residence time of the solute tracer migrating to the adjoining water body through the subsurface under shallow water table conditions.

4.6.2 Methods and materials

The study was carried out at the Virginia Park (34°38′22.6″S and 138°32′27.6″E) gauging station at Gawler River which is situated at 12 m Australian Height Datum (AHD) (Figure 24). The Gawler River only flows during the rainy season (July to October). Stagnant water (about 30-100 cm)/base flow conditions prevail at other times at the gauging station. The adjacent area, being a part of the vast NAP, has a relatively flat topography with a gentle slope to the west. The NAP experiences a Mediterranean climate, which is characterised 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, resulting in relatively high irrigation demand for crop production (see section 4.2). Water table fluctuations in the area adjacent to the river were monitored in the shallow wells. Location of these wells is shown in Figure 24.

The vegetation buffer at the study site is dominated by River Red Gums (*Eucalyptus spp.*) with its width being highly variable along the longitudinal distance of the river, ranging from a couple to hundreds of metres. The area adjoining the riparian buffer is used for intensive cropping such as almonds, wine grapes, potato, carrot, and onion all along the river. On the southern side of the river where the modelling domain was established, the land has been used for the wine grape cultivation.

The roots of the buffer strip vegetation were assumed to be distributed linearly from the soil surface to a depth of 200 cm. Although roots of *Eucalyptus* can grow to a depth of 6-7 m (Phogat et al., 2017a), due to shallow water table conditions at the site, roots generally do not grow far below a water table due to the lack of the oxygen supply (Baker et al., 2001). Similarly, the rooting depths of 100, 200, and 60 cm for wine grape, almond, and annual horticulture (carrot and potato), respectively, were used in the modelling study based

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on relevant studies from the region (Phogat et al., 2017b, 2018b). The root water uptake parameters for almond and wine grape were also taken from these studies and the HYDRUS database (potato and carrot); Feddes' parameters (Feddes et al., 1978) were used for both the crop and buffer zones.





The transport domain represents a 400 m cross section from the middle of the river (Figure 25). The vertical dimension represents the distance from the Australian Height Datum (AHD) to the soil surface (12 m) at the experimental site. The top width of the river was 10 m, the bottom width 4 m, and the depth 4 m at the study site. The width of the buffer zone is 30 m from the river bank. Therefore, the lateral width of the riparian zone at the Virginia Park gauging station from the middle of the river is approximately 35 m, which also includes an unsealed road which runs along the river. The finite element discretization resulted in 10,000 2D elements in a standard rectangular 2D domain.

On the upper left side of the domain (Figure 25), an atmospheric boundary was considered through which infiltration (flux into the domain) or evapotranspiration (flux out of the domain) occurs. A time-variable flux boundary condition (treated similarly as an atmospheric boundary condition) was imposed on the upper right side of the domain to represent the buffer zone, which had different fluxes than the irrigated surface. The flux at this boundary was given by the difference between daily rainfall and daily potential evaporation (E_s). A special HYDRUS boundary condition (BC) was specified in the river. This special BC assigns the hydrostatic pressure head on the boundary below the water level in the river and a seepage face BC on the boundary above the water level. The specified water levels in the river are linearly interpolated in time in order to smooth the impact of daily fluctuations of water levels in the river (Phogat et al., 2017a). Measured values of water table depths in the well near the left boundary of the domain (PTA100) were used to define initial and time-variable pressure head boundary conditions. No flow was assumed as the boundary. Daily rainfall in excess of the soil infiltration capacity is accounted for as run off by HYDRUS. The longitudinal dispersivity was assumed as one tenth of the modeling domain (with the transverse dispersivity being one tenth of the longitudinal dispersivity) (Cote et al. 2003; Phogat et al., 2014) and the molecular diffusion coefficient in water equal to 1.66 cm²/day (Phogat et al., 2018b).





Measured water table depths (average of four quarterly measurements in a year) in the shallow wells (PTA101, PTG080 and PTG087, Figure 24) near the study site were used for the calibration and validation of the model. Simulations were carried out for 1461 days (1st July 2009 to 30th June 2013) to calibrate the model for water table depths at the middle of the domain (X = 200 m). Model calibration involved manually adjusting the most sensitive model parameters while visually comparing observed and simulated water table depths. A quantitative evaluation of the "best fit" model parameters was undertaken using goodness-of-fit measures similar to other studies (e.g., Alaghmand et al., 2013, 2014). The calibrated model was then validated for 1461 days (1st July 2013 to 30th June 2017) by comparing the measured and simulated water table depths. The calibrated and validated model was then used to assess the impact of other irrigated crops (almond and annual horticulture crops such as carrot and potato) and the buffer zone widths on the migration of water and solutes to the river.

The calibrated and validated model was used to simulate the dynamics of the hydrological fluxes and solute movement for different buffer widths and for various irrigated crops (wine grape, almond, and carrot-potato rotation). The simulations were executed for 8 years (1st July 2009 to 30th June 2017) plus further 8 years if needed (if the solute did not reach the river) for all 3 irrigated crops for varying buffer zone widths (10 - 110 m) from the centre of the river. These simulations were established to evaluate the appropriate width of the riparian zone to control the lateral movement of solutes to the river.

4.6.3 Results and discussion

The measured buffer zone width (35 m from the middle of the Gawler River) and actual crop grown (wine grape) adjoining the study site were considered for the calibration and validation simulations executed from July 1st, 2009 to June 30th, 2013 and from July 1st, 2013 to June 30th, 2017, respectively. The data in Figure 26 demonstrates a consistent performance of the model (i.e. R^2 of 0.66 and 0.64, and E = 0.34 and 0.34, respectively) during calibration (2009-2013) and validation (2013-2017) period. These values fell within the R^2 values (0.35-0.84) reported in other modelling studies (e.g., Coffey et al., 2004; Phogat et al., 2016). Other statistical estimates (ME, MAE, RMSE and SD; see Figure 26) during the calibration and validation period were similar but slightly higher than previously observed values (e.g. Alaghmand et al., 2013). This is because of wide fluctuation within the input data. Overall, all these statistics confirm an adequate representation of groundwater fluctuations by the model.


Figure 26. Relationship between measured and simulated water table depths, statistical error estimates (ME = mean error, MAE = mean absolute error and RMSE = root mean square error), standard deviation (SD) and model efficiency (E) values during the calibration (2009-13) and validation (2013-17) periods.

The extent of average annual irrigation among all crops during 2009-2017 (Figure 27) was the lowest in wine grape (242 and 320 mm), followed by almond (760 and 920 mm) and the highest for annual horticulture (951 and 1226 mm) reflecting their specific evapotranspiration requirements (Phogat et al., 2018b). Correspondingly, the leaching fraction/recharge flux under almond (87-298 mm) and annual horticulture (100-252 mm) was 3-3.8 times higher than under wine grapes. For wine grapes, a negative annual flux balance was recorded in some years but, the overall average balance was positive over 8 years. These observations are consistent with other studies (Green, 2010; Reynolds, 2010; Phogat et al., 2018b). It is well understood that the contribution of leaching fraction/irrigation return flow from irrigated crops can be a critical driver for the river-buffer hydraulic exchange (e.g., Berens et al., 2009).



Figure 27. Annual irrigation (mm) and recharge/discharge (mm) in the domain under a) wine grape, b) almond, and 3) annual horticulture (carrot-potato) crops. Positive fluxes are recharge and negative fluxes are discharge from the domain.

The impact of different buffer widths on the average annual water exchange at the river interface for different irrigated crops is shown in Figure 28. For wine grapes, the average annual hydraulic balance was negative for the 10-20 m buffers during the simulation period (8 years, 2009-2017), indicating the dominance

of flow from the irrigated area to the river system. The reverse was observed for buffer widths > 20 m as the evapotranspiration demand of the buffer vegetation governed the water exchange at the river-buffer interface. In the case of almond, the overall water balance remained negative (discharge to the river) for a buffer zone up to 65 m due to its 3 times higher irrigation than for wine grapes. Similarly, under annual horticulture (carrot and potato) crops, the overall hydraulic balance was similar to almonds and the threshold buffer zone width for equilibrium flow conditions reached at 55 m (Figure. 6). Based on irrigation regime for irrigated crops, different buffer zone widths are required for equilibrium flow conditions at the river-buffer interface.



Figure 28. An average balance of water exchange across the stream-aquifer interface for different buffer widths under a) wine grapes, b) almond, and c) annual horticultural crops.

Salts load transported to the river and the residence time of solutes in the soil for different buffer widths and crops are shown in Figure 29. The amount of salts for the 10 m buffer was very similar for almond and annual horticulture and about 40 times higher than for wine grapes. Meanwhile, the salts transported to the river for the 20 m buffer were higher for annual horticulture than for almond. When the buffer width was increased to 60 m, only a small additional reduction in the salt load was observed. Similarly, for annual horticulture, the average annual load of salts was reduced to 92.2% (to 1566 mg) for the 20 m buffer width is needed. Therefore, it is established that maintaining a 20, 60, and 40 m buffer widths for wine grapes, almonds, and annual horticulture can effectively reduce irrigation induced salts/tracers transport to the river by 99.9%.

The current findings highlight that considerations of local hydraulic, climate, and soil conditions, as well as local geological heterogeneity, can have a marked impact on the requirement of adequate vegetative buffers along rivers. The buffer zone guidelines adopted in most of the states (New South Wales = 40 m, Western Australia = 30 m, Tasmania = 30 m, and Victoria = 60 m) in Australia for maintaining the river water quality are mainly based on overseas studies (Hansen et al., 2010). Therefore, the consideration of the type of irrigated crops grown along the rivers and surface water bodies could have varied impact on the maintenance of the buffer zone and hence the riparian zone guidelines.



Figure 29. The amount of salts (line graph) and their residence times (bars) for different irrigated crops as a function of a buffer width during 2009-2017.

4.6.4 Conclusion

Major findings from the two-dimensional simulations with HYDRUS include:

- The hydraulic exchange at river interface for different irrigated crops was found to be sensitive to the buffer widths.
- The likely average annual water flow from the almond and annual horticulture irrigated area to the river was nearly twice as much (2.1 and 1.8, respectively) than under wine grapes.
- For wine grapes, almonds and annual horticulture, the average annual hydraulic balance reached an equilibrium at 20, 65 and 55 m buffer widths, respectively.
- The average annual load of salts became negligible for wine grapes with a 20 m buffer width.
- This study shows that buffer widths of 20, 60, and 40 m for irrigated wine grapes, almond, and annual horticulture, respectively, are needed to restrict the migration of salts to the river.

The optimised widths in this study differs from the existing guidelines in Australia. It is suggested that there is a strong need to revise the existing riparian width guidelines for maintaining good water quality in surface water bodies near R_W irrigated crops. Further refinements are possible by incorporating the influence of preferential flow paths, improved water stress response functions, and addressing the data limitations for calibration of the model for solute dynamics.

4.7 Boron risks associated with recycled water irrigation

4.7.1 Introduction

Boron (B) is a micronutrient that is required by plants in small quantities (<500 g/ha) (Shorrocks, 1997). Boron is required for the formation of new tissues but not for the maintenance of older tissues, hence actively

growing plants require larger amounts of B than slowly growing or mature plants (Adriano, 2001). Boron deficiency commonly occurs in sandy soils which have low cation exchange capacity (*CEC*) and organic matter (OM) content, where leaching and heavy cropping have diminished the soil B reserves (Adriano, 2001). Boron toxicity on the other hand usually is seen in soil of marine sediments, in soils derived from parent material rich in B, and in arid and semi-arid soils (Adriano, 2001). Of all plant nutrient elements, the range between deficient and toxic levels of available concentration is smallest for boron (Goldberg, 1997). Small increases due to fertiliser application or via boron in irrigation water and natural variations in boron concentration with soil depth may result in a soil transitioning from deficient to toxic levels or vice versa.

4.7.2 Methods and materials

Boron analyses

Plants have varying degrees of tolerance to B in soil solution and Adriano (2001) suggests B concentrations <0.5 mg/L in soil solution are probably safe for most plants but many plants may be adversely affected when B levels are in the range of 0.50 to 5.0 mg/L. Threshold concentration ranges for B concentration in soil solution based on Leyshon and Jame (1993) are given in Table 17, together with percentage of soils (sampled in this study) within each threshold range. The fraction of B in soil that is available for plant uptake is termed the phytoavailable fraction. Total B is an unreliable measure of the bioavailable fraction in soils and often an extractant, such as water or CaCl₂, is used as an index of the phytoavailable fraction (Adriano, 2001).

Table 17. Threshold boron concentration in soil solution for various crops and percentage of total number of soil samples (all data from 0-60 cm) from this study (Task 1 Report, Oliver et al., 2019) within each threshold range. Boron in soil solution determined at maximum water holding capacity. [#] Threshold concentrations from Leyshon and Jame (1993). * data from Gupta et al. (1985).

THRESHOLD CONCENTRATION (Mg/L B) RANGE FOR B IN SOIL SOLUTION (FIELD CAPACITY BASIS)#	PERCENTAGE (NUMBER) OF SOIL SAMPLES. TOTAL SOIL SAMPLES N=109.	CROP WITHIN THRESHOLD CONCENTRATION RANGE
Very sensitive <0.5	72.4% (79)	Lemon*, Grapefruit*, Avocado*, Orange*
Sensitive 0.5-1.0	14.7% (16)	Fig, Grape, Walnut, Onion, Garlic
Moderately sensitive 1.0-2.0	4.6% (5)	Broccoli, Red pepper, Carrot, Potato, Cucumber
Moderately tolerant 2.0-4.0	4.6% (5)	Lettuce, Cabbage*
Tolerant 4.0-6.0	3.7% (4)	Tomato

As part of Task 1, Oliver et al. (2019) determined boron in soil solution at maximum water holding capacity (MWHC) based on McLaughlin et al. (1997). To better represent the soil solution following irrigation, the B in soil solution was measured using a solution with a Cl concentration (550 mg/L) equivalent to that found in one of the primary irrigation water sources being considered, namely recycled waste water.

A subset of soils were sequentially extracted in duplicate with a high Cl (550 mg/L Cl) solution in a 1:5 ratio. The soils selected had been found to have relatively high B in soil solution and the sequential extractions were performed to determine whether B would continue to come into solution with each successive extraction (Appendix 11).

Boron sorption values

Sorption coefficients (K_d values) were determined for boron (B) using a batch equilibrium method (OECD/OCDE, 2000). The soils selected for determining B K_d values were chosen to cover a range of soil textures, soil pH and native B concentrations (for details, see Appendix 11).

Irrigation water quality

Boron concentration in recycled DAFF water were obtained from the Task 3 Report (Awad et al., 2019). A summary of the data is provided in Table 18.

PERIOD	NO. OF OBSERVATIONS	5 TH PERCENTILE	50 TH PERCENTILE	95 [™] PERCENTILE
2001-2011	122	0.204	0.327	0.529
2012-2016	57	0.197	0.334	0.529

 Table 18. Boron concentration (mg/L) in Bolivar DAFF irrigation water.

1D solute transport model

Equilibrium sorption

Boron concentration in soil solution is considered to be determined mainly by adsorption-desorption reactions (Goldberg, 1997). Main sorption sites for boron in soil are clays, aluminium and iron oxides, magnesium hydroxite, calcite, and organic carbon (Goldberg, 1997). For clay minerals, the order of B adsorption per gram is: kaolinite < montmorillonite < illite (Keren and Mezuman, 1981). Calcium carbonate (CaCO₃) acts as an important B adsorbing surface in calcareous soils. Also, addition of CaCO₃ increases B fixation by soils because it increases the soil pH (Goldberg and Forster, 1991).

Modelling of equilibrium boron adsorption on oxides, clay minerals, organic matter and other soil solid phases have typically been described using Langmuir and Freundlich adsorption isotherms (Goldberg, 1997; Marzadori et al., 1991). Equilibruim sorption assumes that the adsorption-desorption process is fast relative to fluid movement in soil and thus not time-dependent (Mallants et al., 2011). We developed both Langmuir and Freundlich isotherms, together with the linear K_d model (for details, see Appendix 11).

Non-equilibrium sorption

When the adsorption-desorption reaction is partially time dependent, the two-site sorption concept can be implemented (Selim et al., 1977; van Genuchten and Wagenet, 1989). In this case the sorption sites are split into equilibrium sites where sorption is instantaneous (type-1 sites with fast exchange between solid and liquid phase: S_{Eq} (µg/g) and sites where sorption is kinetically controlled (type-2 sites with time-dependent sorption: S_{Kin} (µg/g)). The mathematical expression for the mass balance of the two-site chemical non-equilibrium is (Šimůnek et al., 2008; Mallants et al., 2011):

$$S_{Tot} = S_{Eq} + S_{Kin} \tag{11}$$

$$S_{Eq} = f S_{Tot} \tag{12}$$

$$\frac{\partial S_{Kin}}{\partial t} = \alpha \left[(1 - f) K_D \frac{C}{1 + \eta \times C} - S_{Kin} \right]$$
(13)

where S_{Tot} represent the total sorbed phase concentration ($\mu g/g$), f (-) is the fraction of equilibrium sorption sites (defined by Eq. (12)), α is a first-order rate constant (h^{-1}), η and K_D are empirical or quasi-empirical

constants. In Eq. (13) we have assumed that equilibrium sorption is represented by a Langmuir type isotherm, although linear and Freundlich isotherms can also be invoked.

4.7.3 Results and discussion

Boron speciation

Boron chemistry in soil is very simple: it does not involve redox reactions and boron species are not volatile. Dissolved boron in soil pore water is present only in the +3 valence state (Figure 30). The dominant boron species in soils at low pH values is the neutral and weak boric acid, $B(OH)_3$. As the soil pH increases, boric acid forms the borate anion by accepting a hydroxyl ion: as a result, the proportion of the borate anion, $B(OH)_4^-$, increases (Figure 30). The ratio of these two boron species depends on the first dissociation constant of boric acid, K_a . The corresponding pK_a value = 9.24 ($pK_a = -\log(K_a)$). As a result, at pH < 9.2, dissolved boron predominantly exists in the form of an uncharged oxyanion ($B(OH)_3$) while at pH > 9.2, it is mostly present as $B(OH)_4^-$ (Figure 30).



Figure 30. Eh–pH predominance diagram of boron at 25 °C, 1.013 bars and activity of B = 10^{-6} calculated with The Geochemist's WorkbenchTM (Bethke et al., 2019) (left). Distribution of aqueous boron species versus pH in soil water at low EC (ionic strength I = 2.714×10⁻² mol/kgw between pH 7-9) and high EC (5 g/L salinity) (right). Boron speciation calculations based on PhreeqC (Parkhurst and Appelo, 2013).

At low pH, B sorption is low and dominated by the neutral species $B(OH)_3$. As the pH increases, the borate ion, $B(OH)_4^-$, becomes the most abundant species characterised by an increase in sorption (Goldberg and Glaubig, 1986; Adriano, 2001). Further increases in pH (i.e. pH > 9) result in increased OH⁻ concentration relative to $B(OH)_4^-$ causing B adsorption to decrease due to competition with OH⁻ for sorption sites (Goldberg and Glaubig, 1986; Adriano, 2001). Boron adsorption for soils from the Northern Adelaide Plains will be discussed in the next section.

Native boron concentration in NAP soils

Soil solution boron

Of all the soils assessed (surface layers 0-10, 10-30 and 30-60 cm), boron in soil solution was low (<0.5 mg/L B) for 72% of soils, while 13% of soils had >1 mg/L and 8% had >2 mg/L boron in soil solution (Task 1 Report, Oliver et al., 2019). Comparison of these boron levels with threshold values above which crops become sensitive to B indicates that the native B in some of the soils may already be at concentrations that are limiting or toxic to crop growth (Table 17).

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The distribution of B in soil solution at the three sampling depths for the soils sampled across the NAP region is shown in Figure 31. Hard red brown soils display the overall highest concentrations, where for the remaining three soils boron concentrations are similar. Also, hard red brown soils have the highest relative variability in boron as expressed through the coefficient of variation, *CV* (Appendix 11).



Figure 31. Boron in soil solution for soils of the Northern Adelaide Plains (data from Task 1 (Oliver et al., 2019)).

Boron concentration for all soils increases with depth. This may be due to several reasons, including higher organic matter in the top soil layer providing significant sorption capacity, higher concentrations of boron minerals at greater soil depth (inferred from total B versus depth), and leaching of boron under natural rainfall conditions. The mean boron concentration versus depth data was used as initial solute conditions for the simulations with HYDRUS-1D; as the model domain is 2 m deep, the measured concentration at the 0.45 m depth was used throughout the remaining soil depth as initial concentration.

Adsorbed soil boron

The concentration of adsorbed boron was determined in two ways. The first method uses the hot water extraction of boron in 0.01M CaCl₂, commonly used to measure B extracted from the adsorbed pools

(organic, clays) and soluble pools of the soil (Offiah and Axley, 1993). The second method uses the batch method to determine K_d , in which the absorbed concentration is one of the measured parameters (see above).

Adsorbed boron determined with the hot water extraction is shown in Figure 32 for hard red brown and deep uniform to gradational soil. Hard red brown soils have a maximum of adsorbed boron at about 40 cm depth; the deep uniform to gradational soil display increasing adsorbed boron concentrations with depth. Boron behaviour in hard red brown soils is likely related to the depth distribution of the clay fraction; a typical clay fraction is 14 % (0-10 cm), 36% (10-30 cm), 55% (30-60 cm), 37% (60-90 cm), and 29% (90-120 cm). In the deep uniform to gradational soil, clay content more or less continues to increases with depth; a typical profile is 12% (0-10 cm), 4% (10-30 cm), 16% (30-60 cm), 27% (60-90 cm), and 27% (90-120 cm).



Figure 32. Adsorbed boron for soils of the Northern Adelaide Plains based on hot water extraction (data from Task 1, Oliver et al. (2019)). Hard red brown based on data from soil profile NAP3, NAP4, NAP6, and NAP7. Deep uniform to gradational from soil profile NAP1, NP2, NAP5 (see Oliver et al. (2019) for site details).

Total soil boron

The aqua regia digestion method (US-EPA 3050 (1996) or ISO standard 11466 (1995)) is considered effective for measuring "total" trace element in soils and is usually used to give an estimate of the maximum element availability to plants. Depth distribution of total soil boron is shown in Figure 33 for all four soils. With hard red browns showing the overall highest concentrations, these soils could potentially cause suboptimal crop production for boron sensitive crops. Note that the total soil boron determined with the aqua regia digestion is sometimes lower than that determined with the hot water extraction shown in Figure 32. This is because measurements for those two methods were based on samples from slightly different depths; given the vertical variability in clay, organic matter, mineralogy and other properties, vertical variability in total boron is expected to be considerable. It is therefore best to consider both the aqua regia digestion and the hot water extract together to estimate the total boron concentration in this study.



Figure 33. Total boron in soils of the Northern Adelaide Plains (microwave soil digest using reverse aqua regia) (data from Task 1, Oliver et al. (2019)).

Boron desorption

Sequential leaching tests over a period of 96 hours provided data on time-dependent boron desorption which were used to derive the first-order rate coefficient α (h⁻¹). This analysis was undertaken only for hard red brown soil, as this is the soil with the highest concentrations and thus potentially presents the highest risk. Figure 34 shows the desorption curves for hard red brown soil depicted as liquid phase concentration (mg/L) versus time from which the cumulative desorbed boron concentration (mg/kg) was derived. In order to derive the first-order mass transfer coefficient α , the cumulative desorbed boron data were re-arranged based on the following form of the first-order kinetic expression (Pavlatou and Polyzopoulos, 1988):

$$Ln(S_{max} - S) = Ln S_{max} - \alpha t$$
⁽¹⁴⁾

where S_{max} is the total sorption capacity of the soil (mg/kg), and S is the sorbed amount (mg/kg) at time t (h). Values for S_{max} were put equal to the total boron concentration obtained by microwave soil digest using reverse aqua regia. Least squares fitting of Eq. (14) with S_{max} fixed at independently measured values yielded the first-order rate coefficient α (Figure 34). Appendix 11 provides a summary of fitted parameters of Eq. (14).



Figure 34. Desorption data (left) and fitted first-order kinetic model (right). The desorption includes instantaneous (solid lines, left axis) and cumulative values (dashed lines, right axis).

The fraction of equilibrium sites, f, was calculated according to Eq. (12) from values of S_{max} and the total desorbed boron at the end of the desorption tests, considered to be equivalent to S_{Eq} . This assumes that the desorbed boron in the first 96 hrs is readily available for desorption and that it provides a reasonable estimation of the boron on the equilibrium sites. Although the desorption curves have not yet reached a steady-state (Figure 34), considering the very long simulation times (several tens of years) considered here, the desorption data represented here can be considered to only represent relatively rapidly released boron. The second approach assumes that the total desorbed concentration obtained through the hot water extraction is a good estimator of S_{Eq} . Both approaches to estimate f are included in Table 19.

The inherent limitation in the data is that the short time scale involved cannot provide accurate reaction parameters for the long-term release of boron. For this reason the simulated boron releases are considered a sensitivity analysis only, and are not aimed at accurately predicting the boron behaviour in the soil profile under intense irrigation with recycled water.

Boron sorption

Three types of sorption isotherm were derived for boron sorption, based on hard red brown soil: linear, Freundlich, and Langmuir. The mathematical expression for the Langmuir equilibrium isotherm is as follows (Zhang and Selim, 2005):

$$S = S_{max} \frac{K_L \times C}{1 + K_L C} \tag{15}$$

where S is the total amount of adsorbed boron ($\mu g/g$), S_{max} represents the sorption maximum that can be related to soil properties ($\mu g/g$), K_{L} is the Langmuir coefficient which is related to the binding strength (L/mg), and C is the boron concentration in solution (mg/L).

The Langmuir parameters S_{max} and K_L were obtained by fitting Eq. (15) to the isotherm data from Figure 35. The following data points were taken into consideration: equilibrium boron concentrations in liquid and solid

phase from batch tests, and total desorbed boron concentration using the hot water extraction with 0.01 M CaCl₂ solution. The latter is considered to provide an estimate of the boron adsorbed on clay minerals and organic carbon and boron in the soluble pools (Offiah and Axley, 1993). In estimating parameters of Eq. (15) we assumed the hot water extraction data represents S_{max} , which was then fixed for fitting the remaining parameter, i.e. with K_L the only fitting parameter (see Appendix 11 for details).

Table 19. Fitted first-order kinetic parameter S _{max} for data shown in Figure 34. Hard red brown soils (desorbed after
96 hrs). S_{max} = total boron from microwave soil digest; $f = S_1/S_{max}$, where S_1 is cumulative desorbed boron at $t = 96$ hrs
or total desorption from hot water extraction; r = correlation coefficient for linear regression.

SITE AND SOIL DEPTH	REACTION RATE CONSTANT α (h ⁻¹)	LN(S _{MAX})	CORRELATION COEFFICIENT r	FRACTION OF S ₁ SITES, f (-) [DESORBED]	FRACTION OF S₁ SITES, f (-) [HOT WATER EXTRACTION]
CL014 20 cm	0.0070	4.177	0.958	0.467	0.0266
CL014 40 cm	0.01059	4.177	0.924	0.743	0.197
NAP06 20 cm	0.00152	4.177	0.962	0.605	0.610
NAP06 45 cm	0.0105	5.289	0.938	0.605	0.457
NAP07 45 cm	0.0129	3.663	0.977	0.692	0.366
NAP13 45 cm	0.0128	3.200	0.987	0.692	0.580
NAP15 45 cm	0.0164	3.610	0.998	0.797	0.385
NAP20 45 cm	0.00937	3.761	0.966	0.569	0.331

Results from the parameter estimation must be treated with care. Because the use of adsorption isotherms is basically a curve fitting excercise, the fitting parameters are only valid for the conditions under which the experiment was conducted. Therefore, prediction of B adsorption for conditions beyond those of the experiment will be highly unreliable, especially if this involves changes of soil solution B concentration, pH, and ionic strength (Goldberg, 1997).

For hard red brown soils four data sets were considered for estimation of the Langmuir isotherms. The data originates from four soil profiles (NAP4, NAP6, NAP7, and NAP13) at three depths (0-10, 10-30, and 30-60 cm). The liquid phase/solid phase data were grouped according to the main soil sorbing material, i.e. clay and calcite. The four data groups also have a distinctly different pH. The first group (0-10 cm for NAP 4 and 10-30 cm for NAP7) has a pH between 5.9 and 6.3 with an equilibrium boron pore-water concentration of 0.54-0.57 mg/L. Both soil layers have a relatively low clay percentage (8-14%) and low levels of calcite (0.1%). The fitted Langmuir and Freundlich isotherms for the four data groups are shown in Figure 35. Fitting parameters for all data groups are available from Appendix 11. Fitted parameters for the linear isotherm (K_d model) for hard red brown soil are available from Appendix 11.

Isotherm parameters were not determined for the other soil groups mainly for two reasons: i) there is no desorption data for those soils hence there are no first-order kinetic parameter values, ii) hard red brown soil has the highest risk of boron toxicity.

For the purpose of simulating boron behaviour in soil two hypothetical soil profiles were composed, each consisting of a set of the previously defined Langmuir models (Appendix 11). Type-1 profile is based on Langmuir model 1 and 3 has small S_{max} values from 0 to 30 cm, then S_{max} increases to medium values for the remainder of the profile. Type-2 profile is based on Langmuir model 1, 2, and 4 and has a maximum S_{max} from 15-30 cm, representing the effect of a higher clay percentage. For both profiles the Langmuir parameters

have also been recalculated according to Eq. (15), which is the default model used in HYDRUS-1D (Appendix 11).



Figure 35. Langmuir and Freundlich isotherms for boron sorption onto hard red brown soil.

The non-equilibrium parameters α and f as used in HYDRUS-1D for the two-site sorption model are listed in Table 20. Two cases are considered, which differ only in the values of the fraction of S_1 sites, f. The first method derived f from S_{max} based on the amount of boron desorbed after 96 hrs; while the second method derived f from S_{max} based on the hot water extract. As S_{max} values for the second method are larger than those of the first method, its f values are slightly smaller.

Table 20. Two-site sorption model parameters used in Hydrus-1D model. Fraction of S_1 sites, f, calculated as $f = S_1/S_{max}$, where S_1 is cumulative desorbed boron at t = 96 hrs (method 1) or desorbed from hot water extract (method 2). Reaction rate constant α in h^{-1} or d^{-1} .

SOIL TYPE	SOIL DEPTH	REACTION RATE CONSTANT α (h ⁻¹)	REACTION RATE CONSTANT α (D ⁻¹)	FRACTION OF S ₁ SITES, f (-)
Hard red brown – method 1 (S ₁ desorption after 96 hrs)	0-15 cm	0.00426	0.102	0.536
	15-30 cm	0.00426	0.102	0.743
	30-60 cm	0.0129	0.309	0.727
	60-100 cm	0.0129	0.309	0.727
	100-200 cm	0.0129	0.309	0.727
Hard red brown	0-15 cm	0.00426	0.102	0.318
(desorbed from hot water extract)	15-30 cm	0.00426	0.102	0.318
	30-60 cm	0.0129	0.309	0.415
	60-100 cm	0.0129	0.309	0.415
	100-200 cm	0.0129	0.309	0.415

A final step in setting up the boron sorption model is defining the initial boron concentrations in the soil profile. Liquid phase concentration was measured by extraction at maximum water holding capacity, where the latter is defined as the water content at -5 kPa (McLaughin et al., 1997) (Task 1 Report, Oliver et al., 2019). These water content values were obtained from the water retention measurements (Section 3.2). The sorbed concentration was based on the hot water extraction method, while bulk density was separately measured as part of a comprehensive set of soil physical measurements (Section 3.1). The relevant values for *C* and *S* are given in Appendix 11.

Boron simulations

Simulation of boron behaviour in soil was undertaken in a similar way as for the salinity and sodicity simulations, i.e. starting with a warming up period to initialise the soil (from 1970-2017), followed by the 32 years of irrigation with recycled water (2018-2050). During the warming up period, the only boron added to the soil was via the rainwater, with an average boron concentration of 0.05 mg/L (Crosbie et al., 2012). From 2018 onwards, irrigation water with an average boron concentration of 0.33 mg/L is added to the soil. Pasture was used as crop, with water requirements estimated as described in Appendix 6. The distribution of materials (soil horizons), initial solid phase solute concentration and the depth locations of observation points are shown in Figure 36.



Figure 36. HYDRUS-1D input data: distribution of soil materials (soil horizons 1-5), initial boron concentration on the solid phase (mg/kg), and depth location of observation points for outputting liquid phase concentrations.

The two-site non-equilibrium sorption model is selected with parameters estimated in the previous sections. Sorption on the equilibrium site was described by means of the Langmuir isotherm.

Given the uncertainty around the kinetic mass exchange parameter α , the simulations of boron behaviour following irrigation with recycled water are to be considered primarily as sensitivity analysis. Initial simulations with the derived α resulted in an unrealistic boron behaviour, with most of the adsorbed boron being released in the first few years after the start of the simulations. As mentioned in Section 4.7.3.2.5, the duration of the leaching test was too short to be useful for deriving reaction parameters representative of long-term, slow release processes. Therefore, the α was arbitrarily decreased by a factor 10⁻⁴ and 10⁻⁵ to mimic very slow release of boron from the kinetically controlled sorption sites. The boron behaviour was simulated first considering the adsorbed boron concentrations of profile NAP7 (Appendix 11). Subsequent sensitivity analysis were carried out to analyse the effect of the initial sorbed boron concentration on the leaching behaviour.

As part of the sensitivity analysis we tested the effect of initial sorbed boron concentration on boron leaching. Three scenarios were considered: minimum, mean, and maximum values of adsorbed boron concentration in hard red brown soil as reported in Appendix 11. Simulations were carried out with the α value set to 10^{-5} × its base value; this small value was shown to give the most realistic boron behaviour in the warming up period (Appendix 11). Simulated boron concentrations at four depths (30, 60, 100, and 200 cm) for the 80-year simulation period are displayed in Figure 37. While the effect of variability in initial sorbed boron is clearly noticeable in the pore-water concentrations, the overall variability in simulated concentrations is rather small. At the shallow depth (30 cm) concentrations range from 0.3 to 0.5 mg/L B; at 200 cm depth the concentrations range from 0.4 – 0.5 mg/L B. Note that the slightly larger variation at the shallow depth is influenced by the temporal variability in the water flux; deeper in the soil profile such variations typically become smaller (e.g. Mallants et al., 2017). Overall the boron concentration as a result of irrigation increases by about a factor of four compared to the warming up period (where small amounts of boron were added from rainfall, i.e. 0.05 mg/L). Note that through irrigation 0.33 mg/L B is added to the soil profile. This accounts for the total increase in B concentration, i.e. from about 0.1 mg/L to about 4.5 mg/L.

The variability in boron concentration in the irrigation water was also tested. Three scenarios are considered, with the following boron concentrations: 0.2 mg/L (minimum), 0.3 mg/L (mean), and 0.5 mg/L B (maximum), as per the statistical parameters from Table 18. As expected, simulated boron concentrations in the soil profile react in a linear way to the increased concentration in the irrigation water. For example, the maximum B concentration (0.5 mg/L) in irrigation water is about 2.5 times larger than the minimum concentration (0.2 mg/L). As a result, the boron concentration in the soil for the former conditions is also about 2.5 times larger than for the latter, i.e. about 0.7 mg/L versus 0.3 mg/L (Figure 38). This is true for all depths. Interestingly, the variation in B concentration as a result of variation in irrigation water quality is larger than the variation in B concentration due to variability in adsorbed boron (Figure 37). This illustrates that one of the key factors to manage B in soil is through managing the B concentrations in the irrigation water.

In developing sorption models for boron different Langmuir isotherm parameters were derived that resulted in two types of sorption profiles, i.e. Type-1 and Type-2 (Appendix 11). The sensitivity of boron leaching towards these sorption models was tested by running two scenarios, one with the Type-1 and the other with the Type-2 data. As can be seen in Appendix 11, boron leaching is not sensitive to the variation in these parameters (at least not for the variability considered here). Indeed, a nearly identical boron behaviour is observed for both scenarios at all soil depths.

By testing the sensitivity of boron leaching towards several key sources of variability (and thus uncertainty), we demonstrated that the leaching model is least sensitive to the natural soil variability (sorbed boron concentration and sorption models) and most sensitive to the variation in boron concentration in the irrigation water. Considering the mean boron concentration in irrigation water, simulations showed that boron in soil would increase by about a factor of four as a result of long-term irrigation. As the B concentration time series show, a quasi-steady state condition is achieved across all depths illustrating that there does not seem to be a long-term accumulation of B in the soil profile. Over time, an equilibrium is established between the boron added and that leaving the soil profile by drainage. Based on Figure 37 and Figure 38, such equilibrium is established after about 10 years at 30 cm depth and after 20 years at 60 cm depth, disregarding temporal variability due to climate variability.

As can be expected, the final steady-state boron concentration in the soil pore water will also depend on the initial boron concentration prior to adding boron via the irrigation water. As the initial boron concentration (i.e., prior to adding boron containing irrigation water) in the pore water and on the solid phase increases, the relative effect on the long-term boron concentration will diminish. This means that soils with an already high boron concentration (potentially representing non-optimal growth conditions) will be at a lesser risk relative to soils with a much lower boron concentration. For instance, initial pore water boron concentrations in the range 0.2-0.3 mg/L may see an increase of a factor 2 at most. For initial boron concentrations of about 1 mg/L, the increase is not more than 40% (results not shown).



Figure 37. Sensitivity analysis of boron leaching in hard red brown soil (Type-2 sorption parameters, Table 20). Effects of using different initial sorbed B concentration (minimum, mean, maximum). The α value was set to 10⁻⁵ × its base value.



Figure 38. Sensitivity analysis of boron leaching in hard red brown soil (Type-2 sorption parameters, Table 20). Effects of using different B concentration in irrigation water. Mean = 0.33 mg/L B, Min = 0.2 mg/L B, Max = 0.53 mg/L B. The α value was set to 10⁻⁵ × its base value.

Previous studies on boron toxicity in the NAP (e.g. Stevens et al., 2004) analysed soils from the current irrigation region around Virginia and compared virgin, uncropped sites with soils irrigated with recycled water (average boron concentration 0.36 mg/L) and bore water. It was found that after long-term (>28 years) irrigation with recycled water the boron concentration (1:5 water extract) in surface (0-10 cm) soils had increased to an average of 0.25 mg/L compared with approximately 0.1 mg/L in the virgin soils. At greater depths (10-20 cm), the increase was from 0.2 mg/L in the virgin soils to 0.38 mg/L in recycled water-irrigated

soils. The reported boron increases by a factor of 1.9-2.5 are similar to the simulated increases as shown in Figure 38.

4.7.4 Conclusion

Modelling long-term boron transport in soil is complicated by a number of factors, including rates of mineral dissolution, adsorption-desorption processes, linear or non-linear sorption, and instantaneous or kinetically controlled sorption. Based on best available data on boron in soils from the NAP region, the boron adsorption processes were derived by considering the following conceptual model:

- Boron adsorption/desorption is governed by a two-site model, where boron is distributed across equilibrium sites (S_1 : sorption is instantaneous) and kinetically controlled sites (S_2 : sorption is time-dependent). Best-estimate parameter values were derived for the fraction f of equilibrium sites S_1 and the kinetic mass exchange parameter α for S_2 sites. Parameter f was found to vary between 0.32 (most sites are kinetically controlled, i.e. $S_2 > S_1$) and 0.74 (most sites display instantaneous sorption, i.e. $S_1 > S_2$). The α parameter had values between 0.1 and 0.31 day⁻¹. Because α was derived from short-term desorption tests (96 hrs), the values are thought not to be representative for calculating long-term boron behaviour in soil. For this reason this parameter was arbitrarily decreased until realistic boron behaviour was simulated. Future work should address this uncertainty by developing longer-term desorption tests that produce kinetic parameters for long-term simulations.
- Boron isotherms were derived as either linear (the K_d model) or non-linear (Langmuir or Freundlich model). The best estimate parameters from the Langmuir model were used in the simulations, as these provide greatest flexibility in describing the complex sorption process.

Several modelling scenarios were undertaken and mainly served as a sensitivity analysis, given the uncertainty around key parameters such as the α parameter. By testing the sensitivity of boron leaching towards several key sources of variability (and thus uncertainty), we demonstrated that the leaching model is least sensitive to the natural soil variability (sorbed boron concentration and sorption models) and most sensitive to the variation in boron concentration in the irrigation water. Considering the mean boron concentration in irrigation water, simulations showed that boron in soil would increase by about a factor of four as a result of long-term irrigation. As the B concentration time series show, a quasi-steady state condition is achieved across all depths illustrating that there does not seem to be a long-term accumulation of B in the soil profile. Over time, an equilibrium is established between the boron added and that leaving the soil profile by drainage.

While at shallow depths it may still take 5-10 years before an equilibrium condition has been established, for soils with low initial B measurable changes seem reasonable within 2 to 3 years. Therefore, additional experimental work, preferably field based investigations involving monitoring B in soil solution, adsorbed boron and leached boron, is worth exploring. Such data may help establish a simplified B mass balance, and should also be used to further parameterise models to make predictions for other unsampled soils (or for different B input concentration) and further into the future.

Interestingly, the variation in B concentration as a result of variation in irrigation water quality is larger than the variation in B concentration due to variability in adsorbed boron. This illustrates that one of the key factors to manage B in soil is through managing the B concentrations in the irrigation water. The current simulations are preliminary results that need further corroboration, especially to get more representative sorption parameters.

Importantly, the higher the initial boron concentration (i.e., prior to adding boron containing irrigation water) in the pore water and on the solid phases, the smaller the relative effect on the long-term boron

concentrations. This means that soils with an already high boron concentration will be at a lesser risk of concentrations increasing (i.e. minimal increase in B concentration in an already high background concentration, potentially suitable only to B tolerant crops) relative to soils with a much lower boron concentration (i.e. potentially noticeable increase in B concentration in a soil with low B background making the soil less suitable to grow crops with low tolerance to B).

With reference to the boron tolerance/threshold classes listed for various crops (Table 17), the following preliminary conclusions can be made:

- Moderately tolerant (2-4 mg/L B) to tolerant (4-6 mg/L B) class: crops such as lettuce, cabbage, and tomatoes are unlikely to be at risk of yield loss owing to their high tolerance to boron, only a small number of sites (<9%) have been identified with such high B levels (in the 2-6 mg/L range). Further addition of boron at current levels in irrigation water is not expected to increase boron in soil with already high B levels significantly.
- Moderately sensitive (1-2 mg/L B) class: crops such as broccoli, red pepper, carrot, potato, and cucumber are unlikely to be at high risk of yield loss owing to their moderate sensitivity to boron, a small number of sites have been identified with B levels > 1-2 mg/L (<14%). Further addition of boron at current levels in irrigation water is not expected to increase boron in soil with intermediate B levels (1-2 mg/L) substantially.
- Sensitive (0.5-1 mg/L B) to very sensitive (< 0.5 mg/L B) class: crops such as lemon, grapefruit, avocado, orange, fig, grapes, walnut, and garlic could be at risk of yield loss under certain conditions, i.e. where B levels are either already high (above the crop threshold) or where irrigation may increase B levels from below the crop threshold to above their threshold (about 72% of hard red brown soil samples have B levels below the 0.5 mg/L threshold).

4.8 Climate extremes and their impact on crop production

4.8.1 Introduction

Agricultural industries such as viticulture, perennial and annual horticultures can be impacted by climate extremes. In this study, the effect of climate extremes on crop growth and irrigation requirement in the NAP, South Australia, was investigated. The climate indices for historic (1985-2017) and future (2018-2050) climate were analysed to determine the frequency of extreme climate events, and its impact on the growth of horticultural crops (potatoes, carrots, and onions), fruit trees (vines, almonds, and pistachios), and broad acre crops (lucerne and pasture) (for details, see Appendix 12).

Daily climate data for the historic climate (1970-2017) were obtained from the BOM, Edinburgh RAAF site (34.71°S, 138.62°E, elevation 17 m), while 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)⁷, 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 possible future climate change is larger than that obtained from only using the downscaled results from the six better GCMs. The median decrease in annual rainfall by 2050 is 6.8% (relative to 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

⁷ NOAA Geophysical Fluid Dynamics Laboratory, USA

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RCP4.5⁸). A single climate future is used rather than a range of futures to keep the overall number of modelling scenarios to a practical number. As a result, the simulations present one possible outcome. In addition, a number of other uncertainties are not captured in the soil model. However, the tools developed through the project are available to further test additional future climate scenarios.

The median and range (10th to 95th percentile) increase in annual maximum daily temperature is 1.3°C, 1.1°C, and 1.5°C, respectively (for the intermediate-emission Representative Concentration Pathway RCP4.59) (Charles and Fu, 2015).

4.8.2 Methods and materials

A total of ten climate indices were considered here and include i) mean of daily average temperature, ii) mean of daily maximum temperature, iii) mean of daily minimum temperature, iv) mean difference between the daily maximum and minimum temperature, v) the number of days when daily maximum temperature exceeds 35°C (extremely hot days), vi) the number of hot spells¹⁰, vii) number of days when daily precipitation drops below 1 mm (dry days), viii) the number of dry spells¹¹, ix) number of days when daily minimum temperature goes below 0°C (extremely cold or frost days), and x) number of days when daily minimum temperature in winter is below 7.2°C (chilling days). These indices were calculated using climate parameters such as temperature, precipitation, and humidity for historic (1985-2017) and future (2018-2050) climate data. Note that to have the same number of data points in historic and future time series, both time series were limited to 32 years each.

4.8.3 Results and discussion

Effects of extreme climate events are illustrated for the following climate indices: number of days when daily precipitation drops below 1 mm (dry days), the number of dry spells, and the number of days when daily minimum temperature in winter is below 7.2°C (chilling days). We also illustrate the effect of a drier and hotter climate on annual irrigation requirements.

A dry day is defined when daily rainfall is less than 1 mm. The cumulative distribution function (CDF) for both historic and future climate data (Figure 39) indicates a greater occurrence of dry days in the future compared with the historic data, with generally an equal shift towards more dry days across all percentiles. For example, on average (50th percentile), the number of dry days increases from 290 to 296. This is an increase by about 2.1 %. Additionally, the number of spells of three or more dry days (dry spells per year) with rainfall less than 1 mm will on average (50th percentile) increases from 81 to 86 per year (Figure 40). This is an increase by about 6.2 %.

Fruit trees such as almonds and pistachios require a minimum period of cold winter weather after which a fruit-bearing tree will blossom. The chilling requirement can be calculated as chilling hours (or chilling days), which is the sum of total amount of time in a winter spent at certain temperatures (Lockwood and Coston, 2005; Texas A&M University Agrilife Research & Extension, 2019). The adequate amount of winter chilling results in homogeneous and simultaneous flowering (Luedeling et al., 2009a; PGAI, 2019). In South

⁸ RCP4.5 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 CO₂-equivalent) in the year 2100 without ever exceeding that value (Moss et al., 2010).

⁹ RCP4.5 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 CO₂-equivalent) in the year 2100 without ever exceeding that value (Moss et al., 2010).

¹⁰Three to five consecutive days above 35 °C; six or more days above 35 °C are counted as two hot spells.

¹¹ Three or more consecutive days with less than 1 mm of rain

Australia, almonds (Pitt et al., 2013) require a winter chilling period of 400–900 hours (\approx 16.5–37.5 days) and pistachios require a winter chilling period of 600–1050 hours (\approx 25–43.75 days) below 7.2 °C (Küden et al., 1994) to initiate flowering. Figure 41 shows that the annual number of chilling days in the future will decrease on average by 4 days (or about 7.7 %).



Figure 39. Cumulative distribution function for number of days (per year) with a rainfall less than 1 mm for historic (1985-2017) and future (2018-2050) climate data.



Figure 40. Cumulative distribution function for number of spells (3 days or more with rain < 1 mm) per year with for historic (1985-2017) and future (2018-2050) climate data.



Figure 41. Cumulative distribution function for number of annual chilling winter days (with a temperature less than 7.2°C) for historic (1985-2017) and future (2018-2050) climate data.

Figure 42 shows the CDF of annual irrigation requirement (IR) under current and future climate for potato (for other crops, see Appendix 12), cultivated on various soils in the NAP region. Results show that crops will require more annual irrigation under future climate, depending on the soil textures and crop stress tolerance. Regardless of the crop type, sand over clay soils require the highest irrigation while deep uniform to gradational soils need the lowest irrigation among all soils.



Figure 42. Cumulative distribution function of annual irrigation requirement for potatoes under historic and future climate.

4.8.4 Conclusion

The NAP region of South Australia will likely be subjected to warming in the near future, based on greater daily temperature indices and frequency of hot days relative to historic climate. There will also be a higher frequency of dry days (with rainfall less than 1 mm) and dry spells. The NAP region, following global climate change predictions, will likely also be subjected to milder winters based on lower frequencies of frost and chill days.

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Previous research for the NAP region by Thomas et al. (2010) indicated that perennial horticultural crops will be most severely affected by a hotter climate, followed by viticulture, annual horticulture, then cropping and livestock (not assessed here). Climate parameters considered in the assessment were mean temperatures, number of hot days and frequency and length of heat waves, decline in winter, spring and autumn rainfall, increased irrigation demand, and summer rainfall increase. A summary of impacts for annual horticultural crops (vegetables and associated fruits) and annual field crops (cereals, canola and legume crops) is provided in Table 21. Our current analysis builds on this earlier work and confirms their main conclusions, now underpinned with climate data and soil water balance modelling.

CLIMATE PARAMETER	ANNUAL HORTICULTURAL CROPS	ANNUAL FIELD CROPS	
Mean temperature increase	Encourage faster growth, earlier harvest or more crop rotations per year.	Faster developmental phenology increases risk of extreme cold events.	
	disadvantaged (potatoes, carrots).		
	Speed up plant development resulting in insufficient biomass accumulation.		
More hot days; greater frequency and length of heat waves	Visual damage to leaves and fruit. Damage to reproductive crop components.	Affect flowering and reduce wheat yields.	
Decline in winter, spring and autumn rainfall	Increased irrigation costs.	Yield is strongly related to cool season rainfall.	
Increased irrigation demand	Reduced availability of good quality irrigation water.	Most field crops are not irrigated.	
Increase in summer rainfall	Increased risk for leaf and fruit diseases. Flooding risk and spreading of soil borne diseases and weeds.	Increased risk of crop diseases.	

Table 21. Summary of key impacts from extreme climate on crops in the NAP region (from Thomas et al., 2010).

Based on the current study, the following consequences are anticipated for the crops in the NAP region, as the result of these climatic shifts:

- Potatoes will likely have a decreased yield and a higher risk to being invaded by pests.
- The growth and yield in carrots may be stimulated due to increased frequency of hot and dry days. Extreme heat events may reduce the quality of carrots and mid-season drought stress can depress the yield in carrots.
- Warmer climate may reduce the duration of crop growth, yield, and seed production for onions; lower rainfall conditions may reduce the risk of infection by pests (i.e., leaf blight).
- The projected drought and extremely hot weather in the NAP region is expected to negatively impact vines, which may result in poor budburst, leaf loss, bunch damage, and consequently low yield and production or even crop loss.
- For almonds and pistachios, it is expected that their yield and production may be impacted by drought in the NAP region if not properly managed. While the current NAP climate hardly accommodates chill requirements for these fruits, the projected climate shows there would be some years that this requirement cannot be met at all.

• As the NAP region will likely be subjected to an increased number of hot days, a decline in pasture production is anticipated for this region.

In order to understand the effect of weather extremes on irrigation practices, the irrigation requirement for abovementioned crops was calculated using the FAO-56 dual crop coefficient method (for details see this report, Appendix 7). The irrigation requirements for these crops were compared under historic and future climate scenarios to provide insights of future climate impact. Results showed that crops will require a higher amount of annual irrigation under the future climate, depending on the soil textures and crop stress tolerance. Regardless of the crop type, sand over clay soils require the highest irrigation (714 – 956 mm) while deep uniform to gradational soils need the lowest irrigation (643 - 910 mm) among other soils. It was concluded that annual horticultural crops could face more irrigation related risks in the future climate as compared to deep rooted perennial horticultural crops.

The results of water balance simulation showed that under future climate, pastures on deep uniform to gradational soils will experience 243 extra water stress days (over a 32 year period) compared to historic climate, or 7.6 days per year. Over the 32 years period, hard red brown soils will experience 105 extra water stress days or 3.3 per year under future climate. This implies that pasture's yield and production will be reduced if not irrigated.

To improve understanding of how crops might respond to more extreme climate conditions, the concept to climate analogues can be considered. This concept is based on (i) finding sites whose current climate more or less corresponds to the projected climate on the NAP, and (ii) collecting yield data on relevant crops that are growing in those areas. For example, potato production occurs around Lameroo (Murray Mallee region of South Australia), which is slightly warmer than the NAP (22.9°C mean maximum versus 22.7°C), more prone to heatwaves and drier (382 mm versus 475 for NAP). Another example exists for wine grape production, with potential climate analogues in the Riverland, Sunraysia and Riverina (Thomas et al., 2016). A systematic study of such analogues would provide a valuable data set to complement the predicted impacts and develop improved recommendations for growers and water managers around impacts from climate change.

5 Conclusions and recommendations

5.1 Estimating annual irrigation requirements under historic and future climate

Planning for the extension of irrigated cropping area in the NAP requires that reliable estimates of annual irrigation requirement are available for expected soil-crop-climate conditions. The estimated average annual irrigation requirement for the historic climate of the region was 407, 989, 798, 1041, 1017, 655, and 573 mm for wine grapes, almonds, pistachios, pasture, carrots, onions and potato crops, respectively.

For all crop types, sand over clay soils had the overall largest irrigation requirement (384-1089 mm), while deep uniform to gradational soil had the lowest irrigation requirement (310-990 mm). Pasture had the highest average annual irrigation requirement (993-1089 mm), while wine grapes required the least amount of irrigation (306-384 mm).

The average annual irrigation requirement under future climate increased by 3.5-5.8, 6.0-7.2, 3.0-4.5, 7.0-8.4, 6.2-7.4, 9.2-10.3, and 8.8-11.0% for grapes, almonds, pistachios, pasture, carrot, onion and potato crops, respectively, with the variation for a particular crop depending on the soil textures and year-to-year climate variability.

The above results are based on considering a single climate future rather than a range of futures to keep the overall number of modelling scenarios to a practical number. As a result, the simulations present one possible outcome. In addition, a number of other uncertainties are not captured in the soil model. However, the tools developed through the project are available to further test additional future climate scenarios. The single climate future has a median decrease in annual rainfall by 2050 of 6.8% for the region (relative to 1986-2005 baseline); by comparison, the 10th percentile decrease is 8.8%, and the 95th percentile decrease is 3.5%

5.2 Impact of long-term irrigation with recycled water on crop yield, soil salinity and sodicity

The multicomponent UNSATCHEM module of HYDRUS-1D was used to evaluate the impact of long-term (2018-2050) use of recycled water (R_W) on crop yield, soil salinity and sodicity. Simulations revealed that irrigation with recycled water can potentially increase the soil solution salinity (EC_{SW}), sodium adsorption ration (*SAR*) and exchangeable sodium percentage (*ESP*). The average *EC*_{SW} by the year 2050 in the soil profile under different crops in the 10th to 90th %tile range varied from 2.9-10.5 dS/m. The average *EC* in the upper soil layers (<30 cm) remained roughly below 4 dS/m for almonds (threshold *EC*_{SW} = 3 dS/m), wine grapes (threshold *EC*_{SW} = 3 dS/m), pistachios (threshold *EC*_{SW} = 18.6 dS/m) and pasture (threshold *EC*_{SW} = 11.2 dS/m). Under annual horticulture (carrot, onion, potato with thresholds of 2, 2.4, and 3.4 dS/m, respectively), salinity may rise between 4.9 and 9.5 dS/m due to upward movement of salts during the cover crop season. Average profile soil salinity at lower depths (> 30 cm) ranged from 3.6-10.8 dS/m under all crops.

Increased salinity in the soil reduced the potential yield in almond by 12-20% in different soils, with higher yield loss in hard red brown soils, followed by calcareous soils. No yield loss was observed in perennial pastures and pistachios as they are relatively salinity tolerant crops. Annual horticulture crops (carrots, onions, potatoes, brassicas) showed yield losses from 4-32% due to the increased salinity.

Use of recycled water increased the soil *SAR*. After 32 years of irrigation, the simulated profile average *SAR* was 17.4, 15.8, 15.5, and 16.3 for calcareous, hard red brown, sand over clay and deep uniform to gradational

soils, respectively. These values were higher than the threshold *SAR* derived in this study (i.e. a *SAR* of 4, 3.5, 6 and 3 for calcareous, hard red brown, sand over clay and deep uniform to gradational soils). The predicted profile average *ESP* increased by 22.7, 21.6, 19.4, and 10.5% in calcareous, hard red brown, sand over clay and deep uniform to gradational soils, respectively. These values were much higher than the accepted *ESP* thresholds (*ESP* > 6%) for Australian soils. In other words, high *SAR* and *ESP* build up in the soils as a result of recycled water irrigation could adversely impact the physical properties of soils. This could lead to clay dispersion, porosity and hydraulic conductivity reduction, and overall loss of structural stability of the soils which can severely impact the sustainable crop production, if no management intervention for mitigation occurs.

5.3 Evaluation of soil management strategies for long-term irrigation

The sustainable use of recycled water for irrigation requires designing and implementing effective farm-scale and regional-scale solutions. This modelling study evaluated the impact of long-term (2018-2050) management options when using recycled water (R_W), and included the use of good quality (G_W), blending R_W and G_W (B), and alternate use of R_W and G_W . Management options tested further included the annual application of varied rates of gypsum (0, 1.7, 4.3, 8.6, and 12.9 t/ha) to reduce sodicity hazards (*SAR* and *ESP*). Finally, simulations were also conducted to evaluate the impact of different leaching fractions (0.2, 0.3, 0.4, and 0.5) for reducing salinity and sodicity problems.

In sandy soils, use of various irrigation water qualities had relatively little negative impact on salinity and sodicity, although the long-term use of R_W may increase *SAR* and *ESP* to a level which could lead to structural problems in the soil profile. Adoption of gypsum at 4.3 t/ha/yr with 0.2 *LF* could suitably manage the hazards associated with the use of R_W .

In contrast, the degree of salinity and sodicity problems increased many folds in calcareous soils with longterm use of R_w . Annual gypsum applications of 8.6 t/ha decreased the *SAR* below its threshold (< 3), especially for the blended water type and the blending combinations, but not under R_w . While the *ESP* reduced four fold with gypsum application (8.6 t/ha) and *LF* (0.5), the *ESP* was still higher than the threshold value (< 6%) for Australian soils, under all water quality combinations. Reliance on regular soil amendment with gypsum should be tempered by a better understanding of soil water interactions, clay mineralogy and the fate of salts as well as the effectiveness of drainage in the NAP soils.

Hard red brown (HRB) soils developed the overall highest salinity and sodicity levels, regardless of water types used. Gypsum application at 8.6t/ha with a *LF* of 0.5 decreased the EC_{sw} to become close to the threshold for almonds. This gypsum application resulted in *ESP* values that were still higher than the critical threshold value of 6% for Australian soils for all irrigation scenarios and at all soil depths.

5.4 Impact of irrigation under greenhouse cropping conditions

The effects of long-term (2018-2050) irrigation with blended water for soil grown tomato, cucumber, capsicum and eggplant under unheated greenhouse conditions were evaluated. The results revealed that irrigation schedules that do not apply a significant leaching fraction may lead to high salt build up and *ESP* development in the soil while accounting for future climate projections. The soil solution salinity (EC_{SW}) increased to 6.5-9 dS/m at year 2050 and *ESP* increased to 27-33% for all crops considered. These conditions could render the soil unfit for crop production and could potentially degrade the associated environment. Therefore, appropriate management options should be implemented to keep the irrigation induced harmful impacts under control.

The study evaluated the efficacy of increased leaching and gypsum application to control salinity and sodicity. Management scenarios with different leaching fractions for salinity control showed that 15-20% more water per irrigation would be required to keep the salinity under control for soil grown greenhouse vegetables. Results obtained in various scenarios for amelioration of soil with high *ESP* suggested that annual gypsum application at a rate of 1.7 t/ha was adequate for managing this hazard. Ideally, both management options (i.e. leaching fraction and gypsum use) need to be implemented simultaneously. Finally, long-term monitoring of highly efficient greenhouse production systems is essential for early identification of irrigation induced soil issues.

5.5 Optimising riparian zone widths to control lateral solute migration

Major findings from the two-dimensional simulations with HYDRUS (2D/3D) around optimising riparian zone widths to control lateral solute migration from irrigated fields to streams, include:

- The hydraulic exchange at river interface for different irrigated crops was found to be sensitive to the buffer widths.
- The likely average annual water flow from the almond and annual horticulture irrigated area to the river was nearly twice as much (2.1 and 1.8, respectively) than under wine grapes.
- For wine grapes, almonds and annual horticulture, the average annual hydraulic balance reached an equilibrium at 20, 65 and 55 m buffer widths, respectively.
- The average annual load of salts became negligible for wine grapes with a 20 m buffer width.
- Buffer widths of 20, 60, and 40 m for irrigated wine grapes, almond, and annual horticulture, respectively, are needed to restrict the migration of salts to the river.

It is suggested that there is a strong need to revise the existing riparian width guidelines for maintaining good water quality in surface water bodies near R_w irrigated crops. Further refinements are possible by incorporating the influence of preferential flow paths, improved water stress response functions, and addressing the data limitations for calibration of the model for solute dynamics.

5.6 Boron risks associated with recycled water irrigation

Based on best available data on boron in soils from the NAP region, the boron risks associated with long-term use of recycled water irrigation containing low levels of boron were evaluated. Adsorption processes were derived by considering a two-site kinetically controlled sorption model with non-linear sorption.

Several modelling scenarios were undertaken and mainly served as a sensitivity analysis, given the uncertainty around key parameters such as the kinetic parameter controlling time-dependent sorption/desorption. By testing the sensitivity of boron leaching towards several key sources of variability (and thus uncertainty), we demonstrated that the leaching model is least sensitive to the natural soil variability (sorbed boron concentration and sorption models) and most sensitive to the variation in boron concentration in the irrigation water. Considering the mean boron concentration in irrigation water, simulations showed that boron in soil would increase by about a factor of four as a result of long-term irrigation. As the B concentration time series show, a quasi-steady state condition was achieved across all depths illustrating that there does not seem to be a long-term accumulation of B in the soil profile. Over time, an equilibrium was established between the boron added and that leaving the soil profile by drainage. Importantly, the higher the initial boron concentration (i.e., prior to adding boron containing irrigation water) in the pore water and on the solid phases, the smaller the relative effect on the long-term boron

concentrations. This means that soils with an already high boron concentration will be at a relative lesser risk relative to soils with a much lower boron concentration.

Interestingly, the variation in B concentration as a result of variation in irrigation water quality was larger than the variation in B concentration due to variability in adsorbed boron. This illustrates that one of the key factors to manage B in soil is through managing the B concentrations in the irrigation water. The current simulations are preliminary results that need further corroboration, especially to get more representative sorption parameters.

5.7 Climate extremes and their impact on crop production

The NAP region of South Australia will be subjected to warming in the near future, based on greater daily temperature indices and likely frequency of hot days relative to historic climate. There will likely also be a higher frequency for dry days (with rainfall less than 1 mm) and dry spells compared with historic data. The NAP region, following global climate change predictions, will likely be subjected to milder winter climate based on smaller frequencies of frost and chill days.

The following consequences are anticipated for the crops in the NAP region, as the result of these climatic shifts:

- Potatoes will likely have a decreased yield and a higher risk to being invaded by pests.
- The growth and yield in carrots may be stimulated due to increased frequency of hot and dry days. Extreme heat events may reduce the quality of carrots and mid-season drought stress can depress the yield in carrots.
- Warmer climate may reduce the duration of crop growth, yield, and seed production for onions; lower rainfall conditions may reduce the risk of infection by pests (i.e., leaf blight).
- The projected drought and extremely hot weather in the NAP region is expected to negatively impact vines, which may result in poor budburst, leaf loss, bunch damage, and consequently low yield and production or even crop loss.
- For almonds and pistachios, it is expected that their yield and production may be impacted by drought in the NAP region if not properly managed. While the current NAP climate hardly accommodates chill requirements for these fruits, the projected climate shows there would be some years that this requirement cannot be met at all.
- As the NAP region will likely be subjected to an increased number of hot days, a decline in pasture production is anticipated for this region.
- Annual horticultural crops could face more irrigation related risks in the future climate as compared to deep rooted perennial horticultural crops.

The results of the water balance simulation demonstrated that under future climate, pastures on deep uniform to gradational soils will experience 243 extra water stress days (over a 32 year period) compared to historic climate, or 7.6 days per year. Over the same period, hard red brown soils will experience only 105 extra water stress days or 3.3 per year under future climate.

6 References

- Abliz A, Tiyip, T, Ghulam A, Halik U, Ding J, Sawut M, Zhang F, Nurmemet I and Abli A (2016). Effects of shallow groundwater table and salinity on soil salt dynamics in the Keriya Oasis, Northwestern China. *Env. Earth Sci.* 75:260-275.
- Adriano D (2001). Trace elements in terrestrial environments: biogeochemistry, bioavailability, and risks of metals. 2nd Edn.
- Alaghmand S, Beecham S and Hassanli A (2013). Impacts of groundwater extraction on salinization risk in a semi-arid floodplain. *Nat. Hazards Earth Syst. Sci.* 13: 3405–3418.
- Alaghmand S, Beecham S and Hassanli A (2014). Impacts of vegetation cover on surface-groundwater flows and solute interactions in a semi-arid saline floodplain: A case study of the Lower Murray River, Australia. *Environ. Process.* 1: 59-71.
- Allen RG, Pereira LS, Raes D and Smith M (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56, FAO, Rome, Italy.
- 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.
- Arris (2015). Northern Adelaide Irrigation Scheme: Market Proving Study.
- Askri B, Ahmed AT, Abichou T and Bouhlila R (2014). Effects of shallow water table, salinity and frequency of irrigation water on the date palm water use. J. Hydrol. 513: 81–90.
- Awad J, Vanderzalm J, Pezzaniti D, Olubukoa Esu O-O and 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.
- Baker TT, Conner WH, Lockaby BG, Stanturf JA and Burke MK (2001). Fine root productivity and dynamics on a forested floodplain in South Carolina. *Soil Sci. Soc. Am. J.* 65(2): 545-556.
- Batelaan O, Hatch M, Banks E, Flinchum B and Hancock M (2019). Sustainable Expansion of Irrigated Agriculture and Horticulture in Northern Adelaide Corridor: Task 4 Assessment of Depth to Groundwater (Proof of Concept). Goyder Institute for Water Research Technical Report Series No. 19/17, Adelaide, South Australia.
- Berens V, White MG and Souter NJ (2009). Injection of fresh river water into a saline floodplain aquifer in an attempt to improve the condition of river red gum (*Eucalyptus camaldulensis* Dehnh.). *Hydrol. Process*. 23:3464–3473.
- Bethke CM, Farrell B and Yeakel S (2019). The Geochemist's Workbench[®] Release 12. GWB Reference Manual. Aqueous Solutions, LLC Champaign, Illinois.
- Biggs A, Witheyman SL, Williams KM, Cupples N, de Voil CA, Power RE and Stone BJ (2012). Assessing the salinity impacts of coal seam gas water on landscapes and surface streams. August 2012. Final report of Activity 3 of the Healthy HeadWaters Coal Seam Gas Water Feasibility Study. Department of Natural Resources and Mines, Toowoomba.
- Charles SP and 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.

City of Playford (2016). Virginia and Northern Adelaide Horticultural Plains Study.

- Coffey ME, Workman SR, Taraba JL and Fogle AW (2004). Statistical procedures for evaluating daily and monthly hydrologic model predictions. *Trans. ASAE* 47:59-68.
- Cote CM, Bristow KL, Charlesworth PB, Cook FJ and Thorburn PJ (2003). Analysis of soil wetting and solute transport in subsurface trickle irrigation. *Irrig. Sci.* 22:143–156.
- Cresswell RG, Dighton J, Leaney F, Vleeshouwer J, Morrow D, Harris M and 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.
- Crosbie RS, Morrow D, Cresswell RG, Leaney FW, Lamontagne S and Lefournour M (2012). New insights into the chemical and isotopic composition of rainfall across Australia. CSIRO Water for a Healthy Country Flagship, Australia.
- de Herralde F, Biel C and Savé R (2003). Leaf photosynthesis in eight almond tree cultivars. *Biol. Plant*. 46: 557-561.
- 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.
- DERM (Department of Environment and Resource Management) (2011).Salinity management handbook. Second Edition.
- Döll P and Siebert S (2002). Global modeling of irrigation water requirements. *Water Resour. Res* 38:1037, 10.1029/2001WR000355, 2002.
- Egea G, Nortes PA, Domingo R, Baille A, Perez-Pastor A and Gonzalez-Real MM (2012). Almond agronomic response to long-term deficit irrigation applied since orchard establishment. *Irrig. Sci.* 31: 445-454.
- Espino A, Mallants D, Vanclooster M and Feyen J (1995). Cautionary notes on the use of pedotransfer functions for estimating soil hydraulic properties. *Agric. Water Manage.* 29: 235-253.
- Feddes RA, Kowalik PJ and Zaradny H (1978). Simulation of Field Water Use and Crop Yield. Simulation Monographs, Pudoc, Wageningen, The Netherlands.
- Gapon EN (1933). Theory of exchange adsorption V. J. Gen. Chem. (USSR) 3: 667–669, Chem. Abstr. 28: 4516.
- Girona J, Mata M and Marsal J (2005). Regulated deficit irrigation during the kernel-filling period and optimal irrigation rates in almond. *Agric. Water Manage*. 75 152–167.
- Goldberg S and Glaubig RA (1985). Boron adsorption on aluminium and iron-oxide minerals. *Soil Sci. Soc. Am. J.* 49: 1374-1379.
- Goldberg S and Forster HS (1991). Boron sorption on calcareous soils and reference calcites. *Soil Sci.* 152: 304–310.
- Goldberg S (1997). Reactions of boron with soils. Plant and Soil 193: 35-48.
- Goldhamer DA and Viveros M (2000). Effects of pre-harvest irrigation cut-off durations and post-harvest water deprivation on almond tree performance. *Irrig. Sci.* 19: 125–131.
- Green GP (2010). Point and regional scale modelling of vadose zone water and salt fluxes in an area of intensive horticulture. Thesis submitted to Flinders University, South Australia. https://flex.flinders.edu.au/file/27320d77-7088-4d13-8bc5-9c2b1fc4a071/1/Thesis-Green-2010.pdf.

- Gupta UC, Jame YM, Campbell CA, Leyshon AJ and Nicholaichuk W (1985). Boron toxicity and deficiency: A review. *Can. J. Soil Sci.* 65(3): 381-409.
- Hansen B, Reich P, Sam Lake P and Cavagnaro T (2010). Minimum Width Requirements for Riparian Zones to Protect Flowing Waters and to Conserve Biodiversity: A Review and Recommendations, Report to the Office of Water, Department of Sustainability and Environment, Victoria.
- ISO 11466 (1995). Soil quality: extraction of trace elements soluble in aqua regia. ISO, Geneva, Switzerland.
- Jacques D, Šimůnek J, Mallants D, and van Genuchten MTh (2013a). The HPx reactive transport models: summary of recent developments and applications. 4th International conference "Hydrus software applications to subsurface flow and contaminant transport problems", Czech University, pp. 7-16.
- Jacques D, Perko J, Seetharam S, Mallants D and Govaerts D (2013b). Modelling long-term evolution of cementitious materials used in waste disposal. IAEA-TECDOC-1701 Behaviours of cementitious materials in long term storage and disposal, pp. 26.
- Jones HG (2004). Irrigation scheduling: advantages and pitfalls of plant-based methods. *J. Expt. Bot.* 55: 2427-2436.
- Keren R and Mezuman U (1981). Boron adsorption y clay minerals using a phenomenological equation. *Clays* and *Clay Minerals* 29: 198-204.
- Küden AB, Kaska N, Tanriver E, Tekin H and Ak BE (1994). September. Determining the chilling requirements and growing degree hours of some pistachio nut cultivars and regions. In International Symposium on Pistachio 419:85-90.
- Lenhard RJ and Brooks RH (1986). Effects of Clay-Solution Interactions on Water Retention. J. Irrig. Drain. Engr. 112: 28-38.
- Letey J, Hoffman GJ, Hopmans JW, Grattan SR, Suarez D, Corwin DL, Oster JD, Wu Lu and Amrhein C (2011). Evaluation of soil salinity leaching requirement guidelines. *Agric. Water Manage*. 98: 502-506.
- Leyshon AJ and Jame Y-W (1993). Boron toxicity and irrigation management In: Gupta UC (ed) Boron and its role in crop production, pp 207 226.
- Liddicoat C, Holmes K, Maschmedt D, Rowland J, Searle R and Odgers N (2014). Soil and Landscape Grid Digital Soil Property Maps for South Australia (3" resolution). v3. CSIRO. Data Collection.http://doi.org/10.4225/08/5472DCCD081D2.
- Lockwood DW and Coston DC (2005). Peach tree physiology. Southeastern Peach Growers Handbook, Cooperative Extension Service, University of Georgia. Athens, Georgia, US, pp.5-7.
- Luedeling E, Zhang M, Luedeling V and Girvetz EH (2009b). Sensitivity of winter chill models for fruit and nut trees to climatic changes expected in California's Central Valley. *Agriculture, ecosystems & environment*, 133(1-2):23-31.
- Maas EV (1990). Crop salt tolerance. In "Agricultural salinity assessment and management", Tanji K K (ed.), ASCE Manuals and Reports on Engineering practice, No 71, New York.
- Maas EV and Hoffman GJ (1977). Crop salt tolerance: current assessment. J. Irrig. Drain. Div. Am. Soc. Civil Eng. 103 (IR2):116–134.
- Maas EV and Grattan SR (1999). Crop yields as affected by salinity. In Agricultural Drainage, Agronomy Monograph no. 38, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, 677 S. Segoe Rd., Madison, WI 53711, USA.

- Mallants D, van Genuchten MTh, Šimůnek J, Jacques D and Seetharam S (2011). Leaching of contaminants to groundwater Chapter 18. In Swartjens F. (ed) Dealing with Contaminated Sites. From Theory towards Practical Application, ISBN 978-90-481-9756-9, Springer Verlag, Dordrecht, The Netherlands, 2011, pp. 787-850. (doi: 10.1007/978-90-481-9757-6_1.)
- Mallants D, Šimůnek J and Torkzaban S (2017). Determining water quality requirements of coal seam gas produced water for sustainable irrigation. *Agric. Water Manage.* 189: 52–69 https://doi.org/10.1016/j.agwat.2017.04.011).
- Marzadori C, Antisari LV, Ciavatta C and Sequi P (1991). Soil Organic Matter Influence on Adsorption and Desorption of Boron. *Soil Sci. Soc. Am. J.* 55:1582-1585.
- McNeal BL (1968). Prediction of the effect of mixed-salt solutions on soil hydraulic conductivity, *Soil Sci. Soc. Amer. Proc.*, 32: 190-193.
- McNeal BL (1974). Soil salts and their effects on water movement, In: Drainage for Agriculture, van Schilfgaarde J (ed) Agronomy No 17, *Am. Soc. Agr.*, Madison, WI.
- McLaughlin M J, Tiller KG and Smart M K (1997). Speciation of cadmium in the soil solution of saline/sodic soils and relationship with cadmium concentrations in potato tubers (*Solanum tubersum* L.). *Aust. J. Soil Res.* 35: 183-98.
- Monks DP, Taylor C, Sommer K and Treeby MT (2017). Deficit irrigation of almond trees did not decrease yield. *Acta Hort*. (ISHS) 1150: 251-260.
- Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP and Wilbanks TJ (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463:747–756.
- Mualem Y (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.* 12: 513-522.
- Northcote KH and Skene JKM (1972). Australian soils with saline and sodic properties. Soil Publication No. 27, Commonwealth Scientific and Industrial Research Organisation, Australia.
- Odgers NP, Holmes KW, Griffin T and Liddicoat C (2015). Derivation of soil-attribute estimations from legacy soil maps. *Soil Research*. http://dx.doi.org/10.1071/SR14274.
- OECD/OCDE (2000). OECD Text No. 106: Adsorption Desorption using a batch equilibrium method. http://www.oecd-ilibrary.org/environment/test-no-106-adsorption-desorption-using-a-batchequilibrium-method_9789264069602-en.
- Offiah O O and Axley, J H (1993). Soil testing for boron on acid soils. In Boron and Its Role in Crop Production. Gupta UC (ed.). CRC Press, Boca Raton, FL, pp. 105–123.
- Oliver DP, Fruzangohar M, Johnston C, Ouzman J and 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. 19/14, Adelaide, South Australia.
- Parkhurst DL and Appelo CAJ (2013). Description of input and examples for PHREEQC version 3—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Techniques and Methods, book 6, chap. A43, 497 pp., available only at https://pubs.usgs.gov/tm/06/a43/.

- Pavlatou A, Polyzopoulos NA (1988). The role of diffusion in the kinetics of phosphate desorption: The relevance of the Elovich equation. J. Soil Sci. 39: 425-436.
- Phogat V, Mahadevan M, Skewes M and Cox JW (2012). Modelling soil water and salt dynamics under pulsed and continuous surface drip irrigation of almond and implications of system design. *Irrig. Sci.* 30: 315-333.
- Phogat V, Skewes MA, Mahadevan M and Cox JW (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 MA, Cox JW, Sanderson J, Alam J and 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 MA, Cox J.W and Šimůnek J (2016). Statistical assessment of a numerical model simulating agro hydro-chemical processes in soil under drip fertigated mandarin tree. *Irrigat. Drainage Sys. Eng.* 5(1): 1-9. http://dx.doi.org/10.4172/2168-9768.1000155.
- Phogat V, Potter NJ, Cox JW and Šimůnek J (2017a). Long-term quantification of stream-aquifer exchange in a variably saturated heterogeneous environment. *Water Resour. Manage*. 31: 4353-4366.
- Phogat V, Skewes MA, McCarthy MG, Cox JW, Šimůnek J and Petrie PR (2017b). 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 JW, and 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 JW, Šimůnek J, and Skewes MA (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.
- Pitt T, Osti A, Alcoe D, and Green G (2013). Climate change in the Northern Adelaide Plains and implicationsforhorticulture.DEWNRTechnicalNote.https://www.waterconnect.sa.gov.au/Content/Publications/DEW/DEWNR_TN_2013_09.pdf.
- Pitt T, Phogat V, Fleming N, and Cox JW (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.
- Rallo G, and Provenzano G (2013). Modelling eco-physiological response of table olive trees (Olea europaea L.) to soil water deficit conditions. *Agric. Water Manage.* 120: 79-88.
- Reynolds AG (2010). Viticultural and vineyard management practices and their effects on grape and wine quality. In: Managing wine quality volume 1: viticulture and wine quality. Ed. A.G. Reynolds (Woodhead Publishing: Cambridge) pp. 365–444.
- Rhoades JD, and Loveday J (1990). Salinity in Irrigated Agriculture, In: B. A. Stewart and D. R. Nielsen, Eds., American Society of Civil Engineers, Irrigation of Agricultural Crops, Vol. 30, Monograph, American Society of Agronomists, Madison, 1990, pp. 1089-1142.
- Romero P, Botia P, and Garcia F (2004). Effects of regulated deficit irrigation under subsurface drip irrigation conditions on water relations of mature almond trees. *Plant Soil* 260: 155–168.
- Roques S, Kendall S, Smith K, Newell Price P, and Berry P (2013). A review of the non-NPKS nutrient requirements of UK cereals and oilseed rape. Research Review No. 78. Agriculture and Horticulture Development Board.

- Rouhi V, Samson R, Lemeur R, and van Damme P (2007). Photosynthetic gas exchange characteristics in three different almond species during drought stress and subsequent recovery. *Environ .Exp. Bot.* 59: 117–129.
- SA Government (2017). Primary production priority areas. http://location.sa.gov.au/lms/Reports/ReportMetadata.aspx?p_no=1269
- Sanden BL, Ferguson L, Reyes HC, and Grattan SC (2004). Effect of salinity on evapotranspiration and yield of San Joaquin Valley pistachios. Proceedings of the IVth International Symposium on Irrigation of Horticultural Crops. *Acta Horticulturae* 664: 583-589.
- Schaap M, Leij F, and van Genuchten MTh (2001). Rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *J. Hydrol.* 251: 163-176.
- Selim HM, Davidson JM, and Rao PSC (1977). Transport of reactive solutes through multilayered soils. *Soil Sci. Soc. Am. J.* 41: 1-10.
- Shorrocks V (1997). The occurrence and correction of boron deficiency. *Plant and Soil* 193: 121-148.
- Šimůnek J, and Suarez DL (1994). Two-dimensional transport model for variably saturated porous media with major ion chemistry. *Water Resour. Res.* 30: 1115-1133.
- Šimůnek J, and Suarez DL (1997). Sodic soil reclamation using multicomponent transport modelling. ASCE J Irri Drain Eng 123: 367-376.
- Šimůnek J, and van Genuchten MTh (2006). Contaminant transport in the unsaturated zone: theory and modeling, chapter 22. In: Delleur J (ed) The handbook of groundwater engineering, 2nd edn. CRC, Boca Raton, FL, pp 22.1–22.46
- Šimůnek J, Jacques D, van Genuchten MTh, and Mallants D (2006). Multicomponent geochemical transport modelling using Hydrus-1D and HP1. J. Am. Water Resour. As. 42: 1537-47.
- Šimůnek J, van Genuchten MTh, and Šejna M (2008). Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone J.*, Special Issue "Vadose Zone Modeling" 7: 587-600. doi:10.2136/VZJ2007.0077.
- Šimůnek J, Šejna M, Saito H, Sakai M, and van Genuchten MTh (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, pp. 343.
- Šimůnek J, van Genuchten MTh, and Šejna M (2016). Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone J*. 15: 25.
- Skaggs TH, Shouse PJ, and Poss JA (2006). Irrigating Forage Crops with Saline Waters. 2. Modeling Root Uptake and Drainage. *Vadose Zone J.* 5: 824-837
- Sonneveld C and Vogt W (2009). Plant Nutrition of Greenhouse Crops. Springer Science and Business Media B.V., Dordrecht, The Netherlands.
- Soriano-Disla JM, Janik LJ, Viscarra Rossel RA, Macdonald LM, McLaughlin MJ (2014). The Performance of Visible, Near-, and Mid-Infrared Reflectance Spectroscopy for Prediction of Soil Physical, Chemical, and Biological Properties. *Applied Spectroscopy Reviews* 49: 139-186, DOI: 10.1080/05704928.2013.811081
- Stevens DP, McLaughlin MJ, and Smart MK (2003). Effects of long-term irrigation with reclaimed water on soils of the Northern Adelaide Plains, South Australia. *Aust. J. Soil Res.* 41: 933-948.

Taylor SA, Ashcroft GM (1972). Physical Edaphology. Freeman and Co., San Francisco, California, p. 434-435.

- Texas A&M University Agrilife Research & Extension (2019). "Chilling hours". https://etweather.tamu.edu/chill/ [accessed 07-Febraury-2019].
- US-EPA 3050B (1996). Acid digestion of sediments, sludges and soils. Environmental Protection Agency, Washington, DC.
- Vanderborght J, and Vereecken H (2007). Review of dispersivities for transport modelling in soils. *Vadose Zone J.* 6: 29-52.
- van Genuchten MTh (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Sci. Soc. Amer. J.* 44: 892-898.
- van Genuchten MTh, and Wagenet RJ (1989). Two-site/two-region models for pesticide transport and degradation: Theoretical development and analytical solutions. *Soil Sci. Soc. Am. J.* 53: 1303-1310.
- van Genuchten MTh, Leij FJ, and Yates SR (1991). The RETC code for quantifying the hydraulic functions of unsaturated soils. Report No. EPA/600/2-91/065. R. S. Kerr Environmental Research Laboratory, U. S. Environmental Protection Agency, Ada, OK. 85 pp.
- Wesseling JG, Elbers JA, Kabat P, and van den Broek BJ (1991). SWATRE; instructions for input. Internal note, Winand Staring Centre, Wageningen.
- White N, and Zelazny LW (1986). Charge properties in soil colloids, In: Soil Physical Chemistry, edited by D. L. Sparks, CRC Press, BOCA Raten, FL.
- Youngs EG (2001). Hydraulic conductivity of saturated soils. Chapter 4. In Soil and Environmental Analysis. Physical methods, revised and expanded. CRC Press.





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