Australian Water Recycling
Centre of Excellence

Project Report

Methods to increase the use of recycled wastewater in irrigation by overcoming the constraint of soil salinity

A report of a study funded by the
Australian Water Recycling Centre of Excellence and the
Goyder Institute for Water Research

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Methods to increase the use of recycled wastewater in irrigation by overcoming the constraint of soil salinity

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The mission of the Australian Water Recycling Centre of Excellence is to enhance management and use of water recycling through industry partnerships, build capacity and capability within the recycled water industry, and promote water recycling as a socially, environmentally and economically sustainable option for future water security.

The Australian Government has provided $20 million to the Centre through its National Urban Water and Desalination Plan to support applied research and development projects which meet water recycling challenges for Australia's irrigation, urban development, food processing, heavy industry and water utility sectors. This funding has levered an additional $40 million investment from more than 80 private and public organisations, in Australia and overseas.

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Glossary

AWRCOE	Australian Water Recycling Centre of Excellence
AWQC	Australian Water Quality Centre (SA Water)
BB	Budburst
Cl^-	Chloride ion
Cordon	Arms of a vine, normally trained along a trellis wire
DAFF	Dissolved Air Flotation Filtration
EC	The electrical conductivity (of the irrigation water)
EC1:5	The electrical conductivity of a 1:5 soil:water extract
EC_e	The electrical conductivity of the extract from a saturated soil paste
K_S	Saturated hydraulic conductivity
LAI	Leaf Area Index
Lamina	The expanded portion or blade of a leaf
LD	Leaf Drop
MR	Mid-Row
Na^+	Sodium ion
NAP	Northern Adelaide Plains
Petiole	The stalk that connects a leaf to the stem
PH	Post-Harvest
pH	A numeric scale ranging from 0-14 to specify acidity (0) or alkalinity (14)
ppm	Parts Per Million
RAW	Readily available soil water
SARDI	South Australian Research and Development Institute
TDS	Total Dissolved Solids
TSS	Total Soluble Solids (or °Brix)
UAD	University of Adelaide
UV	Under-Vine

Abstract

This report summarises results from two agronomic field experiments seeking to enhance the value of recycled wastewater for irrigation by overcoming the constraint of salinity. Investigations focussed on wine grapes and almonds located in established recycled wastewater irrigation districts to the south and north of Adelaide, South Australia.

Over two seasons, we assessed whether various changes to vineyard floor management could reduce soil and vine salinity. A major find was that disrupting compacted soils, located in the trafficked wheel lines, reduced soil salinity by 11% on average and reduced the concentrations of sodium and chloride in juice by 17% on average. Soil and vine salts were further reduced by harvesting rain falling in the mid-row and redirecting it to the under-vine soils. The most effective rainfall redirection treatments consisted of a plastic covered mid-row mound, which was either exposed or buried. Both options reduced average soil salinity by more than 27% and reduced concentrations of sodium and chloride in juice by 28% relative to undisturbed controls. Bare earthen mid-row mounds and the periodic application of a crusting agent to that mid-row mound achieved lower salinity reductions.

In a salt affected almond orchard, we assessed the sensitivity of almond growth stages to the removal of the salt stress at different times through the growth cycle. On average, trees exposed to pre-harvest reductions in salt load had 31% lower concentrations of sodium and chloride than those exposed to post-harvest reductions in salt load. Sodium and chloride concentrations in late season leaf samples were most sensitive to reduced salt load between pit-hardening and harvest. The two season investigation period was too short to elicit a yield response to different timings of reduced salt load. However, we suspect that yield components will differentiate once treatment carryover effects have intensified from preceding years. Investigations at the almond trial will continue into 2017, continuing the legacy of the AWRCOE and Goyder Institute investments.

Background and aims

Continuity of water supply is an ongoing concern for many South Australian irrigation districts. For those in close proximity to urban centres, the use of recycled municipal wastewater offers improved security of supply with the added environmental benefits of reduced marine discharge and the easing of demand upon more traditional irrigation water sources. There is also an economic benefit from the lower cost of water and the reduced need of fertiliser. South Australia already recycles more than 30% of its treated wastewater and seeks to increase reuse via irrigated horticulture and amenity plantings in support of the State's strategic priority of *'Clean green food as our competitive edge'*. However, recycled wastewater can be slightly more saline than traditional water sources. Its incorrect use in irrigated crop production can increase soil salinity, raise the concentrations of sodium and chloride ions in leaves and fruit and reduce crop performance more than other irrigation water sources.

The quality of recycled wastewater is often seasonally variable due to the source water catchment demographics (domestic or trade wastewaters) and the condition of pipeline infrastructure. Whilst recycled wastewater can have nutritive value, the elevated level of some ions has seen the long-term use and expansion of recycled wastewater for irrigation being questioned in some regions (McLeod, 2010).

Recycled wastewaters can have salt concentrations in excess of 1000 ppm (1.6 dS/m; i.e. slightly to moderately saline). At these levels, irrigators import 1 tonne of salt with every megalitre of water. Increasingly, this salt is deposited in concentrated strips within the crop's rootzone as irrigators move away from flood and sprinkler irrigation towards precision drip irrigation systems in an attempt to improve their water use efficiencies. High water use efficiency coupled with poor quality irrigation water, regardless of source, promotes the rapid accumulation of salts in the rootzone.

Management of salinity in perennial cropping has tended to focus on preventing yield loss (Ayers and Westcot, 1985; Walker et al., 2002) by maintaining soil salinity below crop specific tolerance thresholds (Maas and Hoffman, 1977). However, soil salinity at levels below those that affect yield and vigour can still affect fruit quality, in terms of sodium and chloride concentrations, and impact upon flavour components or product acceptability in target markets (Sas and Stevens, 1999; Walker et al., 2003; Bastian et al., 2010).

The traditional approach to preventing salinity induced yield and quality losses has been to add water in excess of crop requirements in order to leach salts to below the rootzone. In full irrigation districts, this excess water is supplied by irrigation. Supplementary irrigation districts rely on rainfall to provide the leaching water. In a drying climate, irrigation allocations and rainfall events may not always be sufficient to accommodate the leaching of salts. This reliance on water availability reduces the level of control that irrigators can exert on salt accumulation and increases the risk of salinity impacting on crop performance. A more detailed discussion of recycled wastewater and the salinity risk for irrigated horticulture is offered in Appendix H.

In a drying climate, there is a need for practical salinity management strategies which do not require the use of additional water. Without practical management strategies, the longevity of irrigation with recycled wastewater may be limited for some, particularly perennial, cropping systems.

This collaborative project, funded by The Australian Water Recycling Centre of Excellence (AWRCOE) and the Goyder Institute for Water Research, was initiated to investigate two strategies aimed at supporting the sustainable use of recycled wastewater in irrigated crop production by addressing the constraint of salinity. The project focussed on Australia's two most valuable horticultural export products, almonds and wine, both sourced from cropping systems recognised as being moderately sensitive to soil salinity and both industries with significant plantings located within recycled wastewater irrigation districts.

The project established two field trials north and south of Adelaide, where some cropping systems, with a relatively short history of irrigating with recycled wastewater, had already reported salinity related impediments to production (Biswas et al., 2008; Rawnsley, 2011). Investigations focussed on a vineyard in McLaren Vale and an almond orchard on the Northern Adelaide Plains (NAP), Figure 1.

At the McLaren Vale vineyard, treatments consisted of installing various configurations of rainfall re-direction devices, drawing from a body of work on approaches used to enhance run-off during water harvesting (Richardson et al., 2004; Stevens et al., 2013), to increase leaching under supplementary irrigation conditions. In the NAP almond orchard, irrigation was historically supplied by shandying dual water sources of different qualities, recycled wastewater and groundwater. Treatments sought to temporally separate irrigation with the two water sources in order to identify in which annual growth stage trees were most sensitive to the slightly saline recycled wastewater. Treatment effects at both sites were assessed by measurement of soil salinity and moisture, salt concentrations in leaves and fruit, yield and vegetative growth.

The primary aim of this project was to improve the management of salinity in permanent horticultural plantings which receive supplementary precision irrigation with recycled water. Specific objectives were:

- To test whether redirecting rain falling on the mid-row toward soils under the drip line of vines irrigated with recycled water reduces soil and plant salt levels.
- To test various techniques for redirecting rainfall and identify a technique that is commercially practical.
- To identify the stages within the annual almond growth cycle which are most sensitive to salt when irrigated with recycled water.
- To supervise and support a PhD candidate in undertaking a study evaluating management of rootzone salt accumulation from recycled water by redirecting inter-row rainfall.

Figure 1. Location of SARDI's recycled wastewater irrigation trials in South Australia, 2012-2015. Rainfall Redirection trial at McLaren Vale and Timing of Salinity trial at Northern Adelaide Plains.

Outcomes and Recommendations

The following summarises research findings and outcomes against the project's objectives and makes recommendations where further investigation is required. The project had four specific objectives:

OBJECTIVE 1: *to test whether redirecting rain falling on the mid-row toward soils under the drip line of vines irrigated with recycled water reduces soil and plant salt levels.*

In November 2012, rainfall redirection treatments were installed at a commercial Cabernet Sauvignon vineyard irrigated with recycled wastewater. Redirecting rain from mid-row soils to those under the drip line was found to:

- Reduce soil salinity by more than 17% over the life of the trial.
- Reduce Na^+ and Cl^- concentrations in petiole, lamina and juice samples by at least 14%.
- Increase yield and vigour in the first year, but not in the second.
- Reduce juice brix and increase juice titratable acidity in the first year, but not in the second.

Treatment D
(plastic covered MR mound)

These results strengthened those from a proof of concept trial (Stevens et al., 2012) where vines were growing under different soil and climatic conditions with different water compositions and irrigation scheduling. Achieving the same result in two unique, supplementary, irrigation districts shows that redirecting rain from mid-row soils to those under the drip line is a valid strategy for reducing the effects of irrigation induced salinity.

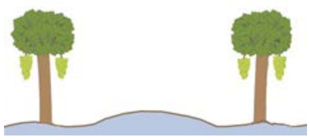
OUTCOME	**Rainfall redirection has potential as a salinity management option that does not require the use of additional irrigation water; an important development when water is scarce.**

OBJECTIVE 2: *to test various techniques for redirecting rainfall and identify a technique that is commercially practical.*

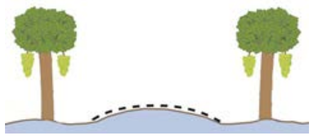
Results reported in Objective 1 were achieved using a plastic covered mid-row mound. Installation and maintenance inputs were too high for this treatment to be commercially viable. More commercially viable rainfall redirection techniques were installed to assess their capacity to replicate the response achieved in Objective 1. The two most easily installed techniques showed:

- No change to soil or juice salinity.
- Intermittent variation to petiole and lamina concentrations of Na^+ and Cl^-.
- Reduced yield in year two.

Treatment B
(earthen MR mound)



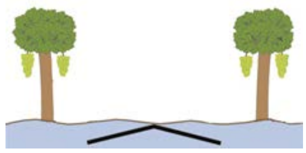
Treatment C
(B + surface crusting agent)



The third technique required a more intrusive installation but delivered a resilient treatment with similar salinity response to that achieved in Objective 1:

- Reduced soil salinity by more than 17% over the life of the trial.
- Reduced Na^+ and Cl^- concentrations in juice by at least 13%.
- Reduced Na^+ and Cl^- in both petiole and lamina.
- No change in yield.
- Reduced juice brix and increased juice titratable acidity in year two.

Treatment E
(buried impermeable layer)



OUTCOME	**Impermeable layer buried in mid-row soils redirected rainfall and reduced soil and plant salt levels.**

RECOMMENDATION	**Assess promising rainfall redirection treatments in alternative locations (including full irrigation districts) and with other cropping systems (eg - vegetables and tree crops).**

The process of establishing rainfall redirection treatments presented an opportunity to test soil and vine response to disrupting compacted soils in the wheel line. Shallow ripping of the compacted wheel line reduced under-vine soil salinity, lowered plant tissue concentrations of Na^+ and Cl^- and increased vine vigour and yield. These changes were significant with potential further benefit using the rainfall redirection treatments D and E.

OUTCOME	**Disrupting the compacted soils in the wheel line increased vine vigour and yield and reduced the expression of salts in plant tissue and juice.**

OBJECTIVE 3: *to identify the stages within the annual almond growth cycle which are most sensitive to salt when irrigated with recycled water.*

In 2013, non-saline irrigation treatments were overlayed across a commercial, salt affected, almond orchard and trees assessed for their response to different timings of reduced salt load. Reductions in pre-harvest salt loads were more effective than those applied post-harvest at lowering Na^+ and Cl^- concentrations in leaf tissue samples. Yield response was less sensitive to the timing of reduced salt load and did not differentiate during the period of investigation. However, normalising yield response with regard to the volume weighted salt load suggested that yield was more receptive to post-harvest reductions in salt load than those applied pre-harvest. This trend requires further data in order to elicit a convincing result.

OUTCOME	**Na^+ and Cl^- uptake was lowest when non-saline irrigation was applied early in the growing season, during periods of leaf emergence and shoot growth.**
OUTCOME	**Yield response did not significantly differentiate during the two season assessment period.**
RECOMMENDATION	**Continue investigations into the response of almond to the timing of salt stress reduction through to the 2017 season, via support from the SA River Murray Sustainability program.**

OBJECTIVE 4: *to supervise and support a PhD candidate in undertaking a study evaluating management of rootzone salt accumulation from recycled water by redirecting inter-row rainfall.*

The University of Adelaide (UAD) was unable to identify a suitably qualified PhD candidate during the course of the project. In lieu of supporting a PhD project, the UAD characterised soil physical and chemical conditions at the rainfall redirection trial site and SARDI used these data to generate numerical modelling domains aimed at predicting the relevance of rainfall redirection as a salinity management tool for different viticultural scenarios.

OUTCOME	**SARDI has developed a numerical model to predict the impact of rainfall redirection treatments on various soil, climatic and irrigation scenarios.**
RECOMMENDATION	**Validate the numerical model against measured field data outside supplementary irrigation districts (eg - Riverland).**

COMMUNICATIONS: Appendix A details project extension activities including workshops, seminars and conference presentations which were attended by 500+ growers, industry representatives and policy developers.

Trial 1. Rainfall redirection to reduce soil and plant salts in vineyards irrigated with recycled wastewater

1.1 Introduction

In many of Australia's wine producing regions, rainfall is high enough to keep the vines well supplied with water in all but the drier months. Over this period, most vineyard managers supplement rainfall using drip irrigation. If the 'supplementary' irrigation water has elevated salt content, as can be the case with slightly to moderately saline recycled municipal wastewater, then irrigation will add salt to the soil. When excessive salts accumulate in the rootzone, vines suffer leaf damage, delayed ripening and elevated concentrations of salts in the fruit; ultimately impacting upon wine marketability.

Soil salinity can be reduced by flushing the soil with low salinity water. This leaches the salt beyond the rootzone. In supplementary irrigation districts, rainfall provides this flushing water.

In 2009, at salt affected vineyards irrigated with groundwater (EC=2-2.35 dS/m), SARDI observed high salinity in the under-vine soils and low salinity in mid-row soils (Pitt and Stevens, 2010). This suggested that rainfall was insufficient to flush salts from the under-vine soil. SARDI hypothesised that increasing the amount of rain leaching under-vine soil and reducing that leaching mid-row soil would reduce rootzone and vine salinity. Between 2010 and 2012 a proof of concept trial tested the response of soil and vine salinity to changes in vineyard floor management. It found that redirecting rainfall from the mid-row to under-vine soil reduced under-vine soil salinity by 40%, leaf sodium and chloride levels by 21%, juice sodium by 25% and juice chloride by 41% across a two year sampling period (Stevens et al., 2013).

Rainfall redirection treatments were based on the construction of earthen mounding along the length of the mid-row, which was then graded and compacted prior to covering with black plastic sheeting (Stevens et al., 2012). Despite its effectiveness at reducing soil and plant salt concentrations, the vulnerability of the plastic covered mound to damage from standard vineyard activities made this salinity management strategy impractical for commercial viticulture and unlikely to gain uptake.

Proof of concept investigations showed that rainfall redirection reduced soil and plant salinity but… could the effect be replicated with commercially practical methods? Would the concept work for vines grown under different soil, water and climatic conditions?

To answer questions of commercial applicability and performance under different growing conditions, the current project installed a field trial to pilot rainfall redirection using more commercially robust treatments. Extending investigations into the McLaren Vale recycled wastewater irrigation district not only introduced different compositions of irrigation water and application schedules but also different soil types. The study site was of heavier textured soils than those previously tested. Further, previous work in this vineyard had identified areas of compacted soils caused by frequent wheel traffic. The higher bulk densities of these soils were anticipated to influence the leaching of salts and possibly produce a different response to rainfall redirection treatments than observed at the proof of concept trial.

Various configurations of rainfall redirection techniques were installed at McLaren Vale and assessed for their ability to influence soil and vine salinity through measurement of soil and water salinity, vine salinity and water status, vine yield and fruit quality. The process of treatment establishment disrupted soils in the compacted wheel line. Any changes relative to current practice may have been produced both by site preparation (breaking up the compacted wheel line) and also by treatment application (rainfall redirection). The project sought to distinguish between these two sources of change by introducing an additional row of treatment plots, outside of the main trial area, that had been exposed to zero soil disturbance through treatment establishment.

Collaboration with the University of Adelaide introduced expertise in the movements of soil water and solutes as modified by variations in soil physical and chemical properties. This collaboration was originally intended to support a PhD candidate whose aim would be to investigate variations in soil properties as influenced by irrigation with recycled wastewater. Unfortunately, a suitably qualified candidate was not identified during the life of the project. In lieu of the PhD, the University of Adelaide characterised soil conditions at the McLaren Vale site, Appendix I, and SARDI numerical modellers incorporated these data in the construction of modelling domains designed to test the relevance of SARDI's rainfall redirection treatments both at McLaren Vale and at other South Australian irrigation districts. Appendix G describes the modelling process and details the predicted response of soil water and solutes at the McLaren Vale (recycled wastewater; EC=1.2 dS/m), Padthaway (groundwater; EC=2-2.35 dS/m) and Loxton (surface water; EC=0.3-0.4 dS/m) irrigation districts.

Figure 2. Recycled wastewater irrigation headworks at McLaren Vale Cabernet Sauvignon trial site.

1.2 Materials and methods

1.2.1 Site description

The experiment was established at a commercial Cabernet Sauvignon vineyard located in the McLaren Vale wine region, approximately 35 km south of Adelaide, South Australia (Lat: -35.238° and Long: 138.524°). The vineyard was planted in 1998 with own-rooted Cabernet Sauvignon at a row by vine spacing of 2.75 m by 1.8 m. Rows were oriented east-west and vines were trained to a single wire trellis at a height of 1.2 m. A mid-row cover crop of various volunteer weeds and grasses (both annual and perennial) was managed with occasional slashing and under vine herbicide operations.

Soils were surveyed by Kew and Wetherby (1998) prior to planting and described as being 15-20 cm sandy loam topsoil overlaying a clay B horizon. The survey also reported readily available soil water

(RAW), defined as the reservoir of soil water within the rootzone which can be stored between 8 kPa (full point) and 60 kPa (refill point). RAW across the trial area was estimated to be between 35-44 mm.

Vine rooting depth was estimated to be 0.6-0.8 m with some larger roots extending into the mid-row. The greatest density of roots was in the top 0.5 m and concentrated 0.6 m either side of the vine-line. These observations aligned with McCarthy et al. (2010) who, in 2006, investigated the root distribution of vines in rows adjacent to those in the present experiment.

The experimental site was managed as per standard commercial vineyard practices. Traffic down the row was associated with mechanical and hand pruning, a full fungicide/herbicide spray program, and mechanical harvest operations.

1.2.2 Trial design and analysis

In October 2012, the mid-row soil of six rows was rotary hoed and then ripped to a depth of 0.3 m at a distance of approximately 0.6 m into the row from the vine-line. This ripping operation facilitated treatment construction which was completed in November 2012. Treatments were laid out as a randomised complete block design along two sets of three rows. Rainfall redirection treatments (B-E) had nine replicates and the control treatment (A) was duplicated to give 18 control replicates. An additional treatment (F) was replicated nine times along an adjacent row and reflected vine performance with undisturbed mid-row soils, to allow comparison against plots where the compacted wheel line had been disturbed. Each treatment plot consisted of three rows of six vines with all plant and soil measurements collected from the four central vines in the middle row.

Figure 3 graphically describes Treatments A – E, in the primary trial area, plus Treatment F, located in an adjacent non-ripped row. Rainfall redirection treatments were designed to test the effect of changes to vineyard floor management, viz.:

- Mound soil along the length of the mid-row
- Mound soil along the length of the mid-row and seal with a spray applied surface sealant
- Mound soil along the length of the mid-row and cover with an impermeable plastic layer
- Install a subsurface plastic covered mound

In treatments B, C and D, mid-row soils were graded and compacted to form a mound to a height of 0.2 m and a width of 1.1 m. Treatment B mounds were left bare through the life of the trial. On 20 May 2013 and 7 May 2014, Treatment C received applications of 5% TGC Soil-loc diluted in water, MSDS in Appendix F. The TGC soil crusting agent was sprayed over a one metre wide strip centred on the top of the mid-row mound at a rate of 1.5 L/m^2, the equivalent of 270 L/ha per year. Treatment D mounds were covered with black plastic sheeting (UV stabilised polyethylene 200 µm thick by 2 m wide). Plastic sheeting was replaced as required over the life of the trial to ensure treatment integrity.

Variables were analysed using the general ANOVA in GenStat 16th Edition (VSNI, Hemel Hempstead, UK). Least Significant Difference (LSD) test was used to compare treatment means at three error levels (P<0.05; 0.01; 0.001). Testing against the doubly replicated control was achieved by reducing the LSD appropriately. A cursory significance test was made against the Treatment F plots, located in a separated row. Covariates (spatial and pre-trial measures of petiole Na^+ and Cl^- concentrations) were included in the regression models and only retained if the P value of their significance was ≤0.05. The significance of treatment effect on soil salinity changes with depth were assessed using linear and quadratic contrasts at 0.2 m intervals.

1.2.3 Meteorological, irrigation and water quality measurements

Rainfall data were sourced from the local Bureau of Meteorology automatic weather station (station number 023885 for Noarlunga). Data on the reference evapotranspiration (ET_o) and rainfall, 1951 to 2015, were generated by running a data drill at http://www.longpaddock/qld/gov/au/silo in April 2015.

Data on irrigation depths were sourced from vineyard management records with scheduling based upon a combination of gypsum block soil moisture sensors and visual assessments of canopy size.

The trial vineyard was irrigated with 1.2 L/h drippers spaced at 0.6 m and aligned along the length of vine rows spaced at 2.75 m. This resulted in an application rate of 0.73 mm/h, distributed uniformly to all treatments as per usual vineyard management. Water for irrigation was drawn from the Christies Beach Wastewater Treatment Plant, located approximately 10 km north of the Willunga Basin, and distributed through a pipeline scheme managed by Willunga Basin Water (WBW). Water samples were collected from irrigation emitters throughout the growing season and assessed for salinity using a temperature compensated conductivity meter (model CON510, Eutech, Singapore) and reported at 25°C. The average irrigation water salinity during the trial period was 1.2 dS/m.

Table 1 summarises the analysis, undertaken by the Australian Water Quality Centre, of Class A recycled water sampled from irrigation emitters in December 2014. A more complete summary of water quality from the Christies Beach Wastewater Treatment Plant is available in Appendix E.

Table 1. December 2014 analysis of McLaren Vale irrigation water (Class A recycled wastewater from Christies Beach via WBW) collected from irrigation emitters within vineyard.

Parameter	Irrigation emitter (Dec 2014)	
EC	1.12	dS/m
TDS (by EC)	620	mg/L
pH	8.0	pH units
Turbidity	0.87	NTU
Colour	42	HU
Chloride	185	mg/L
N as Nitrate	13.5	mg/L
N as Nitrite	0.07	mg/L
Total Nitrogen	15.1	mg/L
Total P	6.05	mg/L
Sodium	147	mg/L
Calcium	31.6	mg/L
Magnesium	18.3	mg/L
Potassium	24.1	mg/L
Bicarbonate	97	mg/L
Alkalinity as $CaCO_3$	79	mg/L
SAR *	5.15	

* calculated as per Ayers and Westcot (1985)

A

18 replicates

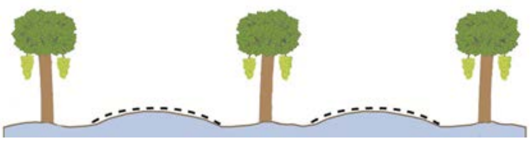
Control (A)
Situated within trial rows and exposed to shallow ripping of wheel lines at trial establishment

B

9 replicates

Mid-row mound constructed

C



9 replicates

Mid-row mound constructed
Periodic application of spray applied surface sealant (Soil-loc TGC)

D

9 replicates

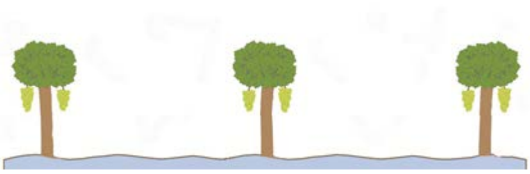
Mid-row mound constructed
Plastic sheet covering mid-row mound

E

9 replicates

Buried plastic covered mound

F



9 replicates

Non-ripped Control (F)
Situated in rows adjacent to trial area and not subjected to any soil disturbance

Figure 3. Illustrations of treatments (A-E) plus the additional, non-ripped, control vines (F) located adjacent to the main trial area.

1.2.4 Soil measurements

Between September 2012 and April 2015, soils were sampled at the beginning and end of irrigation seasons using a hydraulic soil sampling rig with 50 mm diameter collection tube (Christies Engineering, Horsley Park, Australia). Soils were sampled at 0.1 m increments to a depth of 0.8 m from in between two drippers, 0.3 m from the drip line. Mid-row soil samples were collected between two drippers, 1.4 m from the drip line. Table 2 describes the soil sampling regime.

Table 2. Soil sampling regime for Treatments A – F.

Date	Plots sampled (Treatment/Replicate)	Location (Under-vine / Mid-Row)
September 2012 (pre-trial)	Trt A / Rep 4	UV / MR
May 2013	Trt A / Rep 1 – 9	UV / MR
November 2013	Trt A – F / Rep 1 – 9	UV
April 2014	Trt A – F / Rep 1 – 9	UV
November 2014	Trt A – F / Rep 1 – 9	UV
April 2015	Trt A – F / Rep 1 – 9	UV
	Trt A, D, E, F / Rep 2, 4, 7	MR

Soil salinity was measured as the electrical conductivity of 1:5 soil:water extracts ($EC_{1:5}$) following the method of Rayment and Higginson (1992). Electrical conductivity was measured on duplicate samples (<4% RSD between duplicates) using a temperature compensated conductivity meter (model CON510, Eutech, Singapore) and reported at 25°C.

Soil salinity data was reported as the electrical conductivity of the extract from a saturated paste (EC_e) using a conversion factor that was generated by analysing paired data from soil samples which had been split so that both $EC_{1:5}$ and EC_e could be measured. EC_e was determined following the method of Rayment and Higginson (1992). Analysis of soil salinity showed a strong quadratic dependence of EC_e on $EC_{1:5}$ with the values of $EC_{1:5}$ explaining 90% of the variation in EC_e, Figure 5. The slope of the relationship was similar to the range of conversion factors (R values) reported by Cass et al. (1996) as being applicable for heavier textured soils. Clay contents similar to those observed at the McLaren Vale trial site were reported as having R values ranging from 4.9 to 5.7.

Figure 4. Soil pit at McLaren Vale site; root growth extending into mid-row (Nov. 2013).

In November 2013, three soil pits were dug along the length of the trial rows. In each pit, soils were collected from three sampling points at across the row at distances of 0 m (under-vine), 0.6 m (wheel track) and 1.4 m (mid-row) from the vine line. From each of these points, three replicates of undisturbed cores (48 mm diameter and 50 mm length) were collected from the two dominant horizons at depths of 0.1-0.15 m, 0.4-0.45 m and 0.75-0.8m. Disturbed soil samples were also collected. Undisturbed cores were used for determination of soil physical characteristics and disturbed soils for chemical characteristics. Detailed methodology for these parameters described in Appendix I.

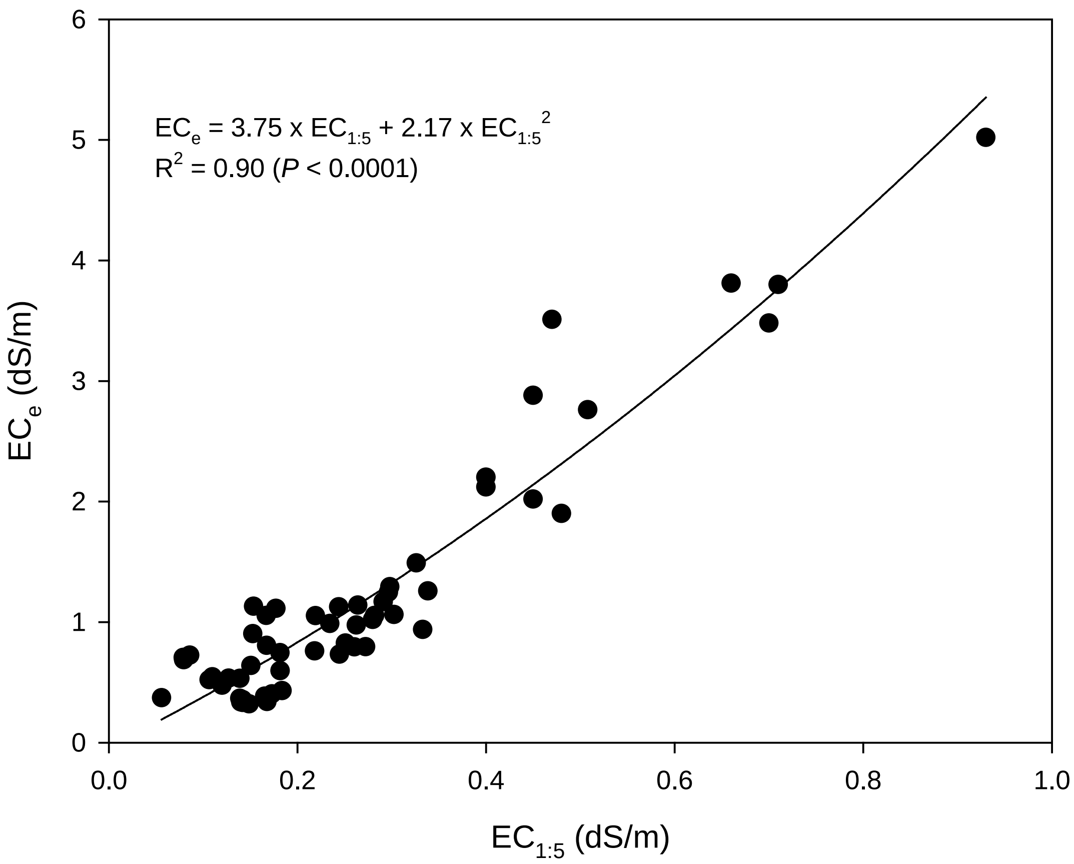


Figure 5. Relationship between soil $EC_{1:5}$ and soil EC_e for a range of soils at McLaren Vale rainfall redirection trial (2013-2015).

Through the 2014/15 irrigation season, volumetric soil moisture contents were monitored, at 0.1 m increments to a depth of 0.8 m, using a Diviner 2000 capacitance sensor (Sentek Technologies, Kent Town, Australia). Access tubes were installed both under-vine and in the mid-row of two replicates within each of Treatments A, B and D plus one replicate within Treatment E. Installation and calibration were as per SENTEK (2009) product manual. Soil moisture data were made available as input data for numerical modelling of rainfall redirection treatments.

1.2.5 Plant tissue concentrations of Na^+ and Cl^-

Measurements of plant tissue Na^+ and Cl^- concentrations were undertaken in all nine replicates. Leaf petiole samples were collected from opposite the basal inflorescences at flowering (E-L stage 23-25) in the 2013 (pre-harvest), 2014 and 2015 seasons. Leaf lamina were collected opposite to basal bunches at harvest (E-L stage 38) in the 2013, 2014 and 2015 seasons. The petioles and lamina were dried at 70°C for at least 72 hours and ground using a Micro Hammer-Cutter Mill (Culatti AG, Zurich, Switzerland) to pass through a 0.5 mm mesh.

Berry samples were collected at harvest (E-L stage 38) in the 2013, 2014 and 2015 seasons. The fruit was crushed in a hand press and the extracted juice was clarified by centrifuging at 10397 x *g* for 10 minutes. Samples were frozen for later measurement of Na^+ and Cl^- concentrations.

The Cl^- concentration was measured by silver ion titration with a Buchler chloridometer (Labconco, Kansas City, MO, USA). Duplicate extracts were prepared by adding 1 mL aliquot of juice to 3 mL of an acid solution containing 10% (v/v) glacial acetic acid and 0.1 M nitric acid and 4 drops of gelatine reagent.

The Na^+ concentration was measured by ICP (Spectro Analytical Instruments, Kleve, Germany). Leaf sample extracts were prepared using 100-300 mg of dried, ground sample in a nitric acid and hydrogen peroxide digestion. Samples were diluted to 25 mL and cold digested overnight. Following this, the temperature of samples was increased over a 2.5 hour time period to a maximum not exceeding 125°C. Juice samples were analysed as per Wheal et al. (2011).

1.2.6 Photosynthesis and plant water relations

In 2014 and 2015, the values of pre-dawn and early afternoon leaf water potential were measured in all replicates on 24 February 2014 and 23 February 2015 respectively. Leaf gas exchange measures were collected on the same days. 2014 measures of leaf gas exchange were compromised and do not form part of this report. Leaf gas exchange was measured with a LICOR-6400 portable infra-red gas analysis system (LI-COR, Lincoln, USA). Prior to entering the chamber, air was scrubbed of CO_2 and then CO_2 was injected to produce an air stream in which the concentration of CO_2 remained constant at 400 μL/L. For early afternoon measures, the leaf was illuminated with light emitting diodes with quantum flux of 1800 $\mu E/m^2.s$. The relative humidity of the sample stream and the cuvette air temperature were maintained at ambient values.

Data were included in analyses when value of LICOR stability statistic was equal to 1. The stability statistics was calculated from the coefficients of variation for CO_2 and H_2O concentrations in the sample air stream and the flow rate over a 15 second sampling period, and the slope of the rate of change in the mean values. If %CV were all less than 1% and slopes less than 1 for all 3 parameters, then the stability statistic was equal to 1 and derived values of assimilation and related variables were considered stable.

One to two hours prior to measurement of leaf gas exchange, an aluminised plastic bag was placed over a leaf adjacent to where leaf gas exchange was to be measured. Within five minutes after measurement of leaf gas exchange, the leaf enclosed in the aluminised plastic bag was excised and sealed within a Scholander Pressure Bomb (Scholander et al., 1965; Turner and Long, 1980). Within 30 seconds of leaf excision, the chamber was pressurised at a rate of 0.01 MPa/s with the end-point to pressurisation observed using a binocular microscope under 10-fold magnification. Dry and wet bulb temperatures were measured with an aspirated psychrometer at a height of 2 m above-ground level. The Vapour Pressure Deficit (VPD) was calculated from these measures using an algorithm from Sargent (1980).

1.2.7 Yield, fruit maturity and vigour

Fruit growth was assessed at harvest by measurement of yield, bunch number and weight of a 100-berry sample in nine replicates. For these measurements, the unit vine length was set as the within-row inter-vine distance between the second and fifth vine in the plot (approximately 5.4 m). Measurements were made in 2013, 2014 and 2015. The 100-berry sample was generated by sampling bunches on both sides of the vine and picking berries from the left, right, top, bottom, back and front of the bunch. The samples were transported from the field to the laboratory in chilled insulated containers.

The fruit was crushed in a hand press and the extracted juice was clarified by centrifuging at 10397 x *g* for 10 minutes. In all years, measures of total soluble solids (TSS), pH and the concentration of titratable acid (TA) were assessed. TSS was measured on clarified juice by digital refractometer (Atago PAL-1, Tokyo, Japan) and expressed as °Brix 20°C. pH and the TA were measured using an auto-endpoint TA and pH meter (Metrohm, Ionenstrasse, Switzerland); the juice was titrated against 0.133 M NaOH. After measurement, samples were frozen for later measurement of Na^+ and Cl^- concentrations.

Vegetative growth was assessed by both leaf area index (LAI) through the growing season and pruning weights in winter.

Leaf Area Index: LAI was measured in nine replicates at flowering (E-L stage 23-25), at veraison (E-L stage 33-34) and just prior to harvest (E-L stage 38) in vintages 2014 and 2015 using an SLR Camera (Leica Digilux 2, New Jersey, USA) at settings of f/2, ISO-100, 1/500 shutter speed and 28 mm focal length. Measurements were collected on three central vines of each plot with LAI calculated from those three images. Images were collected in the two to three hours from dawn with the lens situated directly beneath the canopy central within the inter-vine space in order to capture a below canopy image. Camera sensor was located 900 mm below the cordon allowing 0.84 m of cordon length and width across the canopy of 1.12 m. Photos were processed using an algorithm developed by Fuentes et al. (2014).

Pruning weights: pruning weight measurements were collected from nine replicates and followed the convention of the cooperating corporate grower, that being mechanically pruned. Canes were removed using a hand-held mechanical hedger that replicated the approximate dimensions of the hedge created by the commercial, mechanical pruning operation (saws ~20cm from cordon). Canes were collected from a unit vine length set as the within-row inter-vine distance between the second and fifth vine in the plot (approximately 5.4 m). Pruning weights were measured in the winters following vintage 2013 and 2014.

1.3 Results and discussion

1.3.1 Pre-trial measures of spatial variations in soil salinity

Measures of soil salinity were collected in neighbouring rows by Biswas et al. (2008) prior to the 2006, 2007 and 2008 irrigation seasons. They characterised the condition of soils following the winter leaching period and showed average under-vine salinity in excess of 3.0 dS/m as compared to average mid-row salinity of below 1.7 dS/m (EC_e), Figure 6. Similar measures collected by vineyard managers prior to and following the 2009 vintage showed the same trend of elevated under-vine salinity, >4 dS/m, as compared to that in the mid-row, 2 dS/m (pers. comm. Collaborative grower, 2012). Pre-trial measures by this project, in September 2012, confirmed a trend for higher under-vine salinities, 3.3 dS/m, as compared to that in the mid-row, <1 dS/m, Figure 7.

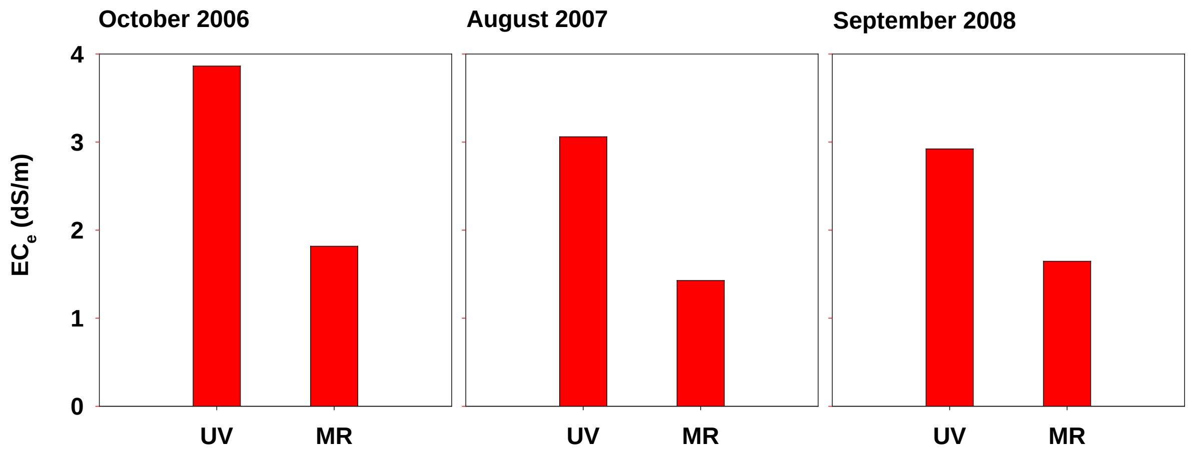


Figure 6. The effect of location across the row on soil salinity (EC_e) in a Shiraz vineyard neighbouring the McLaren Vale trial site. Spring 2006 – 2008.UV = Under-vine, MR = Mid-row.

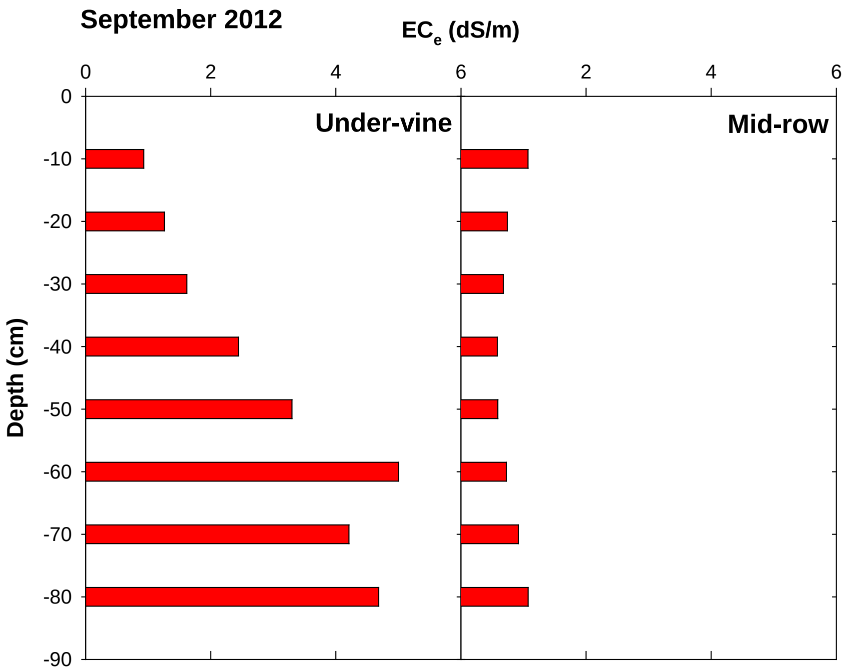


Figure 7. The effect of depth and location across the row on soil salinity at the McLaren Vale trial site. Spring 2012, prior to treatment establishment.

The pattern of low salt accumulation in the mid-row and high salt accumulation under-vine matches that observed by Stevens et al. (2012) in Padthaway SA, a groundwater supplementary irrigation district. While the total salt load observed at the McLaren Vale site was lower than that reported at Padthaway, pre-trial measures demonstrated that irrigation seasons tended to commence with under-vine soil salinity greater than the salinity damage threshold for own-rooted vines, 2.1 dS/m (Zhang et al., 2002).

Pre-trial soil assessments suggested that the degree of flushing provided by winter rain was insufficient to reduce soil salinity below the threshold for salinity damage. In contrast, the degree of mid-row soil flushing provided by rain was in excess of that necessary to maintain soil salts below this threshold.

1.3.2 Irrigation, rainfall and seasonal variations in salinity

Table 3 summarises depths of irrigation, rainfall and evapotranspiration directly preceding and during the period of the investigation. The trial site had historically supplemented rainfall with more than 160 mm/year of irrigation. In the two years preceding trial establishment, irrigation depths reduced by 50% and 30% due to above average rainfall events. Through the period of investigation, closer to average rainfall conditions returned and irrigation depths increased, culminating with the 2014/15 vintage receiving in excess of 200 mm.

Table 3. Seasonal irrigation, rain and evapotranspiration

Year of harvest	Irrigation (mm)	Rain (mm)	ET_o (mm)
2009/10	167	534	1299
2010/11	87	580	1153
2011/12	112	606	1246
2012/13	134	389	1316
2013/14	135	501	1279
2014/15*	203	314	1269

Figure 8. Accumulation of salts beneath in-line drippers, McLaren Vale, 2015.

Pre-trial measures showed that salt accumulation in the soil was focussed under the vine and drip line and not in the mid-row. Figure 9 shows a time series of the measurements of soil salinity taken from under the vine prior to treatment establishment (September 2012) through to the end of season 2015. It was generated by combining measurements taken before the trial installation with those taken in the control treatment during the trial. It also includes measures of soil salinity collected outside the trial area that had not been exposed to any excavation activity as part of the trial setup. The high rainfall winter in 2013 saw average soil salinities drop below the 2.1 dS/m salinity threshold and it remained there through the 2013/14 irrigation season and the following winter. The 2014/15 irrigation season saw the return of drier conditions and greater depths of irrigation. This translated to elevated soil salinities, most notably in the non-ripped control vines, Treatment F. This suggested a potential benefit of ripping alone (with additional benefits from the other treatments).

Between the beginning of the 2012 season and the end of the 2015 season, the average salinity in the topsoils, 1.3 dS/m, was half that of the sub soils, 2.6 dS/m, Figure 10. While surface soil salinity doubled through the 2013 irrigation season and increased by 30% in the 2015 irrigation season, the 2014 sampling campaign did not capture significant increases in topsoil salinity. This can be explained by an unusually high rainfall event in February 2014, >50 mm in 48 hours, followed by another 20 mm in the weeks preceding sampling. The late rains in combination with reduced depths of irrigation limited the opportunity for salt accumulation in the profile through the middle period of investigations.

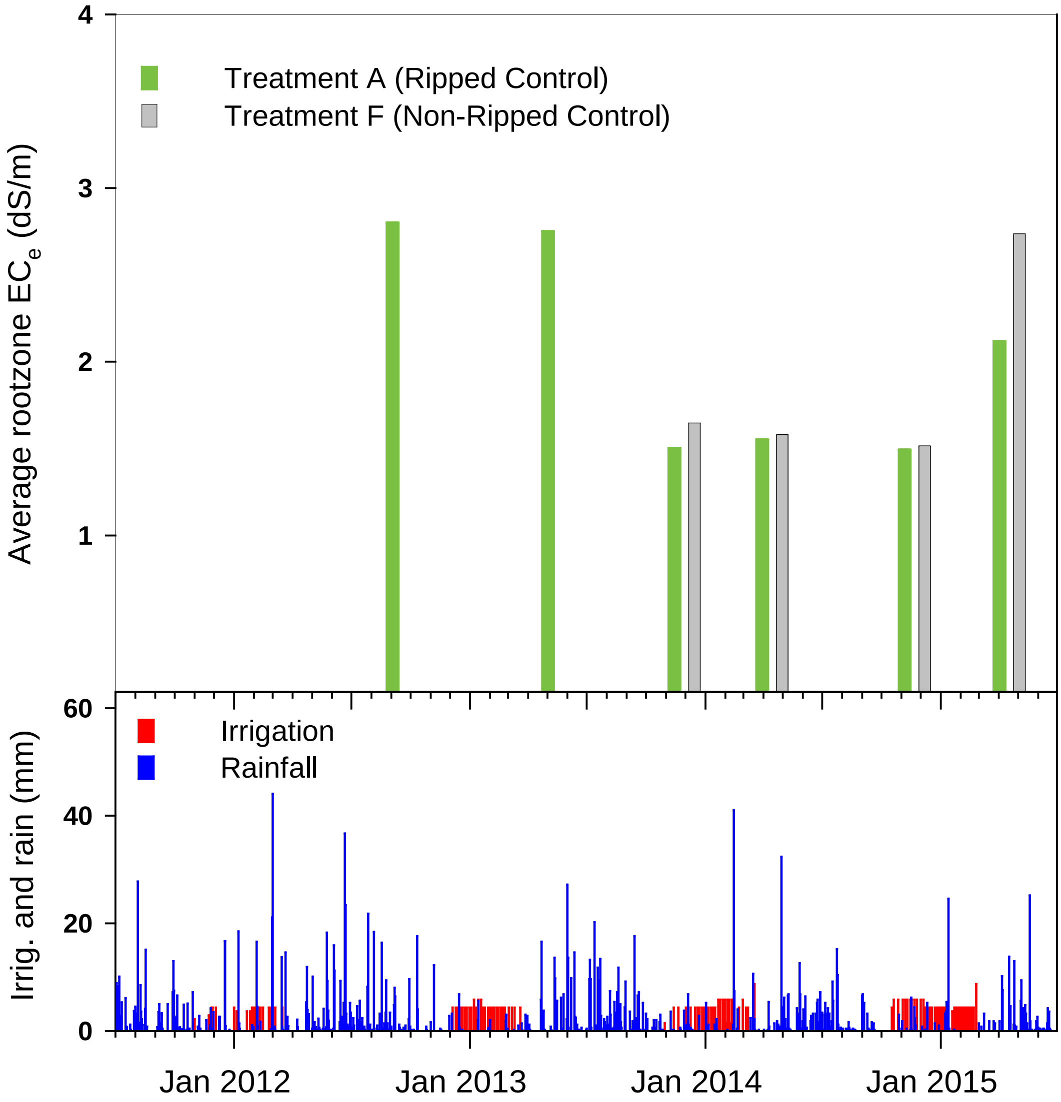


Figure 9. Temporal representation of rainfall and irrigation trends with soil salinity measured within the trial area (ripped controls) and adjacent to the trial area (non-ripped controls).

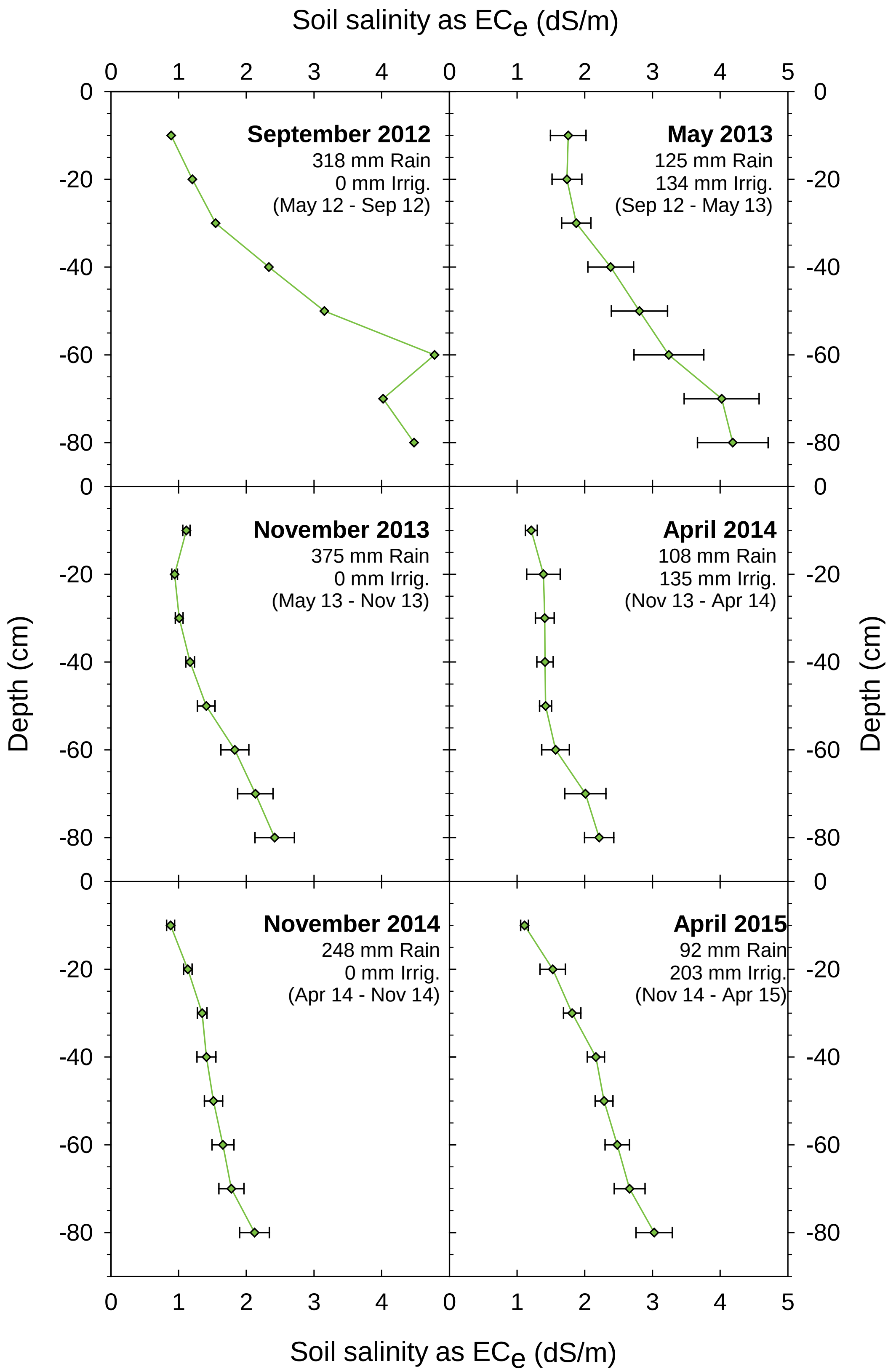


Figure 10. Variations of EC_e under the vine with depth within Control A (ripped) from Sept. 2012 (pre-trial) to end of the 2014/15 irrigation season. Rain and irrigation depths refer to the five to seven month period preceding sampling. Horizontal bars represent standard errors of the means.

1.3.3 Effect of ripping compacted soil in the wheel-lines

1.3.3.1 The effect of ripping compacted wheel lines on soil salinity

All treatment plots, including controls, were exposed to a shallow (<0.3 m) soil ripping operation to assist in construction of rainfall redirection treatments, Figure 11a. This shallow trench accommodated the burying of plastic edging, in Treatment D, and, where required, loosened soil for construction of mid-row earthen mounds. In order to monitor the effect of this shallow ripping event against non-ripped soils, nine plots of Treatment F were established adjacent to the primary trial area, Figure 11b.

Figure 11. Ripping of compacted soils as part of treatment establishment, Control A (a) and non-ripped Control F (b).

Comparison of average profile salinities showed little change through to spring 2014, two seasons after the initial ripping event occurred, Table 4. This is likely related to the lower irrigation inputs in the interim vintages and some large within season rainfall events limiting the opportunity for salt accumulation. Following the 2014/15 irrigation season, average salinity of Treatment A soils, 1.94 dS/m, differentiated from the non-ripped Treatment F soils, 2.57 dS/m. The 2014/15 irrigation season saw lower rainfall conditions and 35% greater irrigation volumes. Much of the salinity difference in this season appears to be occurring at depths beyond 0.5 m, Figure 12.

Table 4. The effect of shallow ripping soil in compacted wheel line, November 2012, on average soil salinity as EC_e (dS/m).

Parameter	**Treatment F** (Control plots adjacent to main trial area; zero soil disturbance)	**Treatment A** (Control plots within main trial area; shallow ripping of wheel line)	***LSD***
§Nov 2013	1.40	1.21	*0.25*
§Apr 2014	1.25	1.29	*0.36*
§Nov 2014	1.15	1.22	*0.23*
§Apr 2015	2.57	**1.94***	*0.38*

† * <0.05, ** <0.01, *** <0.001

§ geometric means

Figure 12 supports a contention that leaching was prevented by compacted soils in the wheel line. Such a position is supported by a number of Australian investigations which have characterised the effects of ripping compacted soils to improve physical condition and enhance infiltration rates (McCarthy et al., 2010; Hamza and Anderson, 2003; Lanyon and Bramley, 2004). McCarthy et al. (2010) extended part of their study into the same McLaren Vale vineyard currently being investigated. They found that while ripping mid-row soils to a depth of 1 m resulted in immediate yield and vigour declines, due to root pruning, the change to soil strength was favourable. Root pruned vines recovered to their original performance within three years. While improved soil water infiltration rates were presumed, they were not measured. Nor did they observe significant reduction in soil salinity due to their ripping treatments.

In March 2014, nine years after McCarthy's ripping treatments were applied, SARDI and the University of Adelaide revisited the site to test for residual effects on saturated hydraulic conductivities (K_S). Results were variable, largely due to soil textural differences, and offered little in terms of explanation for improved infiltration and leaching of the surface soils. However, mid-row surface soils did allude to improved K_S (2.8×10^{-5} m/s) as compared to non-ripped soils (2.2×10^{-5} m/s) (Appendix I).

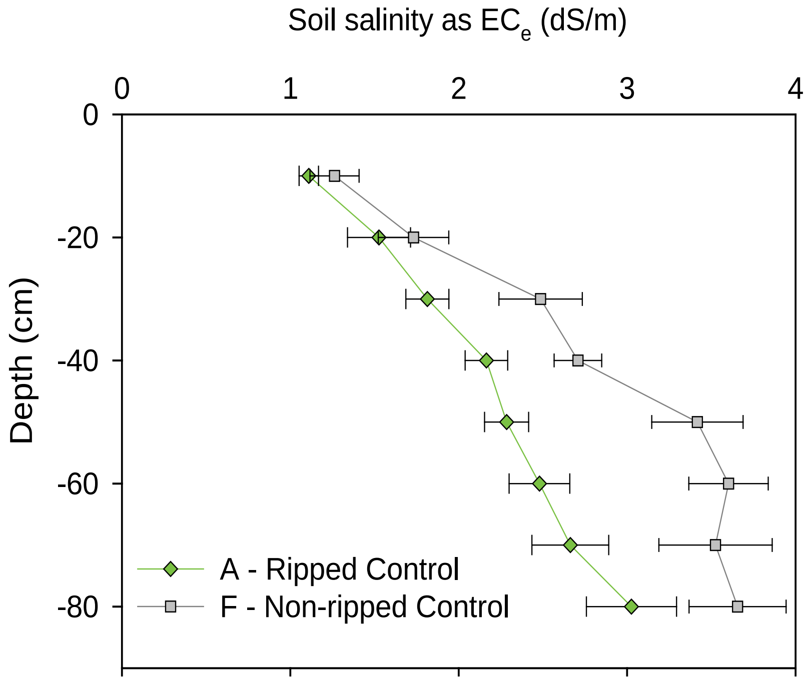


Figure 12. Variations of EC_e under the vine with depth between Control A (ripped) and Control F (non-ripped) in April 2015. Shallow ripping occurred in November 2012. Horizontal bars represent standard errors of the means.

The shallow ripping of the wheel line is likely to have induced a short-term reduction in soil strength and improved the opportunity for infiltration and salt leaching. This is reflected in the current investigation by reduced profile salinity in Treatment A.

1.3.3.2 The effect of ripping compacted wheel lines on the sodium and chloride concentrations in leaves and fruit

Ripping of wheel-line soils lowered petiole Na^+ concentrations by 30% and Cl^- concentrations by 17% in the 2015 vintage. In both the 2014 and 2015 vintages, values were well below the levels that are indicative of a salinity pressure sufficient to reduce yield (Robinson et al., 1997); 0.5% for Na^+ and 1.5% for Cl^-.

Petiole differences extended through to the expression of salts in the juice with ripped soils lowering juice Na^+ concentrations by 11% in 2015 and Cl^- concentrations in both 2014 and 2015 vintages by 23 and 32% respectively. Lamina response was more variable with the greatest change being in 2015 where vines growing in ripped soils had 24% less Cl^-, 0.36 against 0.47% (d.w.), Table 5.

1.3.3.3 The effect of ripping compacted wheel lines on yield components

While soil response did not differentiate until the end of the 2014/15 irrigation season, yield components responded immediately. Shallow ripping of the compacted wheel-line saw an early change in yield with vines growing in ripped soils, Treatment A, producing 41% more fruit than those growing in the non-ripped soils, Treatment F, Table 6.

Table 5. The effect of shallow ripping soil in compacted wheel line, November 2012, on the expression of salts in leaf tissue (% d.w.) and juice (mg/L).

Parameter	Treatment F (Control plots adjacent to main trial area; zero soil disturbance)	Treatment A (Control plots within main trial area; shallow ripping of wheel line)	*LSD*
Petiole			
Na^+ 2014	0.296	0.330	*0.05*
Na^+ 2015	0.144	**0.101***	*0.02*
Cl^- 2014	0.775	0.826	*0.09*
Cl^- 2015	0.684	**0.571***	*0.04*
Lamina			
Na^+ 2014	0.149	**0.130**	*0.01*
§Na^+ 2015	0.089	0.094	*0.01*
Cl^- 2014	0.503	0.469	*0.04*
Cl^- 2015	0.472	**0.359***	*0.04*
Juice			
Na^+ 2014	28.5	28.6	*2.30*
Na^+ 2015	32.3	**28.7***	*1.82*
§Cl^- 2014	47.9	**36.7***	*2.59*
Cl^- 2015	41.6	**28.2***	*2.38*

† * <0.05, ** <0.01, *** <0.001

§ geometric means

Table 6. The effect of shallow ripping soil in compacted wheel line, November 2012, on yield (kg/vine), bunch number (n/vine), berry weight (g), total soluble solids of juice (°Brix), juice pH and titratable acidity (TA g/L).

Parameter	Treatment F (Control plots adjacent to main trial area; zero soil disturbance)	Treatment A (Control plots within main trial area; shallow ripping of wheel line)	*LSD*
Yield			
2014	2.89	**4.81***	*0.67*
§2015	2.25	**2.87***	*0.47*
Bunch No.			
2014	76.9	**110.3**	*10.01*
2015	32.3	**51.1***	*7.03*
Berry Wt.			
2014	0.72	**0.80***	*0.04*
2015	0.96	**1.00***	*0.04*
°Brix			
2014	23.61	**22.93**	*0.33*
2015	26.71	**25.64***	*0.44*
pH			
2014	3.64	**3.55**	*0.05*
2015	3.52	3.50	*0.03*
TA			
2014	4.75	**5.17**	*0.21*
2015	6.87	6.99	*0.23*

† * <0.05, ** <0.01, *** <0.001

§ geometric means

This yield difference continued into the 2014/15 vintage, albeit less pronounced. Yield changes were reflected by higher bunch counts and bigger berries from vines growing on ripped soils. While higher yielding vines with bigger berries may not be in the interest of better quality wines, the effect also comes with a delayed maturity, as indicated by sugar content, pH and titratable acidity, which may be of interest when considering winery intake logistics. Vintages are becoming increasingly compressed with varieties that once had distinctly different harvest dates beginning to overlap. Strategies to influence the timing of maturity, without compromising quality, are worth noting.

1.3.4 Effect of rainfall redirection treatments

Figure 13. Photos of rainfall harvesting treatments, A-ripped control; B-bare earthen mound; C-earthen mound with periodic application of surface crusting agent; D-plastic covered mid-row mound; E-buried plastic mid-row mound.

1.3.4.1 The effect of rainfall redirection treatments on soil salinity

Rainfall redirection treatments did not immediately influence the average profile salinity of the under-vine soils. However, by spring 2014, Treatment E saw a 23% reduction in under-vine salinity relative to Treatment A control plots, Table 7. Treatment D was also trending lower at this time but did not become strongly significant in its difference from Treatment A until after the 2014/15 irrigation season. In April 2015, both Treatments D and E were around 29% lower in average soil salinity compared to Treatment A. In April 2015, Treatment C was trending lower when analysed at a reduced sensitivity ($P<0.1$), but in the context of improvements demonstrated by Treatments D and E, and in the context of plant response data (sections 1.3.4.2), this trend becomes less noteworthy.

Figure 14 details the distribution of soil salinity with depth for each of the four time-steps described above. It includes data from the non-ripped controls, Treatment F, against Treatments A-E. Soil salinity traces highlighted how little difference there was between treatments until soils were exposed to the lower rainfall and higher irrigation volumes of the 2014/15 season.

Soils sampled in spring 2013 described the soil condition following the first full winter after treatment construction. At this point, there was no significant differentiation between treatments although Treatment F soils did express a slightly higher salinity bulge at 0.3 m. This bulge equated to a 35% greater salinity at 0.2-0.4 m relative to that of the surface soils and was a trend that did not occur in any other treatment. It is presumed that this was an artefact of the wheel-line ripping event that all other treatments were exposed to during treatment construction, see section 1.3.3.

Following the winter rains of 2013/14, Treatments D and E remained lower in their salinity than all other treatments. In spring 2014, this was most pronounced in the deeper soils where most other treatments expressed at least a 25% increase in salinity when moving from 0.4 m through to 0.8 m. The notable exception was Treatment B, which did not increase salinity in the deeper soils. It is difficult to explain why the salinity trace of Treatment C did not mirror that of Treatment B given their similarities in floor management and that the surface sealant in Treatment C would presumably increase fresh water reaching under-vine soils.

Table 7. The significance† of floor management treatment effects on the average profile salinity (expressed as ECe, dS/m) of under-vine soils sampled autumn and spring 2013/14 and 2014/15.

Sampling Date	Treatment					*LSD*
	A	**B**	**C**	**D**	**E**	
22/11/2013§	1.21	1.27	1.21	1.07	1.15	*0.25*
07/04/2014§	1.29	1.25	1.17	1.17	1.14	*0.36*
14/11/2014§	1.22	1.23	1.21	**0.99***	**0.94***	*0.23*
10/04/2015§	1.94	1.83	1.74	**1.37***	**1.39***	*0.38*

† * <0.05, ** <0.01, *** <0.001

§ geometric means

By the end of the 2014/15 irrigation season, average profile salinities of Treatments D and E were lower than those of all other treatments, and Treatments A-E were lower than the non-ripped Treatment F.

In April 2015, following the 2014/15 irrigation season, additional samples were collected from mid-row soils in both the ripped and non-ripped control plots, Treatments A and F, as well as in the rainfall redirection treatments D and E. These soils were used to characterise the two-dimensional distribution of soil salinity across the row. Figure 15 shows that for each treatment, distance from the vine row, rather than depth, was the greatest source of variation.

Mid-row soils were between 60 and 70% lower in their salinity in the ripped and non-ripped control treatments and around 30% lower in the two rainfall redirection treatments. This trend is consistent with pre-trial measures collected from the site and also to those observed in another supplementary irrigation district, Padthaway SA, where a rainfall redirection proof of concept trial was conducted by Stevens et al. (2012).

Combining soil salinity data from both the under-vine and mid-row sampling points revealed that the non-ripped Treatment F had the greatest overall profile salinity at 1.85 dS/m. Treatment A, 1.5 dS/m, was 19% less saline than non-ripped plots and the rainfall redirection Treatments D, 1.25 dS/m, and E, 1.2 dS/m, were between 30 and 35% less saline than the non-ripped controls respectively.

Floor management effects on under-vine soils were significant, as has been described above. Effects on mid-row soils were more variable with rainfall redirection treatments appearing to show higher salinity at depth than control treatments.

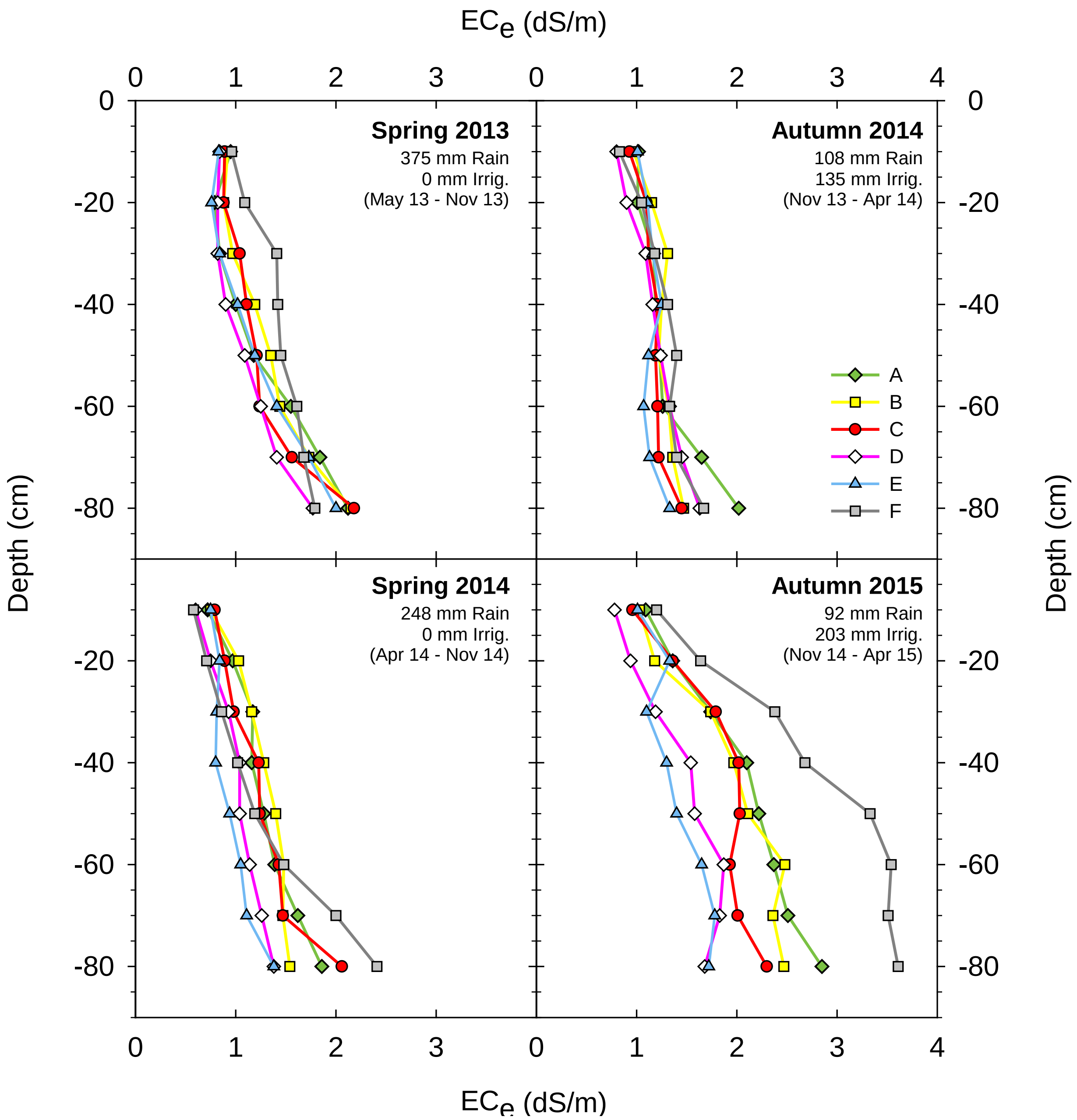


Figure 14. The effect of vineyard floor treatment and sampling depth on soil salinity, prior to and following the 2013/14 and 2014/15 irrigation seasons.

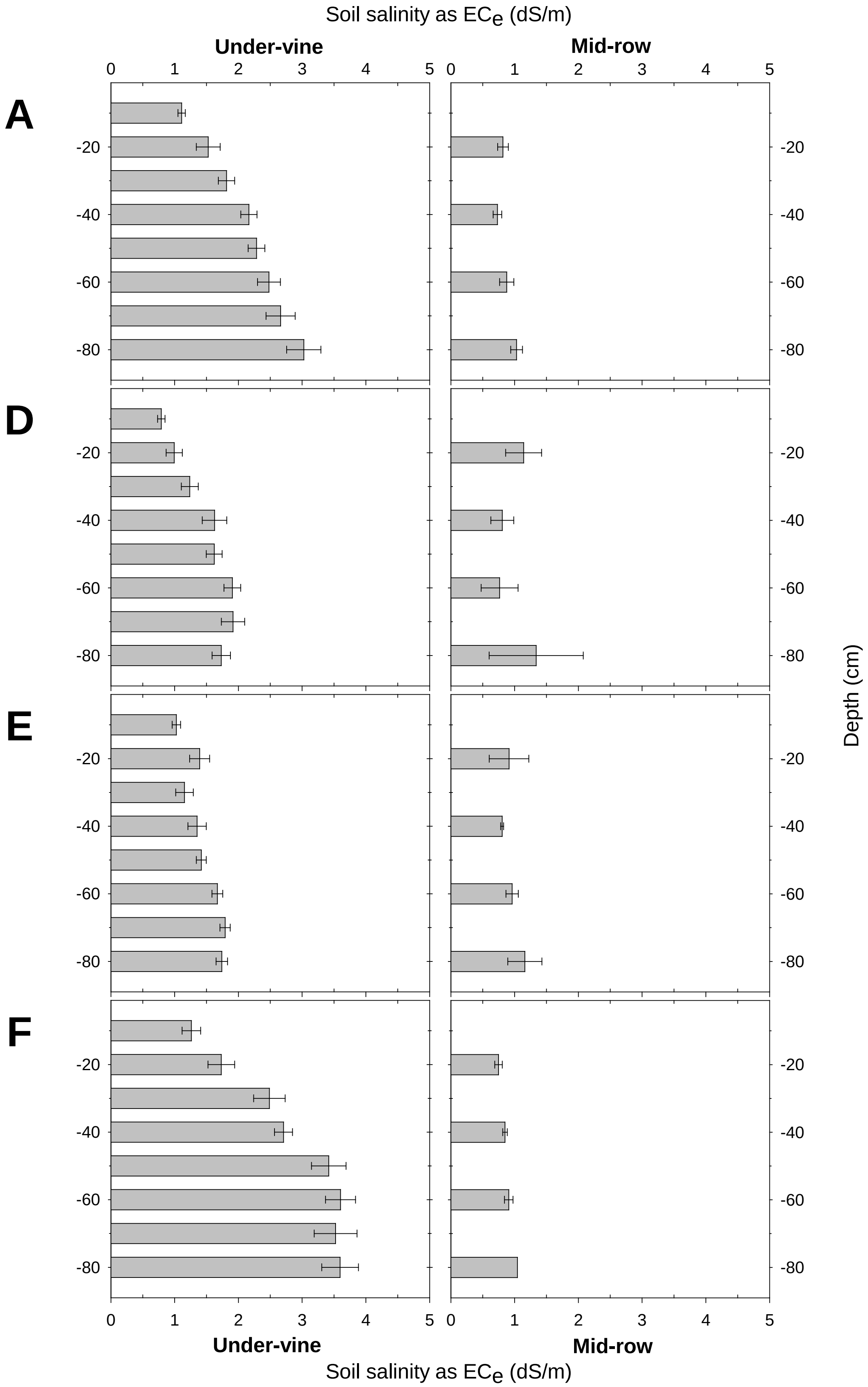


Figure 15. The effect of vineyard floor treatment, depth and sampling position on soil salinity in April 2015, at the end of the 2014/15 irrigation season. Data are geometric means and bars represent standard errors.

1.3.4.2 *The effect of rainfall redirection treatments on the sodium and chloride concentrations in leaves and fruit*

Rainfall redirection by the plastic covered mid-row mound, Treatment D, lowered petiole Cl^- concentrations across both the 2014 and 2015 seasons, by 25 and 12% respectively. In 2014, Treatment D also lowered petiole Na^+ concentrations by more than 30%. In 2015, no treatment significantly impacted on the Na^+ concentrations of the leaf petiole although Treatment E was trending lower and did differentiate when analysed at $P<0.1$. In both the 2014 and 2015 vintages, values were well below the levels of 0.5% for Na^+ and 1.5% for Cl^- that are indicative of a salinity pressure sufficient to reduce yield (Robinson et al., 1997).

An unexpected trend occurred with Treatment C Lamina Na^+ concentrations between the 2014 and 2015 vintages. In 2014, Na^+ concentrations were significantly higher than those of all other treatments and 17% higher than those of control vines. This trend reversed in 2015 with values 32% lower than control vines. It must be presumed that the elevated 2014 values were related to the crusting agent applied to Treatment E mid-row soils. However, isolating the crusting agent as the source of increased Na^+ concentrations is difficult given that petiole and juice samples did not produce the same trend. Also, it is unclear what proportion of the crusting agent is Na^+. The MSDS for TGC Soil-loc indicates product composition as being non-hazardous proprietary ingredients (~100%), ammonia (0-1%) and styrene (0-1%), leaving the concentration of Na^+ as unknown, Appendix F. If the crusting agent were the source of elevated Na^+, it is unlikely to have occurred through spray drift onto the plant as application dates were post senescence in both 2013 and 2014. It would more likely have occurred by plant uptake through root system. It is unclear why the trend was reversed in 2015 following the same treatment protocol.

Table 8. The significance† of floor management treatment effects on the average concentrations of Na^+ and Cl^- in the leaf petiole (% d.w.) sampled at flowering and leaf lamina (% d.w.) sampled at harvest and juice (mg/L) from fruit sampled at harvest. Seasons 2013/14 and 2014/15.

Parameter	Treatment					*LSD*
	A	B	C	D	E	
Petiole						
Na^+ 2014	0.330	0.283	0.299	**0.221*****	0.289	*0.045*
Na^+ 2015	0.101	0.108	0.103	0.104	0.085	*0.015*
Cl^- 2014	0.826	**0.712****	**0.726***	**0.622*****	**0.704****	*0.09*
Cl^- 2015	0.571	0.557	0.548	**0.505****	**0.500****	*0.040*
Lamina						
Na^+ 2014	0.130	0.143	**0.156*****	0.124	0.134	*0.014*
§Na^+ 2015	0.094	**0.061*****	**0.064*****	**0.061*****	**0.059*****	*0.010*
Cl^- 2014	0.469	0.460	0.471	**0.368*****	0.459	*0.043*
Cl^- 2015	0.359	0.320	0.330	**0.310***	**0.318***	*0.036*
Juice						
Na^+ 2014	29	29	29	**24*****	28	*2.3*
Na^+ 2015	29	28	27	**26****	**24****	*1.8*
§Cl^- 2014	37	35	36	**29*****	**32****	*2.6*
Cl^- 2015	28	26	26	**24****	**24****	*2.4*

† * <0.05, ** <0.01, *** <0.001

§ geometric means

In 2015, all rainfall redirection treatments, including Treatment C, lowered lamina Na^+ concentrations. The greatest reduction, 37%, was associated with Treatment E vines.

In both seasons, redirecting rainfall from the mid-row to the under-vine soils, using Treatment D, lowered average juice Na^+ and Cl^- concentrations by 14 and 18% respectively. One of the more commercially viable rainfall redirection options, Treatment E, gave the same response for Cl^- in both years with an average reduction of 14% relative to Treatment A controls. It also produced a significant, 17%, reduction in juice Na^+ in the second year of assessment.

It should be noted that excessive salt concentrations in the juice can impact upon taste and marketability of wine made from such fruit. Elevated levels in the juice of red varietals have greater impact than for whites as red varieties tend to increase in their Na^+ and Cl^- concentrations through the process of vinification from juice to wine. Ratios of Na^+ concentrations in wine to those in juice have been reported at around 1.3:1 and those of Cl^- at more than 1.7:1 (Walker et al., 2010; Rankine et al., 1971). Through the period of this investigation, the maximum concentration of Na^+ and Cl^- in juice extracted from fruit in Treatment F, were 32 and 48 mg/L respectively. Even after vinification, these concentrations are well below the maximum Na^+ specified for entry into markets in Switzerland, South Africa and some provinces of Canada (Stockley, 2009) and the maximum Cl^- specified by Food Standards Australia New Zealand (2010).

1.3.4.3 The effect of rainfall redirection treatments on yield components

In February 2013, yield and maturity components were assessed across all rainfall redirection treatment plots. These were the first measures collected following the construction of treatments in November 2012 and data reflected the performance of vines recovering from soil disturbance, plus the influence of <20 mm of rain on rainfall harvesting treatments. At this time, there was no significant difference observed in any of the measured parameters, Table 9.

Table 9. Yield components assessed shortly after treatment establishment, February 2013.

Parameter	**Block average** (no sig. diff.)
Yield (kg/vine)	2.2
Sugar (°Brix)	25.3
pH	3.5
TA (g/L)	6.0

In vintages 2014 and 2015, nine replicates of non-ripped controls, Treatment F, were included in yield and maturity assessments. Yield performance of Treatment F vines reflected regional scale yield trends (pers. comm. Collaborative grower, 2014) producing 25% greater yield in 2014 (2.9 kg/vine) than either the previous or subsequent vintages; 2.2 kg/vine in 2013, Table 9, and 2.3 kg/vine in 2015, Table 6.

In 2014, yield from all plots within the rainfall redirection trial area were significantly higher than those of the non-ripped Treatment F vines. Differences between Treatments A and F are described above. Treatment D vines (6.0 kg/vine) produced 20% more fruit than Treatment A and 52% more than Treatment F. The presence of significance between A and D, in addition to that between A and F, indicates that the increased yield was not only influenced by breaking up the compacted wheel-line but also from rainfall redirection. Yields from the more commercially viable rainfall harvesting treatments B, C and E were equivalent to the ripped control but significantly higher yielding than the non-ripped, Treatment F, vines. Presumably, much of this yield response can be attributed to the breaking up of compacted soils in the wheel line.

2014 bunch counts and berry weights mirrored the yield response. Treatments with the greatest propensity for redirecting rain and limiting evaporation from the soil, Treatments, D and E, produced the greatest bunch number and heaviest individual berry weights. Both these treatments were significantly higher than the non-ripped Treatment F (*P*<0.001) and trending higher than the ripped Treatment A control (*P*<0.05). Grapevine yield has been shown to be proportional to water use (Williams et al., 1993) and the presence of a yield response to the most active rainfall redirection treatments in 2014 suggests that these treatments had enabled vines to increase their water use in 2014 and to a lesser extent in 2015. This response was also suggested by the simulated water balance described in Appendix G and section 1.3.6. The simulation predicted Treatments D and E as having the highest water uptake of those treatments modelled.

Table 10. The significance† of floor management treatment effects on yield (kg/vine), number of bunches per vine (n), berry weight (g), total soluble solids concentration in juice (°Brix), juice pH and titratable acidity of juice (TA, g/L) in the 2013/14 and 2014/15 seasons.

Parameter			**Treatment**			*LSD*
	A	**B**	**C**	**D**	**E**	
Yield						
2014	4.8	5.2	5.2	**6.0****	5.2	*0.67*
§2015	2.9	2.6	**2.2***	2.7	3.0	*0.47*
Bunch No.						
2014	110	115	110	118	114	*10.01*
2015	51	**42***	**40***	44	48	*7.03*
Berry Wt.						
2014	0.80	0.82	0.82	**0.85***	0.84	*0.04*
2015	1.00	1.04	1.04	1.03	1.00	*0.04*
°Brix						
2014	22.9	23.0	23.0	**22.2****	**22.6***	*0.33*
2015	25.6	25.7	25.8	25.8	25.5	*0.44*
pH						
2014	3.55	3.56	3.53	3.53	3.54	*0.05*
2015	3.50	3.50	3.50	3.51	3.49	*0.03*
TA						
2014	5.2	5.3	5.4	**5.7****	**5.6****	*0.22*
2015	7.0	6.8	6.7	6.8	6.8	*0.23*

† * <0.05, ** <0.01, *** <0.001

§ geometric means

In 2015, higher yields were less pronounced and in some cases reversed. Treatment E (3.0 kg/vine) was again significantly higher yielding than the non-ripped Treatment F, but equivalent to ripped Treatment A controls. Yields from other treatments were either equivalent to control vines or marginally lower, with both Treatments B and C having a lower bunch count in 2015. Treatment C yields declined relative to the ripped controls, 2.2 and 2.9 kg/vine respectively. Whilst the significance of this difference is marginal, in the context of previously discussed vigour and leaf sodium results, it may forecast drawbacks associated with the use of TGC soil-loc as a surface crusting agent within the vineyard.

In 2014, the fruit maturity indicators of total soluble solids concentration in juice (°brix) and titratable acidity indicate a delayed ripening of both Treatments D and E relative to both the ripped and non-ripped controls. This response is typical of vines carrying heavier crop loads (Coombe and Dry, 1992). In 2015, these maturity indicators were equivalent to controls, in line with the yield response.

1.3.5 The effect of vineyard floor management changes on vine water relations, gas exchange and vegetative growth

1.3.5.1 Effects on vine water relations and leaf gas exchange

Vine water relations and leaf gas exchange were measured in February, just prior to harvest, in both the 2014 and 2015 irrigation seasons. 2014 measures of leaf gas exchange were compromised by operator error and do not form part of this report. 2015 measures of leaf gas exchange were collected from treatments A-E but Treatment F was omitted due to time/resource constraints at the time of collection.

In neither 2014 nor 2015 was there any difference between the ripped control, Treatment A, or the non-ripped control, Treatment F, in their values pre-dawn or midday leaf water potentials, averaging -0.35 and -1.27 MPa respectively across both years, Table 11.

Table 11. The effect of shallow ripping soil in compacted wheel line, November 2012, on the mid-day and pre-dawn leaf water potentials (Ψ_{MD} and Ψ_{PD}, respectively, MPa) measured in February 2014 and 2015.

Parameter		Treatment F (Control plots adjacent to main trial area; zero soil disturbance)	Treatment A (Control plots within main trial area; shallow ripping of wheel line)	*LSD*
Ψ_{PD}	Feb 2014	-0.35	-0.33	*0.03*
	Feb 2015	-0.35	-0.35	*0.01*
Ψ_{MD}	Feb 2014	-1.38	-1.44	*0.09*
	Feb 2015	-1.12	-1.15	*0.05*

† * <0.05, ** <0.01, *** <0.001

§ geometric means

The afternoon value of Vapour Pressure Deficit (VPD) was 1.95 kPa in 2014 and 1.56 kPa in 2015.

Table 12. The significance† of floor management treatment effects on the early afternoon leaf photosynthetic rate (A, µmol $CO_2/m^2.s$) and stomatal conductance (g, mol $H_2O/m^2.s$) in February 2015 and mid-day and pre-dawn leaf water potentials (Ψ_{MD} and Ψ_{PD}, respectively, MPa) in February 2014 and 2015.

Parameter		Treatment A	B	C	D	E	*LSD*
A	2015	10.2	10.4	10.5	10.4	10.4	*1.7*
g	2015	0.062	0.058	0.063	0.062	0.066	*0.009*
Ψ_{PD}	2014	-0.33	-0.32	-0.33	**-0.30****	-0.32	*0.03*
	2015	-0.35	**-0.34***	**-0.34***	**-0.33****	**-0.33****	*0.01*
Ψ_{MD}	2014	-1.44	-1.45	-1.45	**-1.29****	-1.47	*0.09*
	2015	-1.15	-1.13	-1.13	**-1.09***	-1.12	*0.05*

† * <0.05, ** <0.01, *** <0.001

Treatments testing changes to vineyard floor management had no effect on the 2015 measures of either leaf photosynthetic rate or stomatal conductance, with averages of 10.4 µmol $CO_2/m^2.s$ and 0.062 mol $H_2O/m^2.s$, respectively.

Treatment D vines had significantly higher pre-dawn (-0.32) and midday (-1.19) LWP's in both assessment years, suggesting reduced stress relative to both control treatments, Table 12. In the 2015 season, Treatments B, C and E midday readings also differentiated from Treatment A, particularly Treatment E which was also significantly higher than the non-ripped Treatment F. Soil moisture monitored through the 2015 season showed Treatments D and E as being 7 and 12% higher in soil water contents relative to the ripped controls, Treatment A (data not shown). This trend agrees with the modelled predictions, described in Appendix G, and may explain the reduced leaf water potentials reported by the rainfall redirection treatments. Both Treatments D and E incorporated an impermeable plastic layer in their construction which likely reduced evaporative losses and so maintained soils moistures at higher levels.

1.3.5.2 Effects on vegetative growth

Between treatment establishment and the end of the 2013 growing season, vines received <40 mm of rain. Thus, measures of pruning weights in June 2013 reflected the uniformity of vine recovery from treatment establishment rather than the influence of rainfall redirection treatments. Cane weights were equivalent at this time at 1.65 kg/vine, Figure 16. Uniformity of vigour in this first year aligns with that of yield and fruit maturity trends measured in March 2013, Table 9.

The 2013/14 growing season saw increased vigour in treatments with the greatest propensity for redirecting rain. Irrigation was below average through 2013/14 and Treatment D benefited from its ability to redirect rain from the mid-row towards the under-vine soils with 14% greater pruning weights (1.42 kg/vine) than Treatment A (1.22 kg/vine) and 21% greater vigour than the non-ripped control, Treatment F (1.12 kg/vine). Treatment E was also 13% more vigorous than Treatment F with pruning weights at 1.3 kg/vine. These trends match within season vigour assessments as measured by Leaf Area Index (LAI), Figure 17.

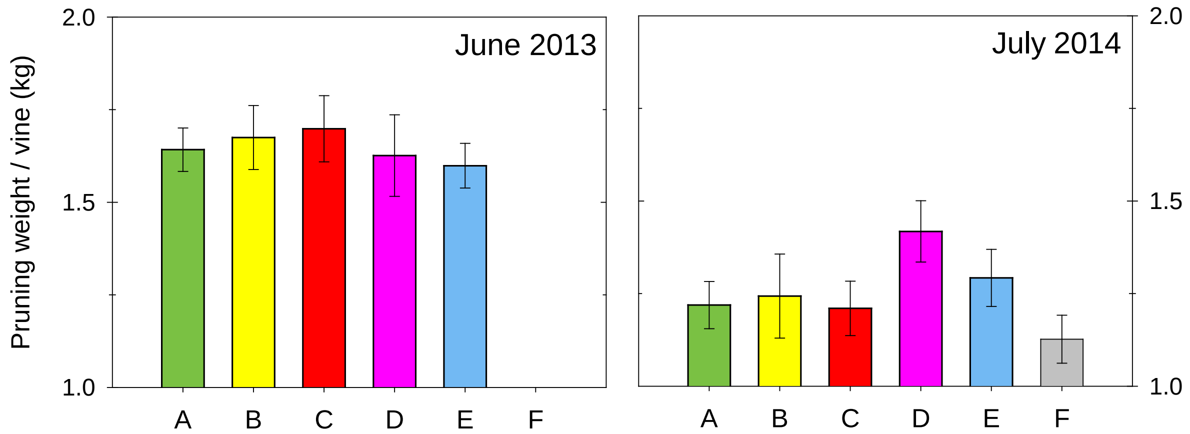


Figure 16. The effects of vineyard floor management treatments on vine vigour as measured by winter pruning weights (kg of cane/vine). July 2013 and July 2014. Vertical bars indicate standard errors of means.

While winter pruning weights are a recognised measure of a vine's vigour through the preceding growing season, this destructive method does not offer any insight into the progression of growth through the season. LAI is a non-destructive measure of plant vigour that can complement end of season pruning weights. Measures of LAI were collected at three growth stages in 2013/14 and 2014/15 viz., Flowering, Veraison and Harvest. Measures of LAI suggest that there was little difference between Treatments A, B, D and E in the period between November 2013 (flowering) and January 2014 (veraison). In the approach to harvest, Treatment D and E vines retained and/or produced more leaf cover than control vines.

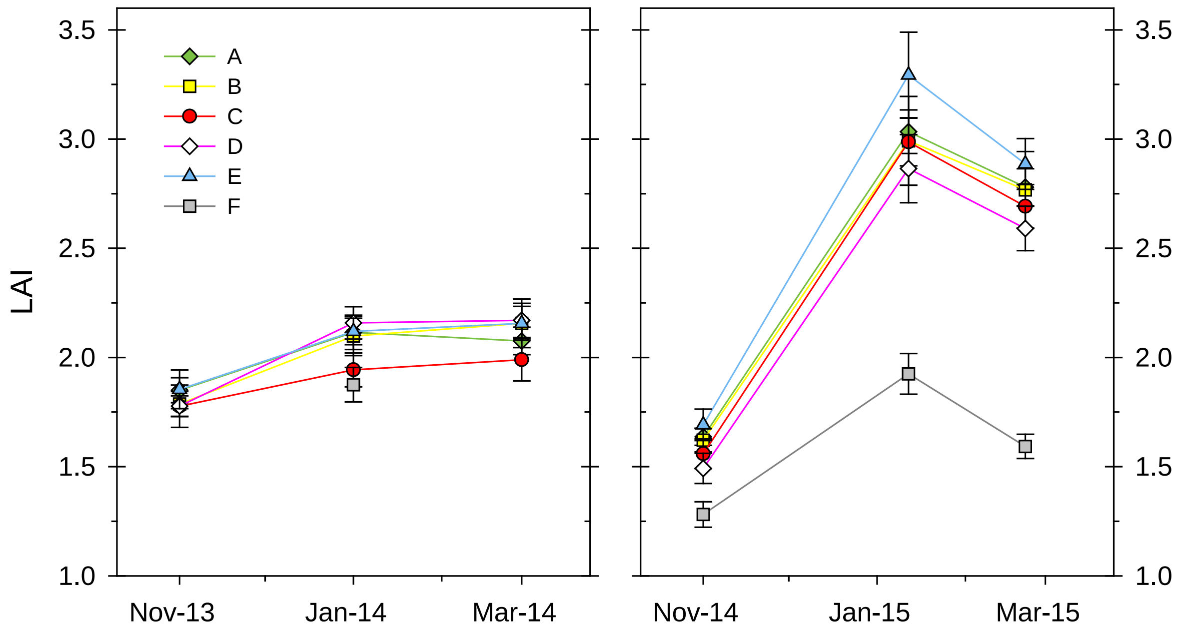


Figure 17. The effects of vineyard floor management treatments on vine vigour as measured by Leaf Area Index through the 2013/14 and 2014/15 growing seasons. Vertical bars indicate standard errors of means.

Through this same season, Treatment C vines reported lower LAI values but ultimately caught up to the control vines. A single measure of LAI in non-ripped controls, Treatment F, saw the first signs of vigour differences between the ripped, Treatment A, and non-ripped, Treatment F, controls, Figure 17. This trend was reflected in the July 2014 pruning weights, Figure 16. Following the heavy crop of the 2013/14 irrigation season, trial vines commenced the 2014/15 with lower vigour, averaging 1.65 LAI as opposed to the 1.81 of the previous season. This rapidly changed as the mild season combined with a lower crop load and a more generous irrigation schedule (35% greater than previous seasons) to encourage rapid vegetative growth. At the January 2015 (veraison) sampling point, average LAI was in excess of 3 and Treatment E had differentiated from control vines. Treatment D vigour was not as precocious as the previous season and was likely recovering from the previous season's high vigour and heavy crop loads. All treatments were significantly more vigorous than the non-ripped control, Treatment F.

1.3.6 Numerical modelling of vineyard floor management changes and their predicted effect on soil water and solute dynamics

The project had originally been written to support a PhD candidate in answering questions around irrigating viticulture with recycled wastewater, with specific reference to the interaction between slightly saline wastewater and the physical and chemical properties of soils. Unfortunately, a suitably qualified PhD candidate was not identified through the course of the project. However, SARDI and University of Adelaide staff did collect numerous intact cores in 2013 which were subsequently analysed by the University for their physical and chemical properties, Appendix I.

In lieu of the PhD, SARDI nominated to make use of the University's field data in the construction of numerical modelling domains that would add the value to both SARDI's and the University's field measurements. At the same time, SARDI constructed modelling domains for the Padthaway irrigation district (saline groundwater) and the Loxton irrigation district (non-saline surface water). Results from these three models are described in Appendix G and extend the usefulness of the current field trial beyond the McLaren Vale recycled wastewater irrigation district to other soils, climates and irrigation sources.

The conceptual modelling analysis compared Treatments A, B, D and E. A summary of the McLaren Vale modelling component follows.

1.3.6.1 Modelled impact of rainfall redirection treatments on soil water balance and distribution of soil salinity

A three-year simulation of rainfall redirection treatments at McLaren Vale predicted that both Treatments D and E would have elevated plant water use as compared to Treatments A and B. The impermeable plastic layer covering the surface of Treatment D produced a 54% reduction in evaporation flux, a four-times increase in the soil water storage and a two and a half times increase in drainage, Table 13. This simulated response would have a significant impact upon the removal of salts from the system.

Table 13. The effect of rainfall redirection treatments on components of the simulated annual water balance (mm). Average values for the period 2011-2014. Full data, Appendix G.

Parameter	Treatment			
	A	B	D	E
Irrigation	115.6	115.6	115.6	115.6
Rainfall	525.1	525.1	525.1	525.1
Transpiration	234.4	233.4	272.0	249.8
Evaporation	322.5	323.5	148.3	323.3
Drainage	81.8	81.7	207.8	61.5
Soil storage/depletion	3.9	4.1	15.7	8.4

The model predicted a progressive increase in the soil salinity over the simulation period. This was not matched by field measurements, which did not report significant salinity increases within the first year and a half. Field measured salinity did not increase until the 2014/15 irrigation season, at which point Treatments D and E began to differentiate from controls. Despite the field measures not matching modelled predictions in the first year and a half, the overall predictions for salt distribution did mirror those reported by field samples collected in April 2015 (i.e. the worst case scenario due to very low rainfall the preceding 5 months). At this time, under-vine salinities were predicted to be significantly higher than those of mid-row soils, Figure 18. Similarly, the model agreed with field measurements that rainfall redirection effects in Treatments D and E had significantly lowered the under-vine salinity as compared to the control.

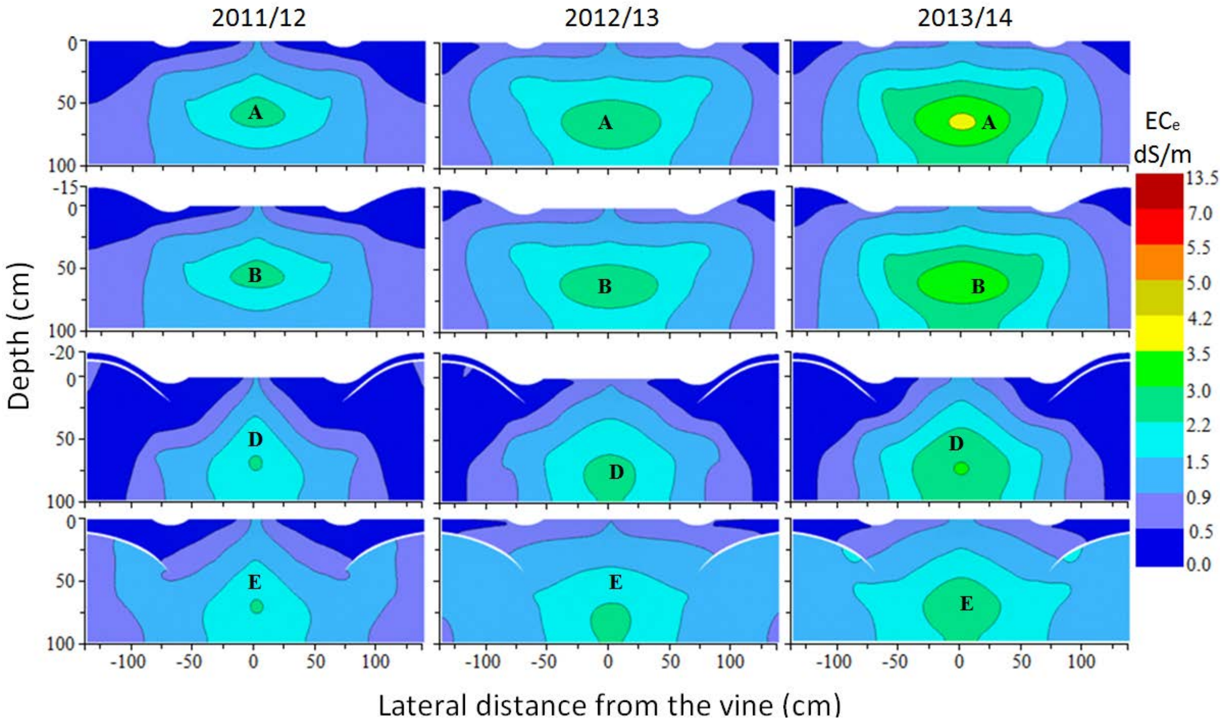


Figure 18. Simulated distribution of soil salinity (dS/m) as influenced by rainfall redirection treatments over a three year period.

The model suggests that while Treatments D and E tend to have sharp depressions in under-vine salinity during winter and spring, these salts accumulate again through the irrigation season (Figure 6, Appendix G). The favourable effects of reduced soil salinity are apparent for soils directly under the dripper, but the benefits appear marginal when considering the whole of profile salinity, particularly for Treatment E whose mid-row soils were predicted to increase relative to controls. This is despite it having the greatest leaching efficiency in terms of the ratio of salt leached against drainage flux, Table 14. Treatment D was predicted to have the lowest leaching efficiency but remained the least saline treatment due to its very high drainage flux relative to the other rainfall harvesting treatments.

Table 14. Simulated drainage flux (m3/ha), salt leached (kg/ha), leaching efficiency (kg salt/m3 drainage) and salt stored. Data averaged over the period of simulation, 2011-2014.

Parameter	Treatment			
	A	B	D	E
Drainage flux (m^3/ha)	767.4	766.2	2023.2	577.2
Salt leached (kg/ha)	406.1	429.3	883.8	563.3
Leaching efficiency (kg/m^3)	0.52	0.55	0.44	0.95
Salt storage (kg/ha)	831.9	812.8	434.6	695.8

In general, the modelled trends in soil salinity approximated those reported by the field measurements collected through the life of the trial. The only exception being that measured values of Treatment E mid-row soils were not as high as those predicted by the model. The differences between the simulated soil salinities of surface plastic and subsurface plastic treatments were driven by modelled evaporation flux and the corresponding changes to drainage, Table 13. The discrepancy between measured and modelled data suggests a need for greater replication of field measures and a refinement of simulated evaporative/drainage conditions for those treatments comprising mid-row plastic. Refining the model to better reflect real world evaporative and drainage conditions would produce a simulated response closer to the measured response. Model calibration is ongoing.

A well calibrated and validated model introduces the opportunity to run various climatic, water quality and irrigation scheduling scenarios to inform irrigators' decisions around strategies to manage their water resources. Applying the model to conditions found in the Padthaway and Loxton irrigation districts further extends the value of the modelling exercise. More detailed interpretation of the numerical modelling exercise for each of McLaren Vale, Padthaway and Loxton are described in Appendix G.

1.4 Conclusion

Soil and vine salts were reduced by harvesting rain falling in the mid-row and redirecting it to the under-vine soils using a plastic covered mid-row mound. Soil salinity was reduced by more than 27% and juice concentrations of sodium and chloride were reduced by 28% relative to undisturbed controls. This result strengthened findings from a proof of concept trial (Stevens et al., 2012) where the same treatment was tested under different growing conditions. Favourable results from two distinct investigations demonstrated that rainfall redirection works as a salinity management concept.

Burying the plastic covered mid-row mound below the soil surface produced equivalent reductions in soil and plant salts, without the high labour inputs associated with maintaining the surface exposed plastic covered mound.

Constructing a bare earthen mound in the mid-row did not achieve the same salinity reductions, nor did the periodic application of a crusting agent to that mid-row mound.

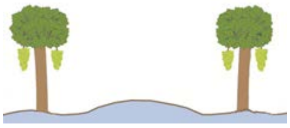
Shallow ripping of compacted soils, located in the trafficked wheel lines, saw an early increase in vine vigour and yield with average soil salinity reductions of 11% and reductions of juice sodium and chloride concentrations of 17%. This "value for money" treatment could initially be used by growers in areas where juice salt limits are being approached, with the mounding treatments providing further benefit.

Yield and vigour increases were observed in all experimental plots and largely attributed to the breaking up of compacted soils in the wheel line. Vines exposed to rainfall redirection using a plastic covered mid-row mound, either buried or exposed, were slower to ripen in the first year of assessment as indicated by reductions in juice °Brix and increases in juice titratable acidity. These early changes in maturity corresponded to increased yields, with 20% more fruit and 10% greater berry weight produced by vines treated with the exposed plastic covered mid-row mound. Yield and maturity responses to rainfall harvesting did not persist into the second year of assessment.

1.5 Practical considerations of rainfall redirection

Treatment B

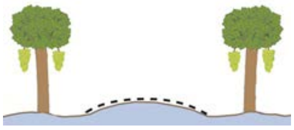
Bare earthen mound



A compacted earthen mid-row mound is a cheap and simple rainfall redirection structure. However, it is likely to have low runoff efficiency and be susceptible to weed growth. The earthen mound is suitable for the application of infiltration reducing chemicals or installation of a physical barrier. Best runoff efficiency will come with higher clay contents. It is likely to have a long lifespan, requiring occasional spraying out of weeds if wanting to maximise runoff efficiency. Some sites may be able to delve clay to form a naturally impermeable crust on the soil surface. However, delving may result in damage to root systems and may best be considered as a pre-planting operation.

Treatment C

Spray applied surface sealant



The use of infiltration reducing chemicals requires the construction of a graded surface such as that described above. The spray applied surface sealant has a finite life with good runoff that tails off with time. Runoff efficiency will depend on a smooth surface with minimal to no weed growth. Cracking clays will reduce runoff as will mechanical disturbance from traffic. The attraction of this option is that mounds can be prepared for rainfall harvesting as required (eg - when salt pressure is excessive and high rainfall period is forecast).

Treatment D

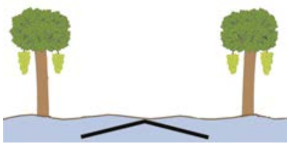
Plastic covered mid-row mound

Covering the earthen mound with an impermeable plastic membrane produces high runoff efficiency. However, the plastic material is susceptible to rapid deterioration, particularly on rough surfaces with stone or cane material trapped between soil and plastic leading to punctures. Highly susceptible to mechanical damage from vineyard operations and susceptible to deterioration from UV (recycled materials especially sensitive to UV). Susceptible to ponding of water in slow draining soils

NB – This treatment was effective at reducing soil and plant salts during the current investigation.

Treatment E

Buried plastic covered mid-row mound



Impermeable layer buried at depth via grading and covered with native soil. Requires significant earthworks (although existing equipment in other industries may be suited to large scale installations). Runoff efficiency is dependent on soil type, soil thickness above impermeable membrane and rainfall intensity. A durable treatment requiring low maintenance, although it may be susceptible to waterlogging and bogging in slow draining soils. Worth considering installations in alternating rows.

NB – This treatment was effective at reducing soil and plant salts during the current investigation.

The following summary of general considerations combines observations from this and a previous investigation (Stevens et al., 2012) and is included to assist irrigators in deciding the suitability of rainfall redirection for their operation.

Cost	The treatments described within this report were assessed in a randomly designed replicated trial that necessitated a 'patchwork quilt' of different treatments along the lengths of multiple rows. This meant that treatments were largely constructed by hand and commercially realistic costings of large-scale construction were not determined. However, the authors believe that the type of equipment that could apply, or could be modified to apply, such treatments on a large scale already exist within other industries (eg - vegetable/strawberry bed former, graders, rollers etc).
Rainfall	Performance of rainfall redirection treatments will vary widely depending on the intensity, frequency, duration and timing of individual rain events. Earthen mounds are more likely to store and then allow evaporation of low intensity rain events, whilst rainfall redirection treatments involving a physical barrier can produce runoff from much lower intensity rain events.
Soil	Performance will also vary with soil type, firmness of the surface and slope. Soil type will influence the runoff efficiency of earthen rainfall redirection mounds with higher clay contents resulting in more effective runoff. Soils with low clay content will require compaction and/or the application of an infiltration reducing material such as a dust suppressant, clay, plastic membrane etc. Soil type will also affect how receptive the target soil is to infiltration (and leaching) by the harvested rainfall. Rainfall redirection toward a heavy textured under-vine soil is more likely to result in ponding and may make site access difficult during the wetter months. *NB – Whilst high runoff efficiency may be desirable for leaching of salts, receptivity of soils and historic rainfall patterns must be considered. Had the current project taken place during the wet 2011 and 2012 seasons, Treatments D and E (comprising plastic sheeting in the mid-row) would likely have been too boggy for spray equipment to traffic rows leading to logistical problems during the critical fungal control period. At this trial site, above average rains through the growing season have historically occurred once every 3-4 years.*
Weeds	Weeds can dramatically reduce runoff from the surface of a rainfall redirecting mound. They can break the compacted or chemically sealed surface and create pores (normally encouraged for increased infiltration rates but not desirable on the surface of a rainfall redirection mound).
Traffic	Viticulture is a highly mechanised industry requiring frequent traffic of the mid-row. Any changes to the geometry of soils or introduction of impermeable materials need to accommodate this traffic, ie - machinery wheel clearance, draw bars, pruners, sweepers, harvesters etc. Livestock within the vineyard will initially avoid constructed mounds. However, both native and domestic stock can cause erosion and puncture damage once they become accustomed to a rainfall redirection structure.

Durability of impermeable layers	The installation of a plastic impermeable layer on the surface of a mid-row mound worked well as an experimental rainfall redirection treatment. However, the authors DO NOT recommend it as a commercial rainfall redirection strategy as it requires significant maintenance to retain treatment integrity due to mechanical damage and eventual UV instability, Figure 19. Virgin grade plastic sheeting will last longer than recycled grade plastics but remains susceptible to mechanical damage from normal vineyard operations. Both virgin and recycled products, ranging from 200 – 400 µm appear to have good longevity when incorporated as a sub-surface impermeable film, and should last years.

Figure 19. Mechanical damage of plastic covered mound

There are numerous products, more robust than black builders plastic, that would also produce favourable runoff efficiencies. These include semi-permeable geofabrics, artificial turfs, rubber sheeting, moulded plastic soil stabilisers etc. Semi-mechanised application of these treatments on an 'as needs' basis, similar to the way some growers install and remove bird netting, may improve the cost benefit ratio of these expensive alternatives.

Infiltration reducing chemicals	Chemical sealants can reduce infiltration for a few weeks after which the effect deteriorates. Their performance will differ with soil type, smoothness of surface, weeds, traffic etc. These products are used extensively in the mining industry to control dust and increase runoff from gravel roads. However, the lack of disclosure around proprietary ingredients introduces questions around their suitability for use around food crops. Further detail on the runoff efficiency of different chemicals, around and within vineyards, can be found in the GWRDC final report RT 03/20-4 by Short and Lantzke (2006).
Changes to microclimate	Covering areas of the soil surface with impermeable or semi-impermeable materials can change the microclimate in terms of soil and canopy temperature, light distribution and soil moisture in mid-row soils. Changes to soil biological activity and plant physiology are likely to result.
Root pruning	Installation of earthen rainfall redirection mounds is likely to require soil disturbance and some level of pruning to the shallow roots. In the current investigation, vine response was an initial increase in vigour as new roots were able to explore beyond the previously compacted soils of the wheel lines.

Trial 2. Almond sensitivity to salt stress at different growth stages

2.1 Introduction

Horticultural enterprises on the Northern Adelaide Plains (NAP) are fortunate to have access to multiple sources of reliable water suitable for irrigation. Groundwater has been the traditional source of irrigation water since the district was established in the 1950's but, since 1999, it has been increasingly supplemented by tertiary treated wastewater from SA Water's Bolivar Wastewater Treatment Plant. Bolivar wastewater is delivered to irrigators via the NAP-Virginia Pipeline Scheme and offers a cheap and reliable water source that has enabled the expansion of many of the region's horticultural enterprises. However, the quality of recycled wastewater is variable and often slightly saline. As irrigators increase the volumes of wastewater being applied, they also increase the amount of salt being imported into the soil. On a per hectare basis, almond trees are amongst the highest users of recycled wastewater, increasing their susceptibility to issues of irrigation induced soil salinity. NAP almond growers are justifiably concerned about the cumulative effects that recycled wastewater can have on the salinity of their soils, yields and crop quality.

Most studies into the salt tolerance of almonds focus on seedlings and rootstocks grown under greenhouse conditions (Bybordi, 2012; Yadollahi et al., 2011). These studies have demonstrated reduced root and shoot growth as well as negative changes in photosynthesis associated with increasing salt concentrations. However, they have little connection to the productivity of mature plants grown under field conditions. Of those studies that have investigated the impact of salt stress on fruit production under field conditions, few have focussed on the sensitivity of distinct phenological stages in the growth cycle.

The aim of the present study was to identify the stage within the annual almond growth cycle which is most sensitive to irrigation with a slightly saline water source.

Knowledge around the sensitivity of phenologically different growth stages in almonds would provide an opportunity for irrigators with multiple water sources of different qualities, such as those on the NAP, to manage the timing and duration of salt exposure to their crop.

Lessons learnt could also contribute to management practices for other perennial trees crops as well as council amenity plantings. For the wider almond industry, largely irrigated with surface water from the Murray Darling Basin, knowledge on the sensitivity of different growth stages to a salinity stress would inform decisions around the necessity and timing of leaching irrigations, offering potential water savings during periods of water scarcity. At the whole of industry level, this knowledge would help the Almond Board of Australia (ABA) and Murray Darling Basin natural resource managers understand that salt releases into surface waterways, arising from managed environmental flows, may impact almond production differently depending on the timing of those flows.

2.2 Materials and methods

2.2.1 Site description

The experimental site was established at a mature almond plantation located in the Northern Adelaide Plains irrigation district, approximately 35 km north of Adelaide, South Australia (Lat: -34.628° and Long: 138.683°). The orchard was planted in 1998 and designed to have two adjacent rows of a commercial variety, Nonpareil, bordered on either side by pollinators, Price and Keane. All trees were grafted to peach hybrid rootstock with rows planted in a north south direction. Trees were spaced at a distance of 5.5 m within the rows and 7.5 m between rows. A mid-row cover crop of various volunteer weeds and grasses (both annual and perennial) was managed with occasional slashing and under tree herbicide operations.

Soils were described by Dowley and Fitzpatrick (2001) as being well drained soft sandy loam over hard calcareous clays with tree root development noted as being good in the upper 0.6 m of the profile. Readily Available Water (RAW) for these soils was reported as 20 – 30 mm.

Through 2010 and 2011, measures of soil salinity were collected as part of an investigation into soil health by Rawnsley (2011) and demonstrated the site's susceptibility to salt accumulation and it's receptivity to leaching with fresh water. In April 2010, following the 2009/10 irrigation season, average soil salinity through the profile was greater than 6 dS/m (EC_e). In April 2011, after above average summer rainfall and reduced irrigation events, the average soil salinity was less than 2 dS/m (EC_e). Pre-trial measures by this project, in April 2013, showed that average soil salinity had returned to levels ≥6 dS/m (EC_e).

The experimental site was managed as per standard commercial orchard practices including a full nutrient, fungicide and herbicide spray program plus mechanical harvest operations.

2.2.2 Trial design and analysis

The trial was constructed in winter 2013 as a randomised unblocked design, with four treatments replicated four times plus an additional demonstration plot. Each treatment plot was six emitters (five trees) long and three rows wide and was comprised of a double row of Nonpareil trees plus a single row of a pollinator variety (two blocks of Keane and two blocks of Price). All soil and plant measurements were collected from the three central trees in the middle row.

Figure 20. Recycled wastewater irrigation headworks at NAP almond orchard.

Beginning in the 2013/14 season, fresh water (EC <0.8 dS/m; non-saline) was substituted for the slightly to moderately saline irrigation water (EC >1.8 dS/m) at each of three phenologically different growth stages. Those being: between bud-burst and pit-hardening (BB-PH); between pit-hardening and harvest (PH-H); and between harvest and leaf drop (H-LD). At other times, plots were irrigated with the prevailing recycled wastewater as was the control throughout the entire irrigation season. In addition, a non-replicated plot of trees was irrigated with potable water throughout the entire season for demonstration purposes. Table 15 graphically presents the four replicated irrigation treatments and the non-replicated demonstration treatment. At the transition between growth stages, irrigation valves were switched to direct the appropriate water source to each treatment plot.

Table 15. Timing of exposure to non-saline irrigation water for treatments A-D (replicated) and treatment E (non-replicated demonstration plot).

Treatment	Description of irrigation	Growth Stage 1 Budburst to pit hardening	Growth Stage 2 Pit hardening to harvest	Growth Stage 3 Harvest to leaf drop
A	Saline (slightly to moderately) all year	EC > 1.8 dS/m		
B	Non-saline at BB-PH	EC < 0.8 dS/m	EC > 1.8 dS/m	
C	Non-saline at PH-H	EC > 1.8 dS/m	EC < 0.8 dS/m	EC > 1.8 dS/m
D	Non-saline at H-LD	EC > 1.8 dS/m		EC < 0.8 dS/m
E*	Non-saline all year	EC < 0.8 dS/m		

* Single demonstration plot only

Analysis of variance used an unbalanced factorial regression in GenStat 16th Edition (VSNI, Hemel Hempstead, UK). The regression accounted for the response of the non-replicated demonstration plot (Treatment E) together with the four replicated treatments (A-D). Least Significant Difference (LSD) was used to compare treatment means at three error levels (*P*<0.05; 0.01; 0.001). Covariates (spatial and pre-trial concentrations of Na^+ and Cl^- collected just prior to harvest) were included in models fitted to data on leaf concentrations of Na^+ and Cl^-, and retained in the final model if the P value of their significance was ≤0.05. All data were generated by making repeated observations on the same trees.

2.2.3 Meteorological, irrigation and water quality measurements

Rainfall data were sourced from the Edinburgh RAAF automatic weather station (Bureau of Meteorology station number 023083). Data on the reference evapotranspiration (ET_o) and rainfall, 1951 to 2015, were generated by running a data drill at http://www.longpaddock/qld/gov/au/silo in April 2015.

Irrigations were scheduled to replace the estimated tree evapotranspiration based upon a modified version of the protocol developed by the Almond Board of Australia (2011). Data on irrigation depths were sourced from the collaborating grower and cross-checked against flow meters located in each treatment. Applied depths of irrigation were recorded weekly through the irrigation season to ensure the same depth of irrigation was applied to all treatments at each growth stage.

The orchard was irrigated with Ein-Dor 70 L/hr sprinklers spaced every 5.5 m, halfway between trees, along the length of tree rows spaced at 7.5 m. This resulted in an application rate of 1.7 mm/hr.

Recycled water for irrigation was drawn from the Bolivar Wastewater Treatment Plant, located approximately 17 km south west of the NAP trial site, and distributed through the Water Infrastructure Group's Virginia Pipeline Scheme (VPS). A potable water connection was installed by the project to supply non-saline water to treatment plots. The potable water was sourced from SA Water's Barossa Filtration Plant, located approximately 15 km east of the NAP trial site. Schematics for the Bolivar Wastewater Treatment Plant, the VPS and the Barossa Filtration Plant are available in Appendix E.

Water samples were continuously collected from irrigation emitters throughout the growing season, via micro drippers and sub-sampling collection tanks, and assessed for salinity using the method described in section 1.2.3. Bulked irrigation samples from each growth stage were submitted to the Australian Water Quality Centre for more complete analysis, Table 16. In addition, SA Water provided seasonal water quality data for Class A recycled wastewater produced by the Bolivar Wastewater Treatment Plant, Appendix E.

The EC of water received by trees during each growth stage and for the whole season was expressed as a volume weighted average following a procedure described by Stevens et al. (1999). This calculation accounted for the different depths and qualities of irrigation waters and rainfall received at each growth stage. For the purpose of this calculation, irrigation events and rainfall events ≥5 mm/48 hr (effective rainfall) were considered as water additions. The EC of rainfall was taken as 0.1 dS/m (Crosbie et al., 2012).

Table 16. Summary of NAP recycled water chemistry through period of investigation. Samples collected fortnightly from irrigation emitters and bulked into growth stages prior to analysis by the AWQC.

		2013/14			2014/15		
Parameter		**BB-PH**	**PH-H**	**H-LD**	**BB-PH**	**PH-H**	**H-LD**
EC	dS/m	-	1.67	1.82	1.9	1.63	1.62
TDS (by EC)	mg/L	-	920	1000	1000	900	890
pH	pH units	-	8.5	8.7	8.6	8.1	7.6
Turbidity	NTU	-	3.4	-	6.4	1.7	0.58
Colour	HU	-	6	8	8	7	7
Chloride	mg/L	-	353	384	381	341	266
N as Nitrate	mg/L	-	1.68	1.46	9.52	4.86	2.85
N as Nitrite	mg/L	-	0.014	0.04	0.215	0.021	0.021
Total Nitrogen	mg/L	-	3.18	3.22	20.7	9.95	7.94
Total P	mg/L	-	0.048	0.046	0.030	0.020	0.016
Sodium	mg/L	-	270	298	305	259	238
Calcium	mg/L	-	24.2	27.0	23.4	22.6	33.0
Magnesium	mg/L	-	24.8	26.3	29.9	25.2	22.9
Potassium	mg/L	-	32.4	34.9	37.6	34.2	36.1
Bicarbonate	mg/L	-	87	-	-	101	127
Alkalinity ($CaCO_3$)	mg/L	-	72	-	-	82	104
SAR *		-	9.2	9.8	9.8	8.9	7.8

* calculated as per Ayers and Westcot (1985)

2.2.4 Soil measurements

Soil salinity was assessed at the end of the 2013 season and then at the end of each growth stage in the 2014 and 2015 seasons. Soils were sampled, using equipment described in section 1.2.4, with cores collected 1.0 m into the mid-row from the sprinkler emitter and sampled at 0.1 m increments to a depth of 1.6 m.

Soil salinity was measured as per the method described in section 1.2.4 and reported as the electrical conductivity of the extract from a saturated paste (EC_e) using a conversion factor that was generated by analysing paired data from soil samples which had been split so that both $EC_{1:5}$ and EC_e could be measured. EC_e was determined following the method of Rayment and Higginson (1992). Soil salinity analysis showed a strong linear dependence of EC_e on $EC_{1:5}$, Figure 21.

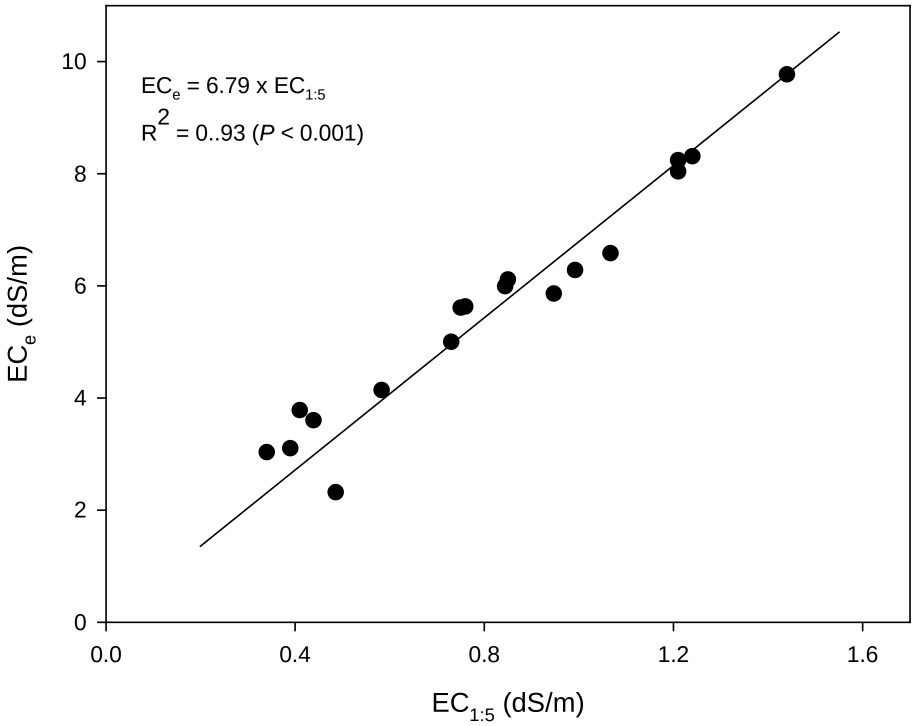


Figure 21. Relationship between soil $EC_{1:5}$ and soil EC_e for soils at the NAP timing of salt exposure trial (2013-2015) plus representative soil core from the site.

Soil water content was measured on a monthly basis through the 2014/15 season using a 503 DR Hydroprobe neutron moisture meter (CPN International, California, USA). Twelve aluminium access tubes were installed in May 2014 and soils retained for assessment of salinity and gravimetric moisture contents. At the same time, undisturbed soil samples were collected from three separate cores for determination of bulk density and conversion of gravimetric to volumetric water contents and calibration against the Neutron Probe. Probes were installed adjacent to sprinkler emitters, mid-way between trees in three replicates of treatments A, C and D, two replicates of treatment B and a single access tube in the non-replicated treatment E. The probe was set to read at 0.1 m depth increments between 0.2 – 0.6 m and at 0.2 m depth increments between 0.6 – 1.6 m.

2.2.5 Nutrition

The experimental site was fertilised via foliar, broadcast and fertigation methods. All experimental plots received the same fertiliser applications as trees outside the trial area. Nitrogen (N), phosphorus (P) and Potassium (K) were applied at rates of approximately 100, 20 and 50 kg/ha/season, respectively. These applications supplemented the inherent nutritive value of the recycled water (ionic composition described in Appendix E) which tended to have elevated levels of N, P, K and Ca relative to those experienced by the wider almond industry in Australia. Most Australian almonds are irrigated with surface water from the Murray Darling Basin which has relatively low nutritive value. Non-saline irrigation treatments did not replicate the ratio of beneficial elements present in the recycled wastewater.

2.2.6 Plant tissue concentrations of Na^+ and Cl^-

Leaf samples were collected from all replicates just prior to harvest in 2013, before irrigation treatments had been installed. These data assisted in characterising pre-trial variation across the block and were available for covariate analysis against future plant tissue data. Following treatment installation, leaf samples were collected at three target growth stages in seasons 2014 and 2015 viz., pit-hardening, harvest and leaf drop. Individual samples were collected from the central three trees within a plot following the method described by the Almond Board of Australia (2008). Tissue was prepared and analysed for Na^+ and Cl^- as described in section 1.2.5 with data from each plot representing the average of the three central trees.

2.2.7 Photosynthesis and plant water relations

In 2014 and 2015, the values of pre-dawn and early afternoon stem water potentials and gas exchange were measured, in all replicates, a day prior to harvest. Measurements of leaf gas exchange were taken within two hours of solar noon upon leaves from each of two central trees within a plot. Data was averaged prior to statistical analysis. Measurements were taken using a modified version of the method described in section 1.2.6, viz. a 6400-40 leaf chamber fluorometer, with 2 cm^2 leaf chamber, was fitted to the LICOR-6400 to accommodate the narrow shape of the almond leaf.

An hour prior to measuring leaf gas exchange, an aluminised plastic bag was placed over a leaf within the inner canopy of the two assessment trees. Within five minutes after measurement of leaf gas exchange, the leaf enclosed in the aluminised plastic bag was excised and sealed within a Scholander Pressure Bomb (Scholander et al., 1965; Turner and Long, 1980). Within 30 seconds of leaf excision, the chamber was pressurised at a rate of 0.01 MPa/s, with the end-point to pressurisation observed using a binocular microscope under 10-fold magnification. VPD was calculated as per method described in section 1.2.6.

2.2.8 Yield components and tree vigour

Yield was measured on the three central trees of each treatment plot. Prior to commercial harvest operations, the orchard floor was raked clear under the target trees. Trees were mechanically shaken on 8 February 2013 (pre-trial), 22 February 2014 and on 16 February 2015 and nuts were left to dry on the ground for four days prior to the experimental pickup operation. A field weight was recorded for each of the three central trees and a 3 kg subsample collected. Additional subsamples were also collected from the first and fifth tree in each plot's central row resulting in five subsamples per plot. Subsamples were dried to a constant weight before being separated into kernel, hull and shell components. Percent crack-out and kernel weight were determined for each subsample and the plot average was calculated prior to statistical analysis.

Tree vigour was determined using a modified version of the LAI method described in section 1.2.7. In 2014, LAI was measured twice; just prior to harvest, February 2014, and again in the weeks approaching senescence, April 2014. In 2015, LAI was measured three times; just after pit-hardening (November 2014), prior to harvest (February 2015) and in the weeks approaching senescence (April 2015). Four under canopy images were collected from each of the three central trees. The sensor was located at ground level and 1.5 m away from the trunk with four images per tree capturing the north, south, east and west portions of the canopy. Images were processed using an algorithm developed by Fuentes et al. (2014) with the mean plot LAI then calculated from the 12 images prior to statistical analysis against the other plots.

2.2.9 Normalising tree response against timing of salt load

The response of yield and end of season leaf ionic composition were normalised to account for different irrigation depths and qualities received by each treatment. Normalising these data focussed on the timing effect of different salt loads. Change in the mean seasonal volume weighted EC_W, as influenced by periods of non-saline irrigation, was calculated using Equation 1. Change in a parameter's response relative to control plots was calculated using Equation 2. The normalised value of a parameter was calculated as the proportion of the difference between a non-saline irrigation treatment and the control relative to the difference between mean volume weighted EC_W of the non-saline irrigation treatment and that of the control; Equation 3.

$$\Delta EC_W = EC_{W\,(control)} - EC_{W\,(Treatment)}$$ **Equation 1**

$$\Delta Parameter = Parameter_{(control)} - Parameter_{(Treatment)}$$ **Equation 2**

$$Normalised\ response\ to\ timing\ of\ non\text{-}saline\ irrigation = \frac{\Delta Parameter}{\Delta EC_W}$$ **Equation 3**

Figure 22. NAP almond tree (in foreground) showing burnt leaf margins and defoliation, typical of salinity stress, following heatwave in January 2013.

2.3 Results and discussion

2.3.1 Irrigation depths and salt loads

The average length of the growing season was 278 days, seasonal timing of phenological events are detailed Table 17. Three phenologically distinct growth stages were targeted for the application of either slightly to moderately saline (recycled) irrigation water or non-saline (potable) irrigation water. These were Bud-Burst to Pit Hardening (BB-PH), Pit-Hardening to Harvest (PH-H), and Harvest to Leaf Drop (H-LD).

Table 17. Dates of phenologically distinct almond growth stages 2013/14 to 2014/15.

Growth Stage	Phenology	Approximate Dates 2013/14	2014/15
	Bud burst	2 Aug	8 Aug
1. BB-PH	Flowering Fruit set		
	Pit hardening	29 Oct	31 Oct
2. PH-H	Hull split		
	Harvest	9 Feb	15 Feb
3. H-LD			
	Leaf drop	10 May	6 May
	Dormancy		

A summary of irrigation, effective rainfall and evapotranspiration (ET_o) depths, for dormancy and each of the three growth stages, is shown in Figure 23. During the growing season, depths of irrigation plus effective rainfall totalled 1176 mm (11.8 ML/ha) in 2013/14 and 1018 mm (10.2 ML/ha) in 2014/15. Evaporative demand through these same periods was 1246 mm and 1218 mm respectively.

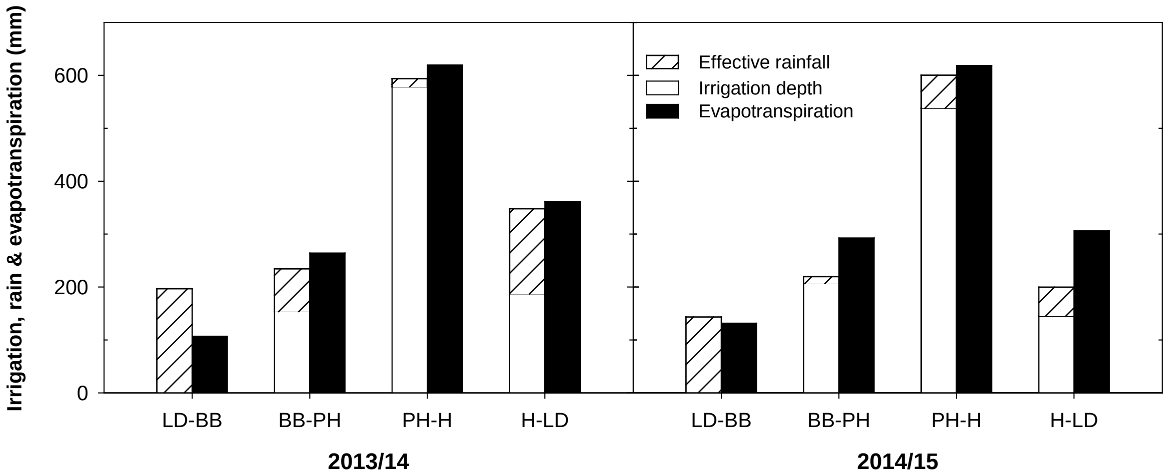


Figure 23. Depths of irrigation, effective rainfall and reference crop evapotranspiration through dormancy (LD-BB) and three growth stages. Effective rainfall through dormancy considered as ≥5 mm/48 hr and through growing season as ≥5 mm/day.

The irrigation schedule maintained average soil water content above 15% at depths from 0.2 to 1.6 m, Figure 24, resulting in the mean depth of irrigation, 903 mm (9 ML/ha), replacing 73% of the seasonal ET_o. The mean effective rainfall of 194 mm (1.9 ML/ha) replaced 16% of the seasonal ET_o through the trial period. This value was strongly influenced by a 100 mm rain event in February 2014, without which mean rainfall would have replaced closer to 10% of the seasonal ET_o. During the growing season, there were inter-treatment differences in the timing and depths of the recycled and non-saline (potable) irrigation waters. Table 18 describes, for each of the three growth stages, the mean volume weighted EC for both irrigation sources and the depths of irrigation, rainfall and ET_o.

Variation in the EC of irrigation water during the BB-PH growth period is attributed to sporadic availability of recycled water and the irrigators' occasional need to supplement recycled wastewater with less saline (~1.2 dS/m) groundwater. The sporadic availability of recycled water through to mid-late September was attributed to SA Water maintenance at the Bolivar DAFF plant and subsequent flushing of the Virginia Pipeline Scheme. The unusually high rain event in February 2014 doubled the mean rain for the H-LD period across the two year assessment period.

Table 18. Mean (±SE) volume weighted EC_W and depths of irrigation, rain and reference crop evapotranspiration through the periods of dormancy (LD-BB) and three growth stages (BB-PH, PH-H, H-LD) in the 2013/14 and 2014/15 irrigation seasons.

	Volume weighted EC_W (dS/m)			Depth (mm)		
Growth Period	**Recycled Water**	**Potable**	**Rain †**	**Irrigation**	**Rain**	**ETo**
LD-BB	n/a	n/a	0.1	0	170 ±27	119 ±12
BB-PH	2.00 ±0.17	0.74 ±0.01	0.1	179 ±25	47 ±34	279 ±14
PH-H	1.91 ±0.01	0.75 ±0.01	0.1	558 ±20	39 ±24	619 ±1
H-LD	1.89 ±0.10	0.76 ±0.01	0.1	166 ±21	108 ±53	334 ±28

† EC of rainfall as per Crosbie et al. (2012)

In treatment A, the slightly to moderately saline recycled water source (denoted saline water, all stages in Figures 24 to 28) accounted for 100% of the annual irrigation volume. In treatments B and D, the recycled water source accounted for approximately 80% of the annual irrigation volume with the balance coming from the non-saline (potable) treatment irrigation applied either BB-PH (treatment B) or H-LD (treatment D). In treatment C, the recycled water source only accounted for 40% of the annual irrigation volume with the balance coming from non-saline potable water applied through growth period PH-H. Treatment E, a demonstration plot, received 100% of the annual irrigation volume from the non-saline potable water source. As a consequence, the annual salt loads were not equal for all treatments. Annual salt loads were calculated as the volume-weighted EC_W for the entire season. This volume-weighted EC_W accounted for the different depths of each water source, including rain, and quantified the average salinity of water received by trees had the same salt load been applied across the entire season. Across the two year assessment period, the mean seasonal volume-weighted EC_W was 1.59 dS/m for treatment A, 1.38 for B, 1.01 for C, 1.42 for D and 0.63 for E, Table 22.

Measures of soil moisture content were collected at a minimum frequency of one reading per month. In combination with in-line irrigation flow meters, the soil moisture data ensured uniformity of irrigation application, both across the whole trial area and between individual treatments. Soil moisture traces, at time-steps equating to the transition point between phenologically distinct growth stages, are depicted for all treatments in Figure 24. Surface soils tended to have more variable wet/dry cycles, reflected by the greater standard error of means. August soil moisture traces show little variation through the profile between replicated treatments. However, the non-replicated treatment E appears to have a greater depletion at 0.4m relative to the others, possibly indicating an earlier commencement of plant water use in this non-saline treatment.

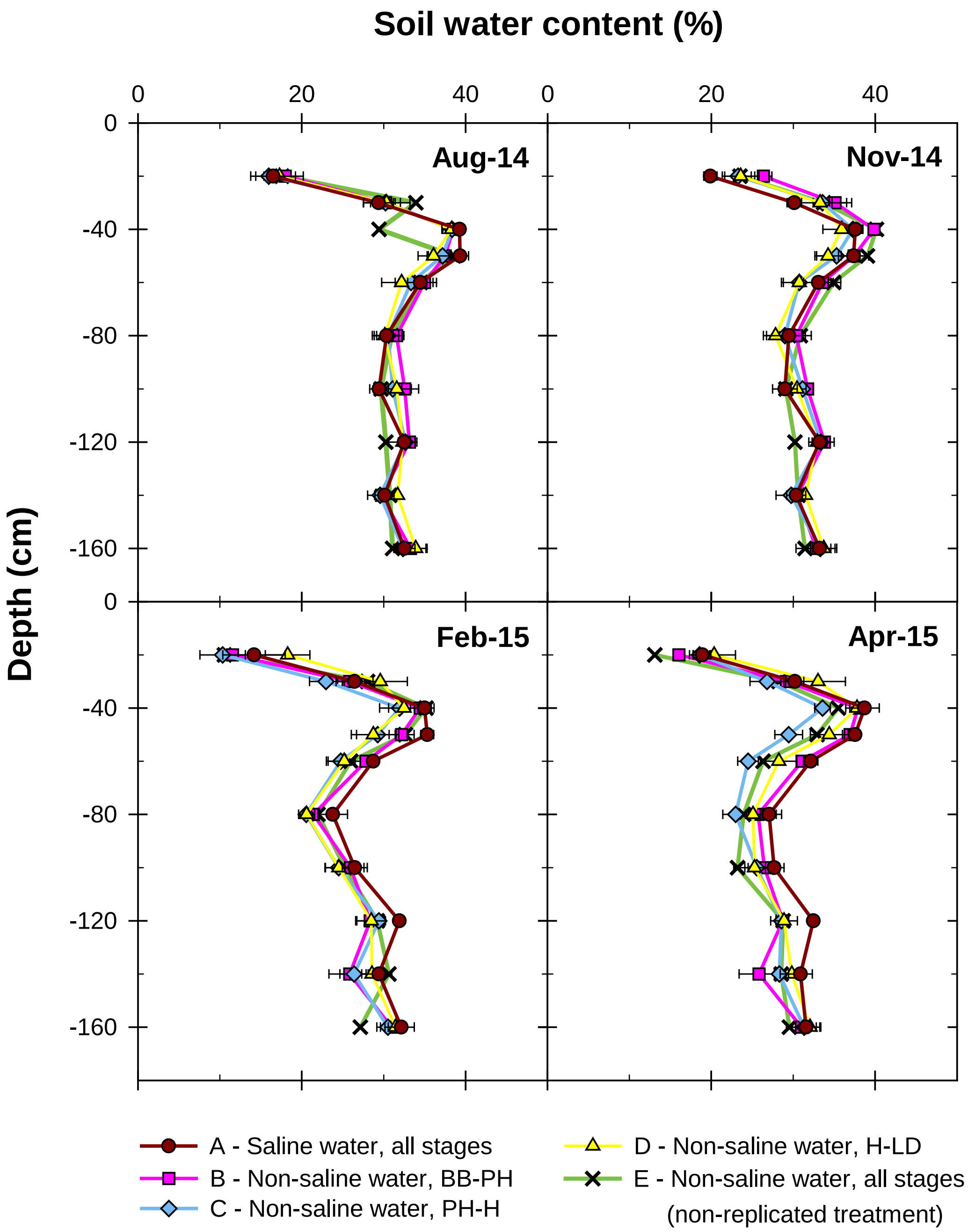


Figure 24. Volumetric soil water content at commencement of 2014/15 irrigation season (Aug-14), at transition between growth stages one and two (Nov-14), at transition between growth stages two and three (Feb-14) and at the end of the 2014/15 irrigation season (Apr-15). Horizontal bars indicate standard errors of means.

In the November (pit hardening) and February (harvest) time-steps, soil moisture traces are equivalent through the deeper soils. This equivalence suggests uniformity in plant water uptake and in irrigation system output for both the recycled and non-saline (potable) irrigation systems. At the final time-step of April 2015, there appears to be a greater depletion in soil moisture at depths of 0.4-0.8 m for treatments C, E and to a lesser extent D relative to the control soils. It is possible that this depletion in soil moisture was due to an extended period of plant water uptake by trees growing in lower salinity soils that faced lower osmotic pressures at the soil root interface and presumably lower ionic stress within the leaf tissues slowing the senescence of older leaves (Munns and Tester, 2008). This supposition is supported by leaf area indexing data (see section 2.3.3) and aligns with soil salinity trends described in Figure 25.

2.3.2 Soil salinity

Soil salinity was measured prior to the commencement of the 2014/15 irrigation season and again at the transition between each of the three phenologically distinct growth stages. Figure 25 shows the changes in soil salinity with depth for each treatment at these time-steps. Through the whole of the 2014/15 season, soils within the non-replicated Treatment E plot received 890 mm of non-saline irrigation water. By the end of the season, the average profile salinity for this demonstration treatment was 29% lower than that of the Treatment A control soils which had received the same depth of irrigation but sourced from recycled wastewater. At each sampling time, salinity trends with depth changed depending on the depth and quality of water that each treatment had received through the preceding growth stage.

In August 2014, following 143 mm of effective winter leaching rainfall, soil salinity values were equivalent across all replicated treatments to a depth of 0.8m, Figure 25. Beyond the majority of roots (1 m), soil salinities became more variable. Average profile salinities of Treatments C and D soils were lower than control soils by 10 and 14% respectively. Much of this difference occurred at depths below 1 m and reflects the previous season's irrigation treatments with Treatment C receiving 578 mm of non-saline water in the middle growth stage and Treatment D receiving 187 mm of non-saline water post-harvest. The non-replicated Treatment E, which received non-saline irrigation throughout the previous season, started the 2014/15 season with average profile salinity 19% lower than control soils, 2.8 and 3.4 dS/m respectively.

Between August and November 2014 (BB-PH), soils received 13 mm of effective rainfall and 207 mm of irrigation. For Treatments B and E, this irrigation was non-saline potable water while Treatments A, C and D received the recycled wastewater. The average profile salinity of Treatment B soils at this time was more than 19% lower than control soils, 3.5 and 4.4 dS/m respectively. Much of this difference was in the surface 0.5 m, Figure 25. In November 2014, average profile salinities for Treatments C and D remained around 10% lower than those for Treatment A. Profile salinity of the non-replicated Treatment E, 3.4 dS/m, was more than 20% lower than that of control soils.

Between November 2014 and February 2015 (PH-H), soils received 62 mm of effective rainfall and 538 mm of irrigation. For Treatments C and E, this irrigation was non-saline potable water while Treatments, A, B and D received the recycled wastewater. The difference in soil salinity between Treatment C and control soils widened through this period with Treatment C being 28% lower, 3.7 and 5.2 dS/m respectively. The salinity of Treatment B remained 20% lower than control soils. While Treatment D salinity was equivalent to controls in the top 0.4-0.5 m, deeper soils were significantly less saline resulting in a 10% lower average profile salinity. Profile salinity of the non-replicated Treatment E, 4.0 dS/m, was more than 20% lower than that of control soils.

Between February and April 2015 (H-LD), soils received 55 mm of effective rain and 145 mm of irrigation. For Treatments D and E, this irrigation was non-saline potable water while Treatments A, B and C received the recycled wastewater. At this point, the average profile salinity of control soils was 5.6 dS/m and the non-replicated Treatment E was 30% lower at 3.9 dS/m. Each of Treatments B, C and D were between 12 and 20% lower in their average salinity. Figure 25 shows that Treatment A, control, continued to accumulate salts in the surface soils, more than 7.5 dS/m at 0.4 m depth while Treatment C was less than 3.4 dS/m at the same depth.

The rapid accumulation of soil salts through the irrigation season, and the sustained salt pressure at depth through the winter period, suggest that the leaching fraction of the existing irrigation schedule was insufficient. Whilst winter rains appear to bring surface soils below the 1.5 dS/m vigour decline threshold for almonds, they do little for the salinity of soils deeper than 0.5-0.6 m. It is arguable that the irrigation schedule should be adjusted to accommodate additional depths of irrigation, a leaching fraction, within the growing season to facilitate the removal of salts from the rootzone. Applying a supplementary leaching irrigation coinciding with the winter rainfall period is most likely to maximise salt displacement from the rootzone with minimum drainage volume (Cook et al., 2006).

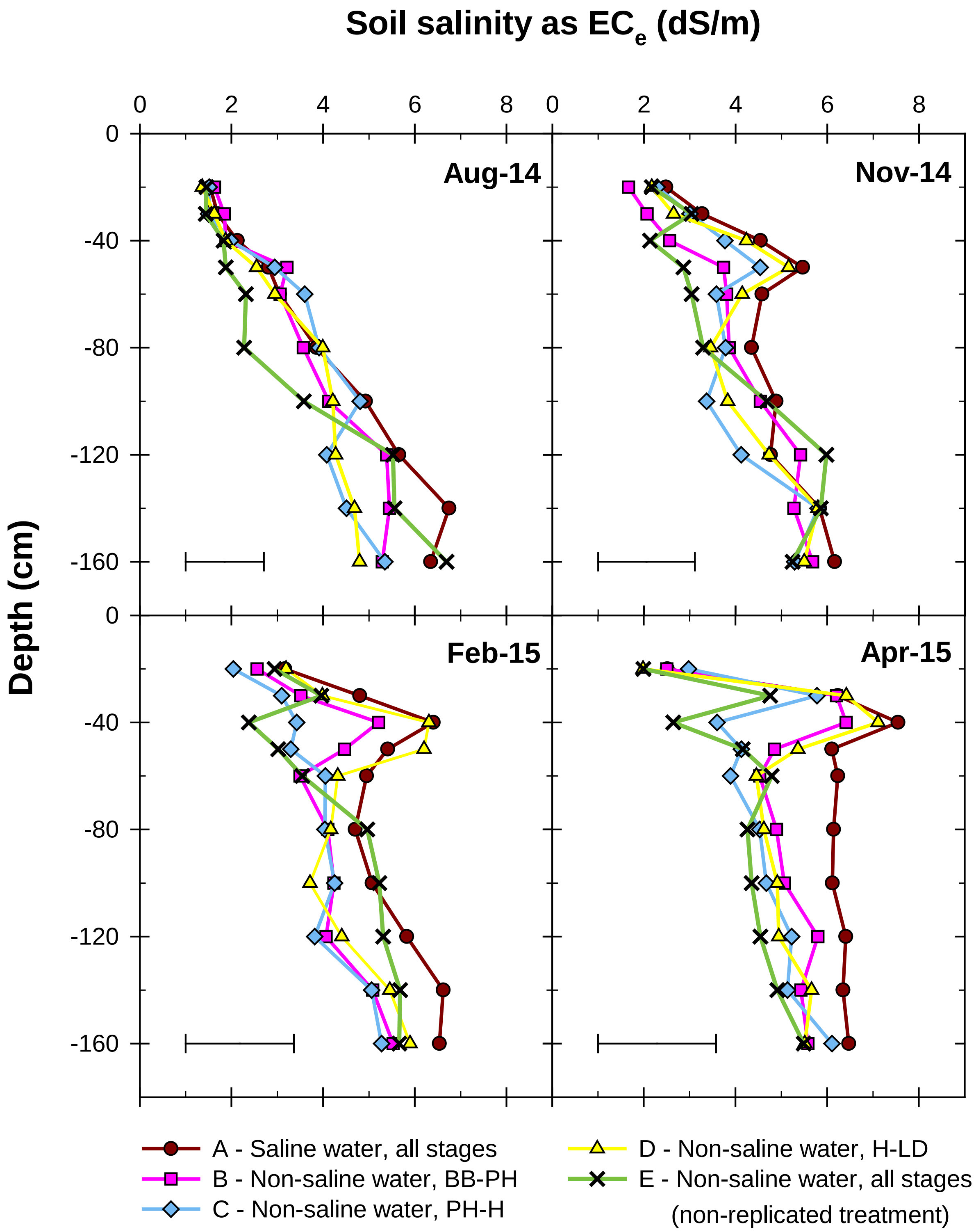


Figure 25. The effect of depth and treatment (timing of exposure to different irrigation qualities) on soil salinity (EC_e). Data are geometric means, horizontal bars represent l.s.d (*P*=0.05).

2.3.3 Canopy size by Leaf Area Index

Periodic measures of canopy development were monitored using Leaf Area Index (LAI) commencing just prior to harvest in 2014 and then collected at the transition between each of the three target growth stages, Figure 26. While treatments did not differentiate through the period of this investigation, there was general agreement between LAI values and the physical development of the canopy as the season progressed. For example, the reduction in LAI between February and April 2014 related to leaf loss, initiated by the shaking operation of harvest and compounded by canopy progression through to senescence, late April/early May.

In 2014/15, LAI values were higher than the same time in the previous year but remained equivalent across treatments. Increases in LAI between November 2014 and February 2015 reflected the emergence and development of shoots following pit-hardening and continued canopy filling through to harvest. It is not uncommon for partial defoliation through the harvest operation. However, it is likely that upgraded harvest equipment in the 2014/15 season increased the level of defoliation during the 2015 harvest. This will have contributed to the April 2015 measures.

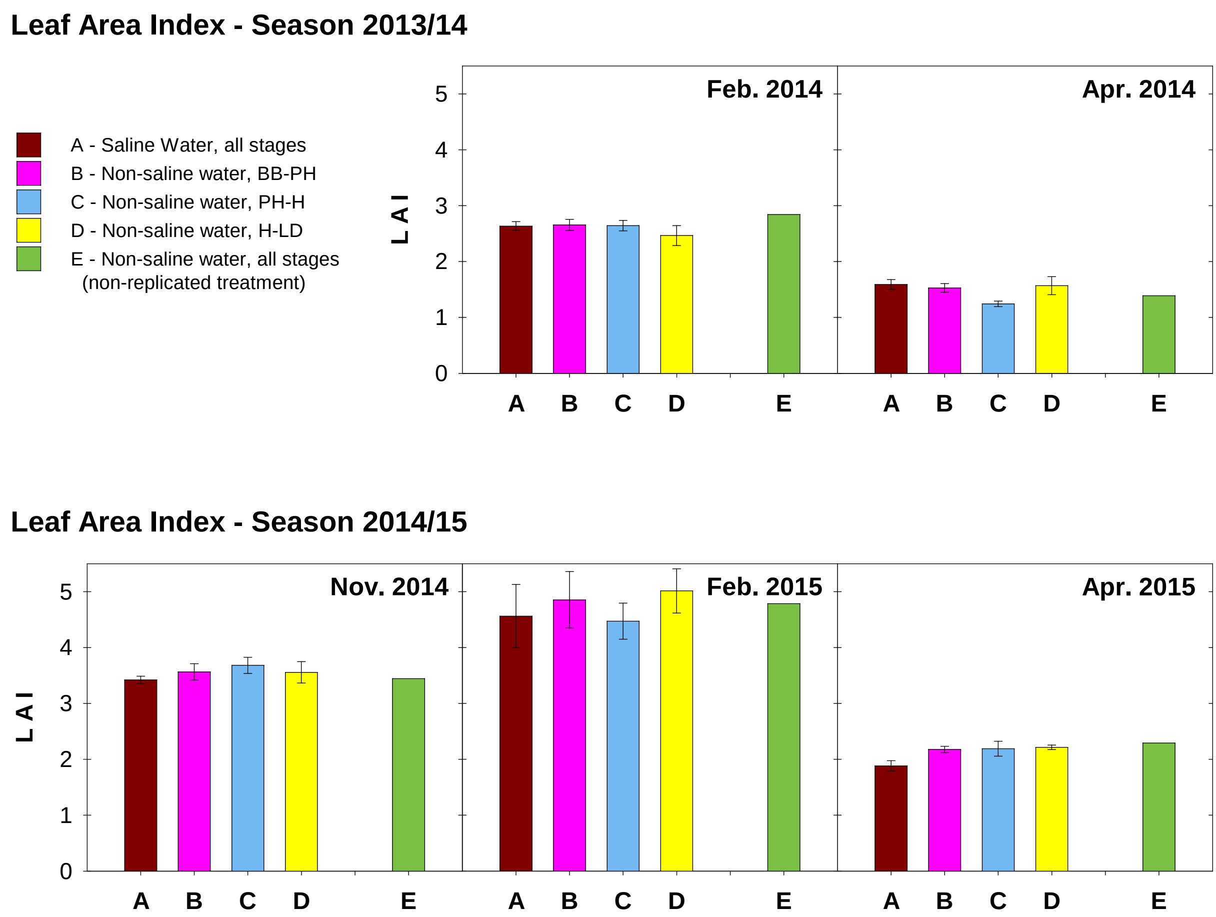


Figure 26. The effects of salinity treatments on the Leaf Area Index (LAI) following growth stages within the 2014 and 2015 seasons. Vertical bars represent standard errors of means.

LAI in April 2015 characterised canopy size in the approach to senescence. While treatment effects were not significant, LAI values for control trees did trend lower than for other treatments. Any difference in the extent and timing of defoliation at this time would impact upon the following year's crop as there would be fewer resources available for the processes of flower bud initiation and development.

2.3.4 Changes in plant water relations and leaf gas exchange

Midday stem water potentials (Ψ_{MD}) were measured through both the 2014 and 2015 irrigation seasons. Towards the end of the first growth stage in 2013/14, the Ψ_{MD} for all trees was equivalent at -0.56 MPa, Figure 27. As evaporative demands increased through the season, the Ψ_{MD} of all treatments began to decline but showed little separation until hot and dry conditions presented in December 2013 and January 2014. At this point, average Ψ_{MD} reduced to around -1.4 MPa with trees that had received the non-saline irrigation water in the BB-PH and PH-H growth stages trending slightly higher (less stressed). As part of normal orchard operations, irrigations were withheld through the harvest period. To condition trees for this short period of water deficit, a deep irrigation event was scheduled in the days leading up to harvest. On 5 February 2014, one day ahead of the pre-harvest irrigation event, and following an extended period of high evaporative conditions, plant average Ψ_{MD} declined rapidly to -2.6 MPa. Even at this level of stress, treatments did not differentiate. However, both Treatments C and E were trending higher than control trees. The rapid recovery of Ψ_{MD} following the harvest period was largely related to the resumption of irrigation and an unseasonably high rainfall event in mid-February 2014, ~100 mm over 48 hr. Ψ_{MD} continued to decline through to the end of the season with no significant differentiation between treatments.

The 2014/15 season followed a similar pattern to that of the previous year, Figure 27. The non-replicated, Treatment E, plot was trending to be the least stressed group of trees with average Ψ_{MD} around 17% higher than that of control trees. Treatment C trees were also more discernible in their difference to controls but these effects were not yet significant.

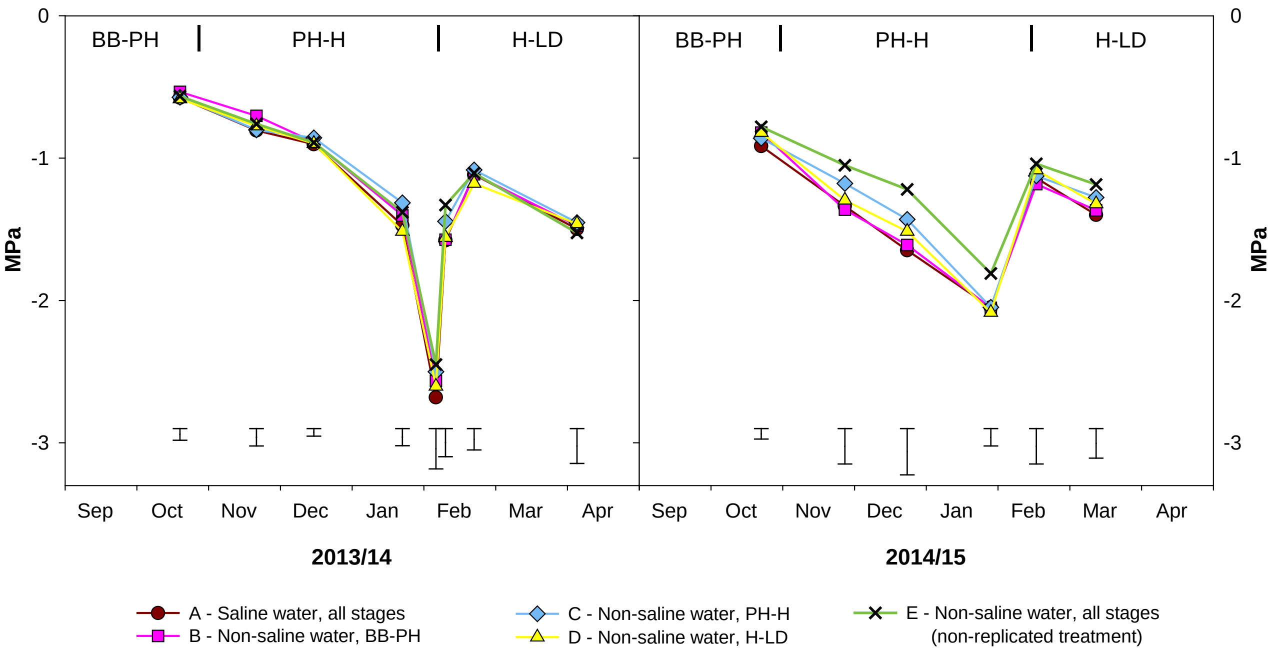


Figure 27. Stem water potential for treatments during 2013/14 and 2014/15 irrigation seasons. Vertical bars indicate l.s.d. (*P*<0.05).

In both seasons, plant water relations and leaf gas exchange were measured a day in advance of the mechanical harvest operation. The afternoon value of vapour pressure deficit (VPD) was 4.13 kPa in 2014 and 1.66 kPa in 2015. In 2014, Treatment C plots expressed a higher photosynthetic rate (A) and greater stomatal conductance (g) than control trees although there was no corresponding changes with either pre-dawn (Ψ_{PD}) or midday (Ψ_{MD}) stem water potentials nor did differences in A and g persist into the following season, Table 19. It is arguable that a more frequent sampling regime is required for A and g to account for the variability associated with the measures relative to Ψ_{MD}. Increasing the intensity of leaf gas exchange measures through the coming seasons, to match that of Ψ_{MD}, would increase the validity of the measure.

Table 19. The effect and significance† of salinity treatments on photosynthetic rate (A, µmol $CO_2/m^2.s$), stomatal conductance (g, mol $H_2O/m^2.s$) and pre-dawn and midday stem water potentials (Ψ_{PD} and Ψ_{MD}, respectively, MPa) measured prior to harvest, February 2014 and 2015.

Parameter		Treatment				*LSD*	
		A	B	C	D	*(A-D)*	E ‡
A	2014	12.4	13.5	**16.7***	14.4	*3.49*	15.1
	2015	15.0	14.1	17.4	14.7	*4.90*	14.5
g	2014	0.111	0.136	**0.185***	0.148	*0.052*	0.169
	2015	0.107	0.133	0.169	0.131	*0.073*	0.199
Ψ_{PD}	2014	-0.75	-0.75	-0.77	-0.76	*0.090*	-0.68
	2015	-0.65	-0.67	-0.66	-0.67	*0.093*	-0.69
Ψ_{MD}	2014	-1.64	-1.36	-1.54	-1.58	*0.376*	-1.49
	2015	-1.10	-1.16	-1.12	-1.06	*0.453*	-1.26

† * <0.05, ** <0.01, *** <0.001
‡ Non-replicated demonstration plot

2.3.5 Changes in yield components

During the period of investigations, yields averaged just over 2 tonnes of kernel per hectare. This is significantly lower than the industry average of around 3.2 tonnes per hectare (ABA, 2015) and is likely related to a combination of factors including, but not limited to, long term exposure to the salinity stress.

Pre-trial measures of yield components were collected in 2013 with trees producing yields of 10 kg of kernel/tree at an average piece weight of 1.26 g/kernel. These data were incorporated in covariate analysis of both the 2014 and 2015 yield and kernel weight measures, Figure 28. 2014 yields averaged around 7.6 kg of kernel/tree, 25% lower than the previous season and 11% lower than the subsequent 2015 season. The reduced yield in 2014 was most likely related to persistent wet and cool conditions that prevailed through the 2013/14 pollination period. The spring of 2014/15 was more conducive to pollination and saw a corresponding increase in the 2015 yield, averaging 8.6 kg kernel/tree.

Although salinity treatments were applied for two complete irrigation seasons, the short time-frame of this investigation meant that it was only the 2015 season where both the pre-harvest and post-harvest salinity treatments had relevance for yield. This is due to almond yield, a product of both kernel weight and fruit count, being influenced by conditions in both the preceding and current seasons. Post-harvest irrigation treatments, following the 2014 harvest, will have coincided with the flower bud development growth stage and, presumably, will have impacted upon the fruit count component of 2015's yield potential in terms of number of viable flower buds.

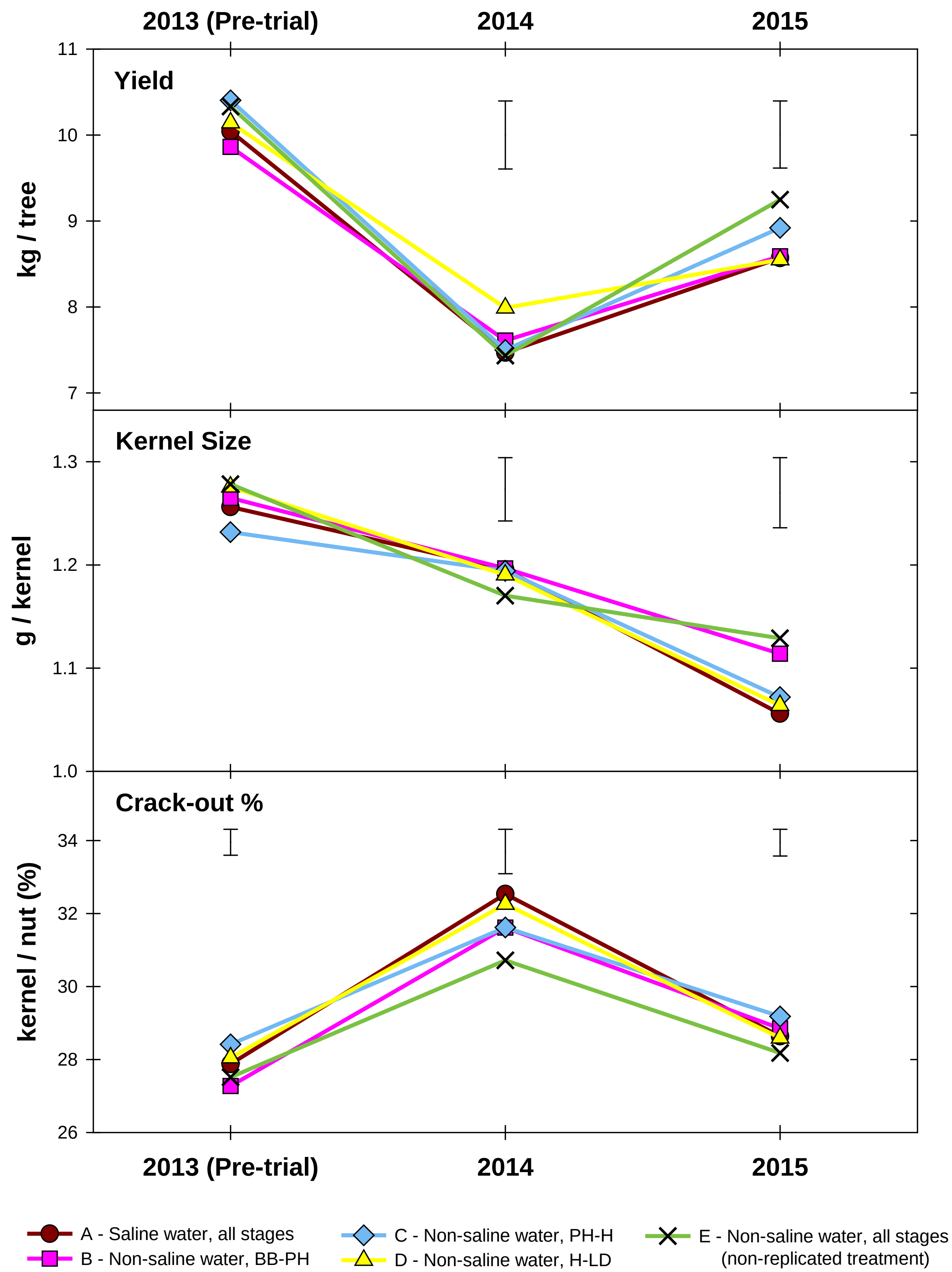


Figure 28. Covariate adjusted tree yield (kg/tree) and kernel weight (g) in 2014 and 2015 against pre-trial data. Unadjusted percent crack-out (kernel/nut) from 2013-2015. Vertical bars represent l.s.d (*P*=0.05).

Pre-harvest irrigation treatments, between September 2014 and January 2015, will have contributed towards vegetative growth and the accumulation of kernel, hull and shell dry matter in the 2015 season.

2015 yield assessments did not elicit a significant yield or kernel size response to the timing of reduced salt pressure, Figure 28 and Table 20. Minimal yield response within the first year/s of this type of investigation is not unique. Previous almond studies have suggested that yield components can be relatively insensitive to a stress in the first years of exposure and that residual effects tend to present in the subsequent years (Goldhamer and Smith, 1995). Similar investigations assessing the timing of salt stress on Colombard grapes also found negligible yield response early in the life of the trial but that differences increased with time (Stevens et al., 1999). If yields within the current trial are to respond to salinity treatments, it is likely that change will occur once treatment carryover effects have intensified from preceding years.

In 2015, trees irrigated with the non-saline water source at all growth stages, non-replicated Treatment E, trended 7% higher in yield and kernel size relative to trees irrigated with the recycled wastewater, Figure 28 and Table 20. Statistical analysis suggests that greater differentiation is required (by adding future seasons data) before the result from Treatment E could be considered real, with any level of confidence.

Table 20. The effect and significance† of salinity treatments on yield (kg/tree), kernel dry weight (g) and the ratio of kernel to whole nut (Crack-out %) from seasons 2013-2015.

Parameter		**Treatment**				***LSD***	
		A	**B**	**C**	**D**	*(A-D)*	**E ‡**
Yield	2013	10.04	9.86	10.40	10.14		10.33
	2014	7.47	7.61	7.50	7.99	*0.79*	7.44
	2015	8.57	8.59	8.92	8.55	*0.78*	9.25
Kernel dry wt.	2013	1.26	1.27	1.23	1.28		1.28
	2014	1.20	1.20	1.19	1.19	*0.06*	1.17
	2015	1.06	1.11	1.07	1.06	*0.07*	1.13
Crack-out	2013	27.9	27.3	28.4	28.1	*0.71*	27.5
	2014	32.5	31.6	31.6	32.3	*1.22*	30.7
	2015	28.6	28.9	29.2	28.6	*0.73*	28.2

† * <0.05, ** <0.01, *** <0.001

‡ Non-replicated demonstration plot

Whilst not significant, there is also a suggestion of yield change with Treatment C trees in 2015. Of the replicated salinity treatments, it was Treatment C that faced the lowest salinity pressure during the 2014 flower bud development stage. In February 2014 the average profile salinity for these plots was 4.3 dS/m, more than 16% lower than that of controls, and it remained 10% lower than control soils through to leaf drop (data not shown). In January 2015, the difference in average soil salinity doubled to 30% with average soil salinity for Treatments C and A at 3.8 and 5.4 dS/m respectively. This suggests Treatment C was facing lower stress around the flower bud development stage. If Treatment C's trend for increased yield despite smaller kernel size persists in coming seasons, it would point to an increased fruit count relative to controls. Such a response would align with observations reported by studies into the timing of water deficit stress.

Various studies have tested the sensitivity of different almond growth stages to water deficit stress (Goldhamer et al., 2006; Klein et al., 2001; Sommer, 2012). A recurring theme has been that almonds tend to adapt more readily to receiving water deficits when biased towards early in the season. Although kernel size has been shown to be dependent upon pre-harvest water deficits, the greater decline in productivity comes from applying the water stress post-harvest. Goldhamer and Viveros (2000) proposed that this post-harvest stress modified flower bud development, impacting upon primordial flower parts, altering stamen emergence and ultimately decreasing flower receptivity to pollination.

Percentage crack-out is the ratio of kernel dry weight relative to that of the whole fruit (kernel, shell and husk). Water deficit investigations have found little response in crack-out percentage when the restrictions are applied evenly across the season (Romero et al., 2004; Egea et al., 2010). However, once a timing factor is introduced, crack-out percentage appears to become a more sensitive indicator of the stress (Goldhamer et al., 2006), in some cases, a more sensitive indicator than kernel weight alone (Sommer, 2012). In the current investigation, crack-out percentage was determined following each year's harvest, Figure 28 and Table 20. The pre-trial crack-out percentage for Treatment B trees was significantly lower than that of Treatments C and D, but analysis showed no influence of these differences upon subsequent year's assessments. While separate analysis of the 2014 and 2015 crack-out percentages showed no within season differences, analysis of the two-year average against pre-trial values, measured in 2013, showed a lower reduction in the crack-out percentage of Treatments C and E relative to that of Treatments A and D ($P<0.05$). Both Treatments A and D were exposed to higher pre-harvest salt loads than Treatments C and E and were presumably facing greater soil osmotic pressures as well as being more prone to leaf toxicity issues through the early growth stages. Higher leaf tissue concentrations of both Na^+ and Cl^- were observed for both Treatments A and D and are discussed in section 2.3.6. The reduced crack-out percentages from these trees would suggest that their kernel growth had slowed relative to that of the husk and shell, an observation that aligns with findings from timing of water deficit investigations where trees subjected to stress early in the production season saw reduced kernel growth, within that same season, relative to the accumulation of weight in the hull and shell components of the fruit (Goldhamer et al., 2006; Sommer, 2012).

2.3.6 Variations in leaf sodium and chloride contents

In the weeks approaching the 2013 harvest, before experimental treatments had been established, leaf samples were collected from across the proposed trial site for analysis of ionic composition. At that time, leaf samples reported Na^+ and Cl^- concentrations at 0.4 and 2.1 % respectively. These concentrations far exceeded levels indicative of salinity pressure sufficient to reduce shoot growth, 0.25% (d.w.) for Na^+ and 0.3% (d.w.) for Cl^- (Robinson et al., 1997) and were well above levels typically reported by industry. For example, the Almond Board of Australia (2011) reported Na^+ and Cl^- concentrations of around 0.07 and 0.33% respectively in their Sustainable Optimisation project. Furthermore, a recently reported rootstock study in California, irrigated with sodium dominated saline groundwater, reported leaf ionic concentrations ranging between 0.04 and 0.4% for Na^+ and between 0.02 and 0.14% for Cl^-, depending which rootstock trees had been grafted to (Doll et al., 2014). At the commencement of investigations, trees within the current study were facing significantly higher and sustained salinity pressure relative to the wider Australian and international industries.

Following treatment installation, leaf tissue samples were collected at distinct growth stages through the 2014 and 2015 irrigation seasons. These data were adjusted for the pre-trial condition by incorporating 2013 data in covariate analysis. Sampling at the 2014 pit-hardening growth stage was unintentionally overlooked.

Table 21 presents the progression of change in concentrations of Na^+ and Cl^- in leaves sampled at distinct growth stages through the 2014 and 2015 irrigation seasons. In general, the concentrations of Na^+ and Cl^- increased at each time-step within a season, irrespective of treatment. The one exception being the non-replicated Treatment E plot whose Cl^- concentrations decreased between the Harvest (1.03%) and Leaf drop (0.79%) sampling times. While this reduction is likely an artefact of poor replication of this single demonstration plot, it is worth noting that in February 2014, directly following the Harvest sampling time, the site received 100 mm of rainfall over a 48 hour period. This rain event may have intensified the observed differences in Cl^- concentrations, but it can't be ignored that a similar response did not occur with any of the replicated treatments.

Non-saline irrigation water decreased the Na^+ and Cl^-concentrations of both the Treatment B and C trees to levels below control trees. This change occurred within the first season of treatment application and persisted into the 2015 season, Table 21.

Table 21. The effect and significance† of salinity treatments on the concentrations of Na^+ and Cl^- in the leaf (% d.w.) following three growth stages in the 2014 and 2015 irrigation seasons.

Parameter			Treatment				*LSD*	
			A	B	C	D	*(A-D)*	E ‡
Leaf Na^+								
	2014	Pit-hardening	-	-	-	-		-
		Harvest	0.362	**0.259***	**0.176*****	0.325	*0.085*	0.209
		Leaf drop	0.448	**0.393***	**0.198*****	0.405	*0.117*	0.290
	2015	Pit-hardening	0.128	**0.102***	**0.069*****	**0.086****	*0.020*	0.066
		Harvest	0.333	**0.204****	**0.132*****	0.292	*0.074*	0.135
		Leaf drop	0.700	0.626	**0.365*****	0.747	*0.148*	0.314
Leaf Cl^-								
	2014	Pit-hardening	-	-	-	-		-
		Harvest	1.94	**1.59*****	**0.87*****	**1.72***	*0.20*	1.03
		Leaf drop	2.27	**1.80****	**0.91*****	**1.79****	*0.24*	0.79
	2015	Pit-hardening	0.64	**0.44****	**0.48****	0.57	*0.10*	0.30
		Harvest	1.75	**1.19***	**0.86*****	1.46	*0.43*	0.53
		Leaf drop	2.77	2.58	**1.71*****	2.60	*0.25*	1.39

† * <0.05, ** <0.01, *** <0.001
‡ Non-replicated demonstration plot

Treatment B trees received the non-saline water early in the growing season, BB-PH, and their average Na^+ concentrations were 33% lower than controls at the harvest sampling, and remained more than 10% lower by the end of the each irrigation season (P<0.05). Average Cl^- concentrations were 25% lower than controls just prior to harvest and remained more than 13% lower by the end of each irrigation season (P<0.01). In the lowest salt load treatment, Treatment C, the non-saline water was applied PH-H and halved the concentration of Na^+ in the leaf at each of the sampling times and reduced leaf Cl^-

concentrations by more than 40% through the period of investigation (*P*<0.001). This rapid and significant effect brought leaf Na^+ concentrations in both Treatments B and C below levels indicative of salinity pressure; 0.25% (d.w.) as measured in the weeks approaching harvest. Whilst Cl^- concentrations had significantly reduced in both Treatments B and C, levels remained well above the 0.3% (d.w.) toxicity threshold.

Treatment D trees were irrigated with the non-saline water source post-harvest (H-LD). The 33% differentiation in leaf Na^+ at the 2015 pit-hardening sampling time was most likely a reflection of timing, late the previous season, rather than extent, of the treatment's reduced salt load. At other sampling times, Na^+ concentrations of Treatment D were equivalent to controls. Cl^- concentrations of Treatment D followed a similar pattern to that of Na^+, although differences at the 2014 harvest sampling point are not easily explained. At that time, both Treatment D and control trees had received exactly the same irrigation treatments and would be expected to be equivalent. Whilst the significance of this difference is marginal, it adds weight to the argument for continued assessment at the site to elicit dependable treatment effects.

Following the 2014 irrigation season, concentrations of Na^+ and Cl^- reflected the effects of exposure to non-saline irrigation, both in the season of measurement and in the previous season. For example, at the sampling time of pit-hardening in 2015, Treatment C and D trees had not yet received non-saline irrigation for that season. Reductions in leaf tissue Na^+ and Cl^- reported at that time were caused by the non-saline irrigation treatments of the previous season.

2.3.7 Characterising the effect of timing

Any effect on tree performance caused by the application of non-saline water into the saline growing environment would have been influenced by inter-treatment differences in salt loads and the timing when those reduced salt loads were applied. Table 23 attempts to focus on the effect of timing by normalising the response of certain parameters with regard to the volume weighted EC of irrigation and rain water (EC_W) received by the trees, as per Stevens et al. (2011). For each treatment, annual salt loads were calculated as the volume-weighted EC_W for the entire season. This volume-weighted EC_W accounted for the different depths of each water source (recycled wastewater, non-saline potable water and rainfall) and quantified the average salinity of water received by trees across the entire season. Table 22 shows the mean seasonal volume-weighted EC_W's across the two year assessment period.

The normalised response (method 2.2.9) of yield and end of season leaf components to different timings of non-saline irrigation are shown in Table 23 alongside the raw data of control trees. The normalised data highlights the influence of timing on parameter response.

Section 2.3.5 showed that yields from non-saline irrigation treatments did not significantly differentiate from controls. However, presenting proportional yield changes against those in volume weighted ECW does suggest that timing of salt load may be influencing the yield response and that continued monitoring may yet elicit a significant yield response, viz., the increase in yield per dS/m reduction in salt load during H-LD is more than twice that when salt load is reduced at BB-PH and more than three times that when salt load is reduced at PH-H.

Table 22. Mean volume weighted salt load (EC_W) through the 2014 and 2015 irrigation seasons.

Treatment†		Mean seasonal volume-weighted EC_W (dS/m)
A	Recycled irrigation all season	1.59
B	Non-saline irrigation from BB-PH	1.38
C	Non-saline irrigation from PH-H	1.01
D	Non-saline irrigation from H-LD	1.42
E	Non-saline irrigation all season	0.63

† BB = Bud Burst; PH = Pit-Hardening; H = Harvest; LD = Leaf Drop

Table 23. Mean EC_W, yield components and leaf ionic composition for control trees; plus the volume weighted change in salt load relative to control (ΔEC_W) and normalised response of parameters to introducing the non-saline irrigation at different growth stages. Mean data for two seasons normalised to remove inter-treatment variation in the annual salt load.

Parameter	**Control** (RW all season)	**Change from control**	**Normalised response to timing of non-saline irrigation †**			
			BB-PH	**PH-H**	**H-LD**	**All Season ‡**
Volume weighted salt load EC_W (dS/m)	1.59	ΔEC_W	-0.21	-0.58	-0.17	-0.96
Yield (kg/tree)	8.0	ΔYield / ΔEC_W	0.51	0.32	1.24	0.32
Kernel size (g)	1.13	ΔKernel / ΔEC_W	0.09	0.00	-0.03	0.02
§Leaf Na^+ % (d.w.)	0.59	$\Delta Na^+ / \Delta EC_W$	-0.32	-0.50	-0.05	-0.28
§Leaf Cl^- % (d.w.)	2.51	$\Delta Cl^- / \Delta EC_W$	-1.95	-2.09	-1.80	-1.49

† Non-saline irrigation applied at different growth stages; between Bud Burst and Pit-Hardening (BB-PH), between Pit-Hardening and Harvest (PH-H), between Harvest and Leaf Drop (H-LD) and through the whole season.
‡ Non-replicated demonstration plot
§ Leaf sampled at end of growing season (April)

In contrast to yield, the late season leaf tissue concentrations of Na^+ and Cl^- appear to have more favourable response to reduced salt loads earlier in the season. Na^+, in particular, is more responsive to pre-harvest reductions in salt load. For every dS/m reduction in salt load applied prior to harvest, leaf tissue concentrations of Na^+ reduced between 0.32 and 0.5% (d.w.) as opposed to only 0.05% (d.w.) reduction for the same reduction in salt load applied late in the season.

Continued monitoring of plant tissue and crop response over the coming seasons is required to better define these early trends and identify the most critical sensitivities for sustained productivity under saline growing conditions.

2.4 Conclusion

Substituting non-saline water for the recycled wastewater reduced the salt content of leaves and its effect was dependent on of the growth stage in which it was applied. On average, pre-harvest reductions in salt load affected a 31% reduction in leaf concentrations of sodium and chloride relative to those exposed to post-harvest reductions in salt load. Normalising plant tissue response, for inter-treatment differences in the seasonal salt load, isolated the effects of timing and showed that sodium and chloride uptake was most receptive to reduced salt load between pit-hardening and harvest and that sodium uptake was particularly insensitive to post-harvest reductions in salt load.

This means that where saline conditions are expected and an opportunity exists to time the application of a non-saline water source, it should be applied during leaf emergence and canopy development (pre-harvest) in order to minimise the expression of salt in the leaf.

Yield response was less sensitive to the timing of reduced salt load and did not differentiate during the period of investigation. Instead the study showed no dis-benefits with using recycled water over the short term. However, we cannot say that this holds over the long term as the treatment carryover effects may intensify. Investigations will continue into 2017 to test this contention. It is also possible that the nutrients and trace elements may be acting beneficially to mask possible impacts of salt content.

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Appendix A – Communication

Industry and Peer Reviewed Articles

Stevens, R.M and Pitt, T.R. (2012). *Removing vine soil mounding is first step to redirecting beneficial rainfall.* Australian and New Zealand Grapegrower and Winemaker 584: 69 [From NPSI Proof of Concept Project].

Stevens, R.M., Pitt, T.R. and Dyson, C. (2013). *Changes in vineyard floor management reduce the Na^+ and Cl^- concentrations in wine grapes grown with saline supplementary drip irrigation.* Agricultural Water Management 129(0): 130-137 [From NPSI Proof of Concept Project].

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Pitt T.R. (2012). *Redirecting rainfall reduces juice sodium by 26% and juice chloride by 41%* (oral). Crush Grape and Wine Science Symposium, Adelaide, South Australia, November 2012.

Pitt, T.R., Stevens, R.M., Dyson, C., Cox, J.W. and McCarthy, M.G (2013). *Can rainfall harvesting reduce soil salinity and increase the appeal of recycled wastewater for irrigation?* (poster and oral). 15th Australian Wine Industry Technical Conference, 13-18 July, 2013, Sydney, Australia.

Pitt, T.R., Stevens, R.M. and Cox, J.W. (2013). *Almonds: Which growth stage is most sensitive to salinity?* (Poster). 15th Australian Almond Conference, 29-31 October, 2013, Glenelg, Australia.

Alcoe, D., Pitt, T., Osti, A. and Green, G. (2014). *Building adaptive capacity in Adelaide's foodbowl – climate change in the Northern Adelaide Plains and implications for horticulture* (oral). NRM Science Conference, 15 May, 2014, Adelaide, Australia

Pitt, T.R., Stevens, R.M., Cox, J.W. and McCarthy, M.G. (2014). *Redirecting rain to manage soil salinity: lessons from groundwater and recycled wastewater irrigated vineyards* (oral). Irrigation Australia Conference, 2-6 June, 2014, Gold Coast, Australia

Pitt, T.R., Stevens, R.M. and Cox, J.W. (2014). *Almonds and recycled wastewater: avoiding salt pressure during critical growth stages* (oral). Irrigation Australia Conference, 2-6 June, 2014, Gold Coast, Australia.

Pitt, T.R., Stevens, R.M. and Cox, J.W. (2014). *Almond sensitivity to salt stress at different growth stages* (oral). 16th Australian Almond Conference, 28-30 October, 2014, Glenelg, Australia

Pitt, T.R., Stevens, R.M. and Cox, J.W. (2015*). New strategies for managing irrigation induced salinity in perennial horticulture* (oral). Goyder Institute Annual Conference, Water Research Showcase. 17-18 February 2015, Adelaide, Australia.

Pitt, T.R., Stevens, R.M. and Cox, J.W. (2015). *Progressing salinity management strategies in recycled wastewater irrigation districts* (oral). Goyder Seminar Series. 18 June 2015, Adelaide, Australia.

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Cox, J.W., Pitt, T.R., and Stevens, R.M. (2012). *Methods to increase the use of recycled wastewater in irrigation by overcoming the constraint of soil salinity*. AWRCoE Project Leaders' Workshop, September, 2012, Brisbane, Australia.

Pitt, T.R. (2013). *Monitor and Manage, An introduction to SARDI's salinity research*. McLaren regional salinity workshop 'Salt – Soil, Vine, Grape & Wine', 30 Apr. 2013, McLaren Vale, Australia.

Pitt, T.R., Cox, J.W., and McCarthy, M.G. (2013). *Recycled water and salinity*. Goyder Institute Science Retreat, 3 June, 2013, Victor Harbor, Australia

Pitt, T., Cox, J. and McCarthy, M.G. (2013). *Identifying the salt sensitivity of different almond growth stages.* Almond Board of Australia Northern Adelaide Plains Grower Workshop, 4 June, 2013, Virginia, Australia.

Pitt, T. (2013). *Recycled water and salinity*. Treasury Wines Estates technical workshop, 1 July, 2013, McLaren Vale, Australia.

Pitt, T.R., Stevens, R.M., Dyson, C., Cox, J.W. and McCarthy, M.G. (2013). *Rainfall redirection for managing soil salinity in the vineyard.* Australian Wine Research Institute Roadshow, 3 September, 2013, McLaren Vale, Australia.

Cox, J.W., Pitt, T.R. and Stevens, R.M. (2013). *Increasing Recycled Water in Irrigation*. Australian Water Recycling Centre of Excellence Project Leaders Workshop, 5 Sep. 2013, Brisbane, Australia.

Pitt, T., Cox, J. and McCarthy. M. (2013). *Irrigation – recycled water and salinity*. Goyder Institute Annual Water Forum, 15 October, 2013, Adelaide, Australia.

Pitt, T.R. (2013). Almond Board of Australia R&D Project Development Workshop, October 2013, Adelaide, Australia

Pitt, T., Cox, J. and McCarthy, M.G. (2014). *Almond sensitivity to salt stress at different growth stages.* Almond Board of Australia Northern Adelaide Plains Grower Workshop, 11 December 2014, Virginia, Australia.

Pitt, T., Cox, J. and McCarthy. M. (2015). *Irrigation – recycled water and salinity*. Presentation to SA Water's Recycled Water and Business Development groups. 26 February 2015, Adelaide, Australia.

Milestone Reports & Project Advisory Committee Meetings

AWRCOE / SARDI Project 3145 – PAC Meeting #1. Urrbrae, South Australia, 18 December 2012

Minutes distributed December 2012

Cox, J.W., and Pitt, T.R. (2012). Goyder Project I.1.3, Recycled Water & Salinity. Progress report to Goyder Institute, Oct-Dec 2012

Cox, J.W., and Pitt, T.R. (2013). Goyder Project I.1.3, Recycled Water & Salinity. Progress report to Goyder Institute, Jan-Mar 2013

Cox, J.W., and Pitt, T.R. (2013). AWRCOE Project 3145, Increasing recycled water in irrigation. Progress Report 1, 31 May 2013

AWRCOE / SARDI Project 3145 – PAC Meeting #2. Urrbrae, South Australia, 7 June 2013

Minutes distributed June 2013

Cox, J.W., and Pitt, T.R. (2013). Goyder Project I.1.3, Recycled Water & Salinity. Progress report to Goyder Institute, Apr-Jun 2013

Cox, J.W., and Pitt, T.R. (2013). Goyder Project I.1.3, Recycled Water & Salinity. Progress report to Goyder Institute, Jul-Sep 2013

Cox, J.W., and Pitt, T.R. (2013). AWRCOE Project 3145, Increasing recycled water in irrigation. Progress Report 2, 30 November 2013

Cox, J.W., and Pitt, T.R. (2013). Goyder Project I.1.3, Recycled Water & Salinity. Progress report to Goyder Institute, Oct-Dec 2013

AWRCOE / SARDI Project 3145 – PAC Meeting #3. Urrbrae, South Australia, 7 February 2014

Minutes distributed February 2014

Cox, J.W., and Pitt, T.R. (2014). Goyder Project I.1.3, Recycled Water & Salinity. Progress report to Goyder Institute, Jan-Mar 2014

Cox, J.W., and Pitt, T.R. (2014). AWRCOE Project 3145, Increasing recycled water in irrigation. Progress Report 3, 31 May 2014

AWRCOE / SARDI Project 3145 – PAC Meeting #4. Urrbrae, South Australia, 20 June 2014

Minutes distributed June 2014

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Cox, J.W., and Pitt, T.R. (2014). Goyder Project I.1.3, Recycled Water & Salinity. Progress report to Goyder Institute, Jul-Sep 2014

Cox, J.W., and Pitt, T.R. (2014). AWRCOE Project 3145, Increasing recycled water in irrigation. Progress Report 4, 30 November 2014

AWRCOE / SARDI Project 3145 – PAC Meeting #5. Urrbrae, South Australia, 25 November 2014

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Cox, J.W., and Pitt, T.R. (2014). Goyder Project I.1.3, Recycled Water & Salinity. Progress report to Goyder Institute, Oct-Dec 2014

Cox, J.W., and Pitt, T.R. (2015). Goyder Project I.1.3, Recycled Water & Salinity. Progress report to Goyder Institute, Jan-Mar 2015

Press coverage – Newspapers & Radio

A press release entitled 'Boosting recycled water use for agriculture' was published by both the AWRCOE and the South Australian Minister for Water and the River Murray, Hon. Ian Hunter MLC, in April 2013. The press release acknowledged support from both the AWRCOE and Goyder Institute in the SARDI led irrigation project. The press release generated two radio interviews, broadcast in both Adelaide and regional South Australia, and more than 14 newspaper and magazine articles.

General Industry Communications

Pitt, T., Osti, A., Alcoe, D. and Green, G. (2013). *Climate change in the Northern Adelaide Plains and implications for horticulture.* Department of Environment, Water & Natural Resources. DEWNR Technical Note 2013/09

Tim Pitt sat on the organising committee of the Crush 2014 – Grape and Wine Science Symposium held in Adelaide in October 2014.

Tim Pitt and Jim Cox participated in Science Alive 2013 and 2014, an annual science expo hosted during National Science Week. The work of the Goyder Institute and the AWRCOE were acknowledged during these three day extension activities.

Appendix B – Intellectual Property

There is no patentable intellectual property arising from this project. Research has focussed on the development of knowledge for industry and is contained herein.

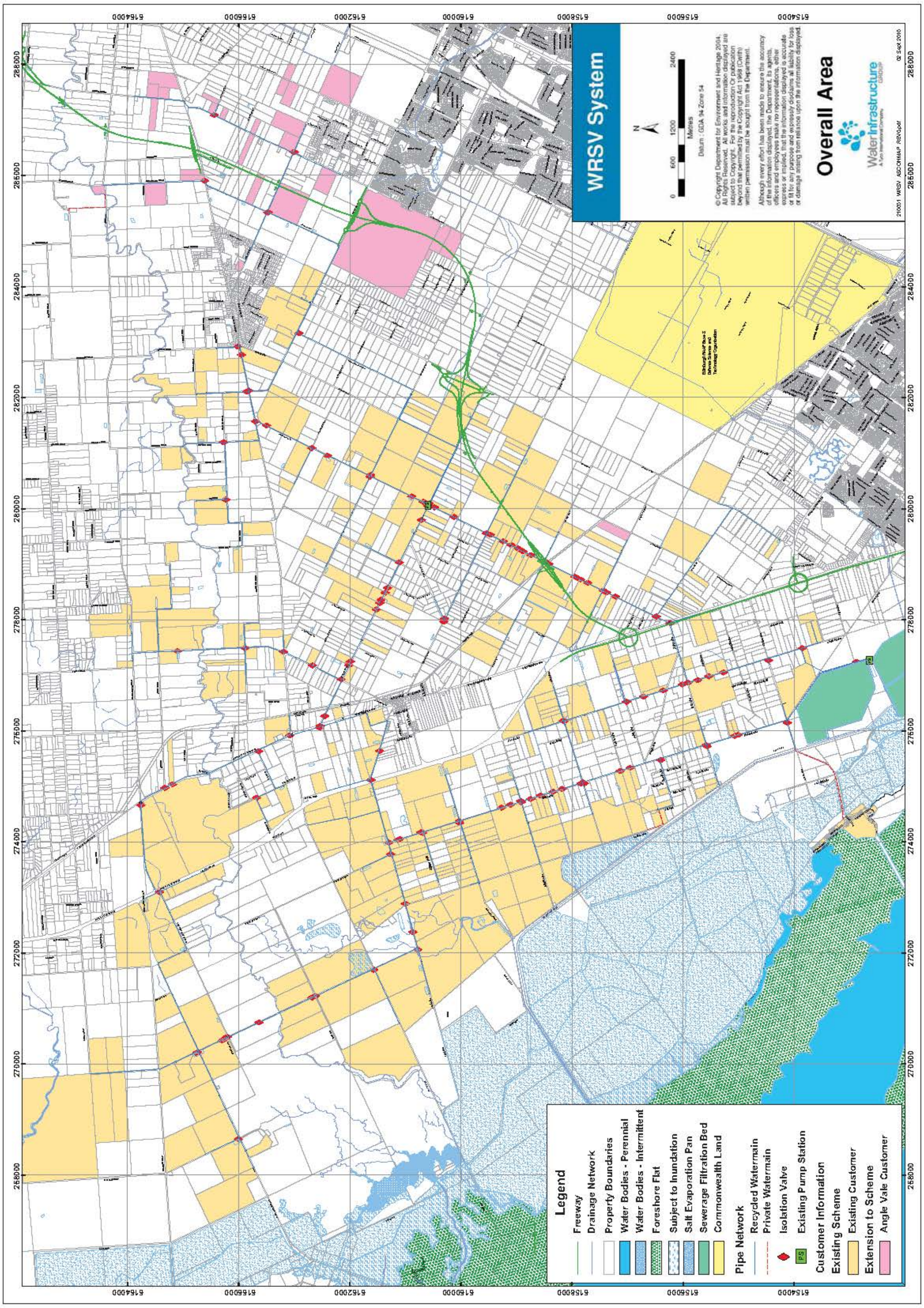
Appendix C – Staff

Personnel	Organisation	Role
Prof. Jim Cox	SARDI	Project Leader
Mr Tim Pitt	SARDI	Principal Investigator
Dr Vinod Phogat	SARDI	Numerical Modelling
Mr Nigel Fleming	SARDI	Literature Review
Dr Mike McCarthy	SARDI	Technical Advice
Mr Nick Pezzaniti	N &WA Pezzaniti	Collaborating Irrigator
Mr Jonathan Shearer	Treasury Wine Estates	Collaborating Irrigator
Dr Cameron Grant	University of Adelaide	Postgraduate Coordinator
Mr Harman Mann	University of Adelaide	Technical Officer
Mr Giacomo Betti	University of Adelaide	PhD Candidate
Ms Shanxiu (Shel) Cong	University of Adelaide	Honours Student
Mr Justice Frimpong	University of Adelaide	Masters Student
Dr John Radcliffe	AWRCOE	PAC Member
Dr Michele Akeroyd	Goyder Institute	PAC Member
Dr Ben Robinson	Independent	PAC Member
Mr Ben Fee	PIRSA	PAC Member

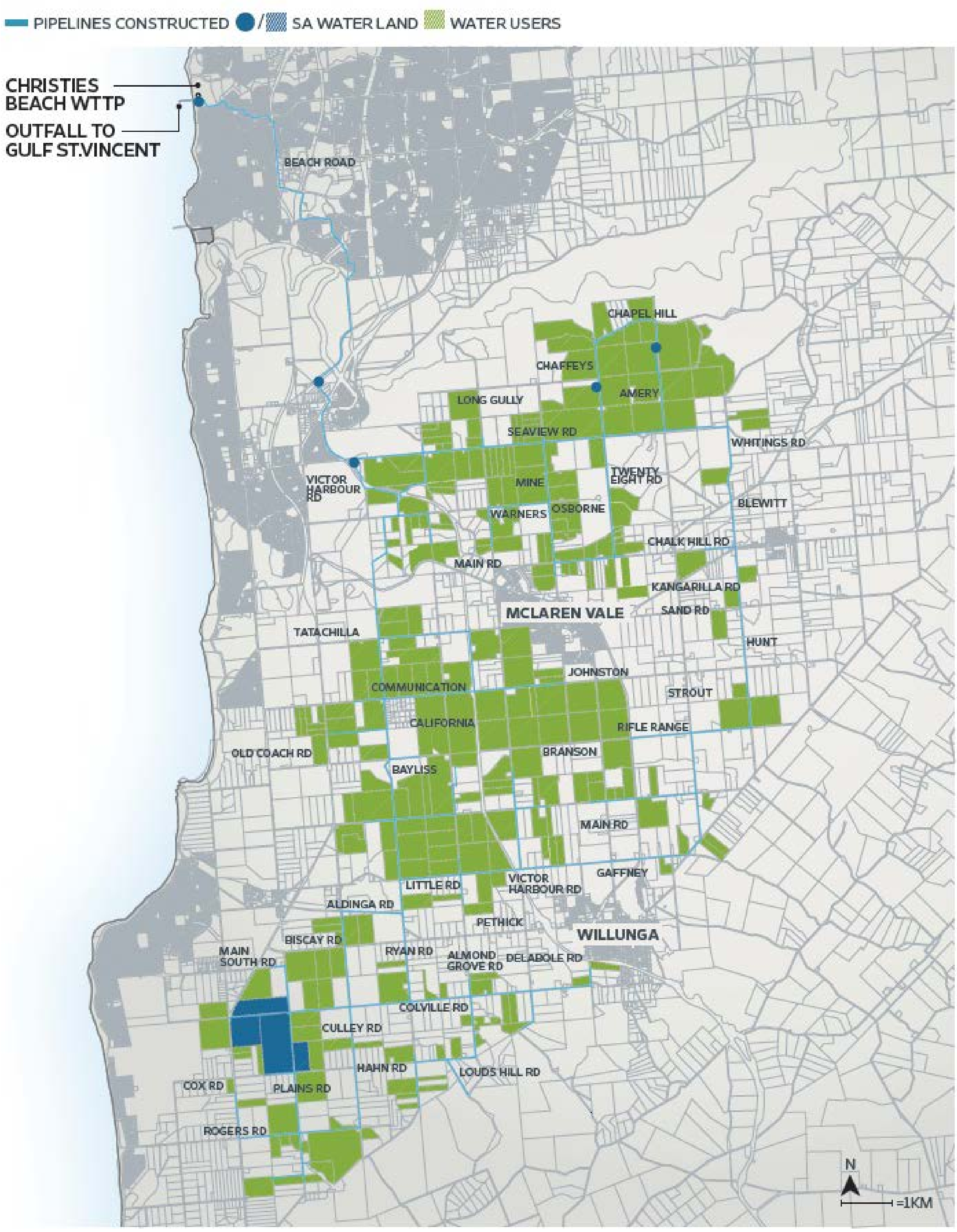
Appendix D – Budget Reconciliation

Appendix E – Pipeline network maps, DAFF schematics and water quality

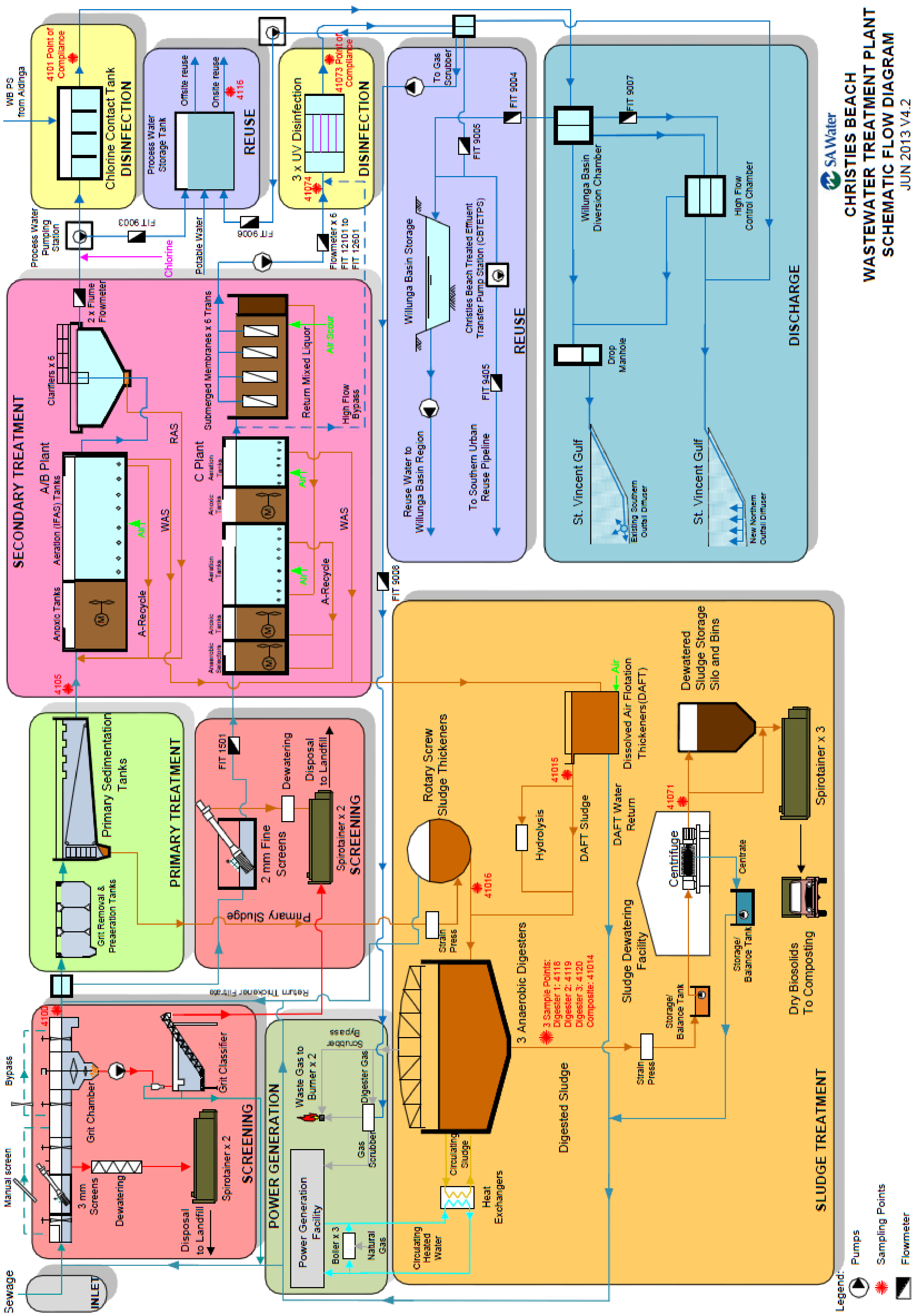
Water Infrastructure Group's Virginia Pipeline Scheme (www.wrsv.com.au 2010).



Willunga Basin Water Company Pipeline Scheme (www.waterrecyclinginvestment.com 2013).



Christies Beach Wastewater Treatment Plant Schematic Flow Diagram (SA Water June 2013).



Christies Beach Wastewater Treatment Plant; Water quality summary for water delivered to Willunga Basin Water in seasons 2012/13 and 2013/14.

NB – data represents the average of measures collected from sampling points 4101 & 41073

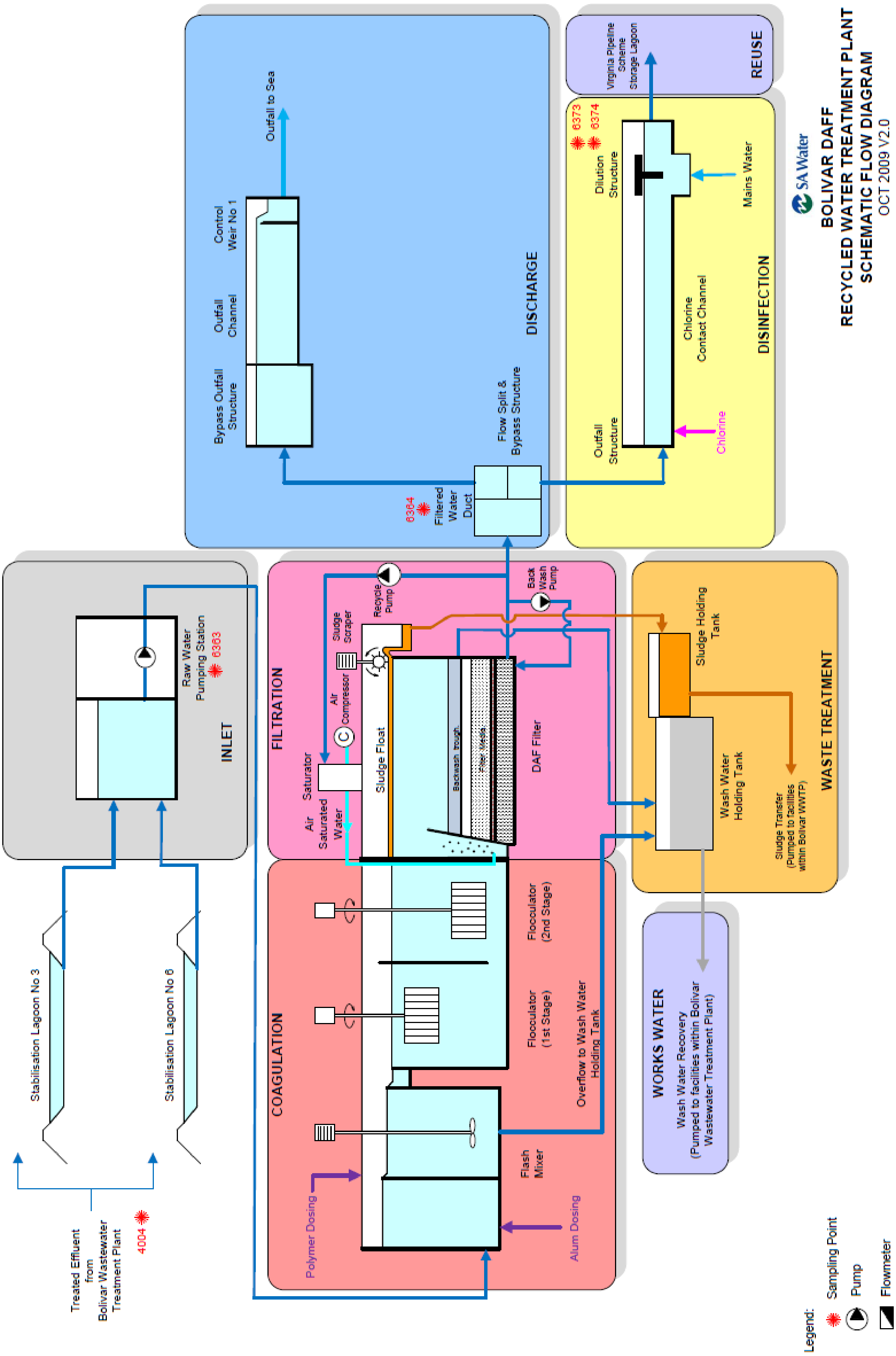
2012/13	Units	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
Biochemical Oxygen Demand	mg/L	3.9	6.6	2.6	3.5	4.8	3.8	3.1	3.7	4.4	2.3	2.4	3.8
pH	pH units	7.5	7.6	7.5	7.5	6.9	6.9	7.4	7.2	7.3	7.2	7.3	7.4
Total Dissolved Solids (by EC)	mg/L	758	764	758	705	648	663	574	527	527	580	587	638
Turbidity	NTU	2.0	1.3	1.6	1.4	2.4	2.6	1.3	1.9	2.2	2.3	2.1	3.6
Phosphorus - Total	mg/L	7.00	6.45	6.83	7.16	7.88	8.48	7.07	7.43	7.62	6.34	8.45	7.45
Nitrate + Nitrite as N	mg/L	11.60	7.27	9.05	11.39	24.28	25.08	10.31	12.08	9.04	10.46	9.27	8.78
TKN as Nitrogen	mg/L	6.69	8.12	4.31	2.47	2.85	3.78	4.54	2.34	3.04	3.47	2.58	4.58
E.coli	/100mL	0	0	14	13	1,708	23	41	9	3	0	7	6,583
Total Chlorine	mg/L	4.8	5.1	6.6	2.3	4.3	3.2	6.5	3.9	3.7	4.4	2.6	3.5
Free Chlorine	mg/L	2.1	2.6	1.5	1.3	0.9	1.3	3.7	1.3	2.1	2.2	0.9	1.2
Chloride	mg/L	252.5	251.0	303.0	232.5	204.0	226.0	193.0	179.0	171.5	189.0	191.7	217.8
Aluminium - Total	mg/L	0.0270	0.0380	0.0360	0.0330	0.0470	0.0320	0.0305	0.0340	0.0398	0.0427	0.0268	0.0355
Arsenic - Total	mg/L	0.0012	0.0009	0.0011	0.0007	0.0007	0.0009	0.0007	0.0006	0.0005	0.0007	0.0005	0.0008
Barium	mg/L												
Beryllium - Total	mg/L	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
Boron - Soluble	mg/L	0.2587	0.3075	0.2860	0.2807	0.2590	0.2775	0.2850	0.2746	0.3654	0.2322	0.2344	0.2658
Cadmium - Total	mg/L	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001
Cobalt - Total	mg/L	0.0008	0.0004	0.0006	0.0008	0.0009	0.0004	0.0004	0.0007	0.0010	0.0026	0.0016	0.0010
Chromium - Total	mg/L	0.0006	0.0004	0.0010	0.0008	0.0009	0.0011	0.0007	0.0006	0.0006	0.0006	0.0005	0.0011
Copper - Total	mg/L	0.0111	0.0118	0.0185	0.0146	0.0189	0.0204	0.0144	0.0123	0.0136	0.0144	0.0110	0.0102
Iron - Total	mg/L	0.0390	0.0412	0.0397	0.0305	0.0389	0.0306	0.0248	0.0214	0.0334	0.0338	0.0247	0.0310
Lead - Total	mg/L	0.0005	0.0006	0.0006	0.0005	0.0007	0.0005	0.0005	0.0004	0.0005	0.0005	0.0004	0.0004
Lithium - Total	mg/L	0.0082	0.0073	0.0072	0.0063	0.0053	0.0052	0.0057	0.0053	0.0052	0.0053	0.0048	0.0069
Manganese - Total	mg/L	0.0357	0.0261	0.0331	0.0252	0.0295	0.0174	0.0134	0.0163	0.0301	0.0168	0.0139	0.0156
Mercury - Total	mg/L	0.0002	0.0001	0.0005	0.0002	0.0001	0.0000	0.0001	0.0000	0.0000	0.0001	0.0001	0.0002
Molybdenum - Total	mg/L	0.0026	0.0015	0.0032	0.0010	0.0011	0.0021	0.0011	0.0009	0.0008	0.0011	0.0016	0.0013
Nickel - Total	mg/L	0.0053	0.0035	0.0070	0.0044	0.0053	0.0072	0.0050	0.0055	0.0061	0.0065	0.0050	0.0040
Selenium - Total	mg/L	0.0011	0.0009	0.0009	0.0008	0.0005	0.0004	0.0001	0.0003	0.0002	0.0003	0.0011	0.0013
Vanadium - Total	mg/L	0.0011	0.0020	0.0032	0.0007	0.0003	0.0012	0.0004	0.0010	0.0003	0.0005	0.0003	0.0015
Zinc - Total	mg/L	0.0280	0.0337	0.0395	0.0389	0.0454	0.0415	0.0465	0.0415	0.0416	0.0449	0.0406	0.0396
Calcium	mg/L	48.0	47.9	48.8	44.6	41.6	38.0	38.0	35.5	36.5	44.5	40.8	44.0
Magnesium	mg/L	26	26	28	22	17	19	16	14	14	18	19	21
Potassium	mg/L	18.9	21.5	23.7	22.8	22.4	23.2	24.6	22.5	23.7	26.0	26.8	22.5
Sodium	mg/L	167.4	176.9	180.0	158.1	139.0	142.0	133.5	121.0	131.0	144.8	159.5	163.5
Bicarbonate	mg/L	192.6	237.9	197.6	168.8	77.0	66.0	127.0	120.3	148.6	126.2	152.1	181.1
Fluoride	mg/L	192.63	237.92	197.61	168.75	77.00	66.00	127.00	120.25	148.58	126.17	152.08	181.08
SAR *		4.9	5.1	5.1	4.8	4.6	4.7	4.6	4.4	4.7	4.7	5.2	5.1

* SAR calculated by SARDI as per Ayers and Westcot (1985)

2013/14	Units	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
Biochemical Oxygen Demand	mg/L	3.5	5.6	2.3	2.1	2.2	2.6	4.9	3.0	2.0	2.4	2.1	2.1
pH	pH units	7.6	7.5	7.5	7.6	7.6	7.4	7.5	7.4	7.4	7.4	7.4	7.6
Total Dissolved Solids (by EC)	mg/L	746	757	763	689	599	599	569	543	546	538	620	630
Turbidity	NTU	3.6	4.6	2.1	6.6	0.8	0.8	2.1	1.5	1.2	2.7	2.2	2.3
Phosphorus - Total	mg/L	6.10	6.04	6.46	6.78	6.71	6.90	8.22	7.55	7.38	7.10	6.39	6.26
Nitrate + Nitrite as N	mg/L	4.02	1.61	5.04	6.68	5.92	5.11	4.79	9.48	12.72	6.99	12.66	11.14
TKN as Nitrogen	mg/L	8.31	14.32	5.19	2.06	2.03	2.18	5.68	1.76	1.64	1.90	1.67	1.48
E.coli	/100mL	0	1	1	7	245	0	1	8	7	12	6	1
Total Chlorine	mg/L	5.8	5.5	3.8	2.1	2.4	4.2	3.4	1.6	1.7	3.7	1.9	4.3
Free Chlorine	mg/L	3.1	2.9	1.7	0.7	1.1	1.3	1.3	0.6	0.5	2.2	0.8	2.6
Chloride	mg/L	240.0	264.0	234.0	215.0	220.5	197.8	181.5	129.0	188.0	156.0	189.5	187.5
Aluminium	mg/L	0.0280	0.0500	0.0270	0.0230	0.0225	0.0230	0.0225	0.0240	0.0248	0.0375	0.0335	0.0315
Arsenic	mg/L	0.0007	0.0009	0.0010	0.0012	0.0005	0.0005	0.0006	0.0006	0.0005	0.0004	0.0005	0.0005
Barium	mg/L												
Beryllium	mg/L	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0006	0.0003
Boron	mg/L	0.2197	0.2780	0.2789	0.3334	0.4186	0.4410	0.5763	0.5357	0.4115	0.4429	0.3394	0.3578
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0005
Cobalt	mg/L	0.0014	0.0013	0.0013	0.0005	0.0014	0.0008	0.0006	0.0007	0.0007	0.0004	0.0009	0.0007
Chromium	mg/L	0.0004	0.0006	0.0006	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0008	0.0006	0.0005
Copper	mg/L	0.0060	0.0094	0.0062	0.0060	0.0058	0.0071	0.0069	0.0115	0.0114	0.0125	0.0110	0.0162
Iron	mg/L	0.0169	0.0409	0.0244	0.0137	0.0164	0.0183	0.0238	0.0200	0.0187	0.0266	0.0238	0.0271
Lead	mg/L	0.0004	0.0005	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0004	0.0005	0.0004	0.0004
Lithium	mg/L	0.0062	0.0075	0.0075	0.0097	0.0063	0.0062	0.0060	0.0050	0.0075	0.0056	0.0065	0.0063
Manganese	mg/L	0.0201	0.0223	0.0193	0.0194	0.0173	0.0162	0.0155	0.0107	0.0137	0.0140	0.0182	0.0144
Mercury	mg/L	0.0001	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
Molybdenum	mg/L	0.0008	0.0012	0.0009	0.0008	0.0007	0.0008	0.0013	0.0011	0.0017	0.0015	0.0008	0.0023
Nickel	mg/L	0.0036	0.0039	0.0043	0.0021	0.0033	0.0031	0.0031	0.0027	0.0025	0.0035	0.0030	0.0023
Selenium	mg/L	0.0008	0.0010	0.0009	0.0005	0.0005	0.0006	0.0003	0.0002	0.0004	0.0002	0.0004	0.0005
Vanadium	mg/L	0.0006	0.0013	0.0033	0.0045	0.0021	0.0009	0.0001	0.0008	0.0002	0.0013	0.0011	0.0007
Zinc	mg/L	0.0416	0.0355	0.0333	0.0328	0.0378	0.0383	0.0426	0.0434	0.0333	0.0334	0.0368	0.0557
Calcium	mg/L	44.7	47.6	44.9	38.5	41.6	40.4	37.5	32.9	40.7	34.1	42.9	41.9
Magnesium	mg/L	24.2	26.0	25.1	18.8	18.7	16.6	15.0	10.7	15.3	11.4	16.3	15.9
Potassium	mg/L	23.0	21.1	21.6	20.7	22.5	23.9	24.2	22.7	24.0	22.0	22.4	20.0
Sodium	mg/L	179.0	185.8	180.5	165.0	153.0	152.3	134.0	129.0	146.0	133.5	157.5	155.0
Bicarbonate	mg/L	241.6	280.4	226.3	188.0	169.2	200.5	159.2	140.8	118.0	147.3	149.7	171.2
Fluoride	mg/L	241.58	280.42	226.33	188.00	169.17	200.50	159.17	140.83	118.00	147.33	149.67	171.17
SAR *		5.4	5.4	5.4	5.5	5.0	5.1	4.7	5.0	5.0	5.1	5.2	5.2

* SAR calculated by SARDI as per Ayers and Westcot (1985)

Bolivar DAFF Recycled Water Treatment Plant Schematic Flow Diagram (SA Water October 2009).



Bolivar DAFF Wastewater Treatment Plant; Water quality summary for water delivered to Virginia Pipeline Scheme in seasons 2012/13 and 2013/14.

2012/13	Units	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
Biochemical Oxygen Demand	mg/L	4	3	4	2	2	4	2	2	2	3	2	2
pH	pH units	7.0	7.0	6.9	6.8	6.9	6.9	6.8	7.1	6.9	6.9	7.0	7.0
Total Dissolved Solids (by EC)	mg/L	1045	1116	1199	1183	1149	1136	1046	990	926	878	879	929
Turbidity	NTU	0.111	0.124	0.141	0.162	0.217	0.250	0.310	0.292	0.253	0.246	0.202	0.153
Phosphorus - Total	mg/L	0.8	0.2	0.5		0.1	0.4	0.1	0.1	0.3	0.2	0.1	0.1
Nitrate + Nitrite as N	mg/L	13.2	14.6	12.7	12.0	12.4	8.4	7.8	5.2	4.8	6.0	6.8	3.5
TKN as Nitrogen	mg/L	2.6	2.3	2.1		2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
E.coli	/100mL	0	0	0	0	0	0	0	0	0	0	0	0
Total Chlorine	mg/L	1.4	1.3	1.6	1.3	1.2	1.4	1.4	1.2	1.5	2.2	2.2	2.4
Free Chlorine	mg/L	0.7	0.5	0.7	0.4	0.4	0.5	0.5	0.3	0.8	1.3	1.1	1.5
Chloride	mg/L												
Aluminium - Total	mg/L	0.0210	0.0220	0.0290	0.0390	0.0830	0.0610	0.1450	1.9000	0.0800	0.0490	0.0680	0.0320
Arsenic - Total	mg/L	0.0011	0.0014	0.0006	0.0009	0.0014	0.0015	0.0009	0.0012	0.0007	0.0006	0.0006	0.0004
Barium	mg/L	0.0044	0.0049	0.0076	0.0083	0.0063	0.0069	0.0066	0.0063	0.0133	0.0101	0.0080	0.0090
Beryllium - Total	mg/L	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
Boron - Soluble	mg/L	0.2460	0.3670	0.2950	0.3870	0.3490	0.3130	0.3450	0.2830	0.2950	0.3010	0.2480	0.3210
Cadmium - Total	mg/L	0.0003	0.0006	0.0008	0.0005	0.0004	0.0004	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002
Cobalt - Total	mg/L	0.0005	0.0007	0.0010	0.0011	0.0013	0.0011	0.0012	0.0008	0.0011	0.0010	0.0010	0.0007
Chromium - Total	mg/L	0.0004	0.0004	0.0006	0.0003	0.0004	0.0003	0.0004	0.0005	0.0005	0.0003	0.0004	0.0002
Copper - Total	mg/L	0.0086	0.0192	0.0238	0.0218	0.0265	0.0257	0.0106	0.0166	0.0093	0.0086	0.0106	0.0108
Iron - Total	mg/L	0.0028	0.0025	0.0024	0.0027	0.0033	0.0038	0.0005	0.0034	0.0114	0.0080	0.0057	0.0066
Lead - Total	mg/L	0.0010	0.0014	0.0015	0.0017	0.0020	0.0019	0.0011	0.0008	0.0028	0.0017	0.0014	0.0013
Lithium - Total	mg/L	0.0064	0.0083	0.0074	0.0080	0.0077	0.0073	0.0074	0.0068	0.0061	0.0053	0.0079	0.0063
Manganese - Total	mg/L	0.0018	0.0165	0.0083	0.0555	0.0270	0.0493	0.0088	0.0028	0.0211	0.0137	0.0055	0.0067
Mercury - Total	mg/L	0.00013	0.00011	0.00016	0.00003	0.00003	0.00006	0.00003	0.00005	0.00006	0.00003	0.00008	0.00007
Molybdenum - Total	mg/L	0.0060	0.0064	0.0072	0.0058	0.0060	0.0063	0.0061	0.0059	0.0063	0.0073	0.0057	0.0050
Nickel - Total	mg/L	0.0071	0.0101	0.0096	0.0108	0.0127	0.0130	0.0100	0.0091	0.0127	0.0092	0.0097	0.0074
Selenium - Total	mg/L	0.0006	0.0009	0.0010	0.0008	0.0009	0.0015	0.0007	0.0004	0.0004	0.0006	0.0012	0.0004
Vanadium - Total	mg/L	0.0056	0.0048	0.0038	0.0046	0.0043	0.0038	0.0067	0.0064	0.0075	0.0050	0.0114	0.0064
Zinc - Total	mg/L	0.0485	0.0648	0.0742	0.0704	0.0666	0.0494	0.0146	0.0045	0.0235	0.0310	0.0297	0.0411
Calcium	mg/L	99	114	116	122	122	142	94	107	101	110	112	125
Magnesium	mg/L	33	36	36	35	34	35	35	26	26	25	27	26
Potassium	mg/L	34	34	36	38	39	40	40	40	42	41	42	35
Sodium	mg/L	252	282	281	281	286	289	286	264	248	216	246	225
Bicarbonate	mg/L	121	139	141	149	149	173	115	130	123	135	137	153
Fluoride	mg/L	0	0.49	0.51	0.44	0.68	0.70	0.64	0.72	0.52	0.48	0.45	0.41
SAR *		5.6	5.9	5.8	5.8	5.9	5.6	6.4	5.9	5.7	4.8	5.4	4.8

* SAR calculated by SARDI as per Ayers and Westcot (1985)

2013/14	Units	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
Biochemical Oxygen Demand	mg/L	2	3	2	2	2	2	2	3	2	3	2	2
pH	pH units	0.7	0.5	0.4	0.5	0.5	0.5	0.4	0.5	0.6	0.4	0.5	0.5
Total Dissolved Solids (by EC)	mg/L	1004	1090	1206	1049	1062	1069		1142	1137	1058	984	1005
Turbidity	NTU	0.547	0.448	0.380	0.426	0.427	0.443	0.324	0.349	0.243	0.204	0.233	0.249
Phosphorus - Total	mg/L	0.4	0.3	0.4	0.5	0.5	0.5	0.6	0.0	0.0	0.0	0.0	
Nitrate + Nitrite as N	mg/L	7.3	6.8	7.0	7.3	21.0	1.7	0.7	0.5	1.4	4.9	7.6	5.4
TKN as Nitrogen	mg/L	2.0	2.0	2.0	2.0	2.1	2.0	1.2	1.0	0.9	1.1	1.1	
E.coli	/100mL	0	0	0	0	0	0	0	0	0	0	0	0
Total Chlorine	mg/L	2.2	3.0	1.7	1.7	3.6	3.6	2.9	3.8	3.9	1.7	2.0	1.2
Free Chlorine	mg/L	1.2	2.0	0.7	0.8	2.6	2.6	1.8	2.9	2.9	0.8	1.1	0.5
Chloride	mg/L												
Aluminium	mg/L	0.0500	0.0475	0.0480	0.0900	0.0570	0.2680	0.0600	0.0520	0.0480	0.0440	0.0450	0.0610
Arsenic	mg/L	0.0008	0.0007	0.0003	0.0003	0.0004	0.0006	0.0020	0.0005	0.0005	0.0005	0.0003	0.0006
Barium	mg/L	0.0061	0.0069	0.0103	0.0089	0.0089	0.0072	0.0084	0.0170	0.0149	0.0150	0.0129	0.0116
Beryllium	mg/L	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
Boron	mg/L	0.3610	0.3775	0.3600	0.5140	0.4220	0.4220	0.4970	0.4290	0.3920	0.4190	0.4180	0.3950
Cadmium	mg/L	0.0003	0.0003	0.0002	0.0002	0.0004	0.0003	0.0013	0.0002	0.0007	0.0002	0.0003	0.0003
Cobalt	mg/L	0.0003	0.0003	0.0002	0.0002	0.0004	0.0003	0.0013	0.0002	0.0007	0.0002	0.0003	0.0003
Chromium	mg/L	0.0008	0.0008	0.0010	0.0011	0.0009	0.0005	0.0004	0.0008	0.0006	0.0009	0.0007	0.0007
Copper	mg/L	0.0050	0.0049	0.0052	0.0174	0.0043	0.0042	0.0086	0.0085	0.0156	0.0063	0.0115	0.0144
Iron	mg/L	0.0013	0.0012	0.0014	0.0017	0.0010	0.0004	0.0012	0.0014	0.0012	0.0011	0.0011	0.0012
Lead	mg/L	0.0078	0.0082	0.0091	0.0074	0.0066	0.0060	0.0061	0.0065	0.0064	0.0062	0.0069	0.0071
Lithium	mg/L	0.0078	0.0082	0.0091	0.0074	0.0066	0.0060	0.0061	0.0065	0.0064	0.0062	0.0069	0.0071
Manganese	mg/L	0.0057	0.0065	0.0197	0.0119	0.0086	0.0036	0.0348	0.0167	0.0234	0.0109	0.0299	0.0332
Mercury	mg/L	0.0002	0.0002	0.0001	0.0001	0.0001	0.0002	0.0000	0.0000	0.0001	0.0000	0.0001	0.0000
Molybdenum	mg/L	0.0061	0.0059	0.0064	0.0061	0.0048	0.0062	0.0050	0.0053	0.0038	0.0052	0.0037	0.0044
Nickel	mg/L	0.0080	0.0081	0.0104	0.0114	0.0094	0.0096	0.0116	0.0120	0.0114	0.0094	0.0088	0.0118
Selenium	mg/L	0.0010	0.0011	0.0016	0.0013	0.0007	0.0006	0.0003	0.0004	0.0003	0.0005	0.0003	0.0004
Vanadium	mg/L	0.0038	0.0044	0.0087	0.0073	0.0030	0.0020	0.0014	0.0032	0.0032	0.0038	0.0015	0.0041
Zinc	mg/L	0.0403	0.0423	0.0518	0.0488	0.0177	0.0025	0.0125	0.0164	0.0131	0.0211	0.0289	0.0231
Calcium	mg/L	128	127	121	122	79	280	157	108	129	113	87	137
Magnesium	mg/L												
Potassium	mg/L	41	39	42	41	43	40	39	43	38	39	37	37
Sodium	mg/L	290	296	435	319	311	292	271	327	291	294	240	268
Bicarbonate	mg/L	156	154	148	149	96	341	192	132	158	138	106	167
Fluoride	mg/L	1	0.49	0.39	0.44	0.34	0.63	0.79	0.42	0.39	0.46	0.29	
SAR *		6.0	6.1	9.1	6.7	7.5	4.4	5.2	7.1	6.0	6.3	5.6	5.4

* SAR calculated by SARDI as per Ayers and Westcot (1985). Missing Magnesium data supplemented from average 2012/13 data.

Appendix F – Total Ground Control MSDS

MATERIAL SAFETY DATA SHEET

Product Name: 'Total Ground Control'
Issued By: Reynolds Soil Technologies Pty Ltd
Item No: TGC
Review Date: 18/02/2010
Issue Date: 18/02/2010
Version Number: 1.0

RST DUST · EARTH · WATER SOLUTIONS

1. IDENTIFICATION OF THE MATERIAL AND SUPPLIER

COMPANY NAME: Reynolds Soil Technologies Pty Ltd (ABN 31 068 825 696)
ADDRESS: 14, Greg Chappell Drive, Burleigh Heads, Queensland, Australia, 4220
EMERGENCY PHONE: 0417 770567
PHONE: 07 5522 0244
FAX: 07 5522 0799
EMAIL: rst@rsth2o.com.au

PRODUCT NAME: Total Ground Control
SYNONYMS: TGC, TGC Dust Suppressant, TGC Crusting Agent, TGC Veneer Coat

USE:
- Soil Binder for Erosion Control
- Broad Acre Dust Suppressant
- Stockpile Binder
- Revegetation Binder
- Hydromulching Binder
- Hydroseeding Binder

2. HAZARD IDENTIFICATION

Based on available information, not classified as hazardous according to the criteria of NOHSC.

RISK PHRASES	None Allocated
SAFETY PHRASES	S24 Avoid Contact with Eyes S25 Avoid contact with Skin

3. COMPOSITION/INFORMATION ON INGREDIENTS

CHEMICAL ENTITY	CAS NO	PROPORTION
Ammonia, aqueous solutions	1336-21-6	0-<1%
Styrene	100-42-5	0-<0.1%
Ingredients determined not to be hazardous including Water	Proprietary	To 100%
Acrylic Monomers	Proprietary	0-0.1%

4. FIRST AID MEASURES

SWALLOWED	Do not induce vomiting. Rinse mouth thoroughly with water. Seek medical attention.
EYES	If in eyes, hold eyelids apart and flush the eyes continuously with running water. Continue flushing for several minutes until all contaminants are washed off completely. Seek immediate medical attention.

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MATERIAL SAFETY DATA SHEET

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SKIN	If skin or hair contact occurs, remove contaminated clothing and flush skin and hair with running water. If irritation develops seek medical attention.
INHALED	Keep patient calm and remove to fresh air.
FIRST AID FACILITIES	Ensure eye wash bath and safety shower is readily accessible.
ADVICE TO DOCTOR	Treat according to symptoms.

5. FIRE-FIGHTING MEASURES

SUITABLE EXTINGUISHING MEDIA	In case of fire use water, carbon dioxide (CO2), foam or dry extinguishing media.
HAZARDS FROM COMBUSTION PRODUCTS	No explosion hazard.
PRECAUTIONS FOR FIRE FIGHTERS & SPECIAL PROTECTIVE EQUIPMENT	Not available.

6. ACCIDENTAL RELEASE MEASURES

EMERGENCY PROCEDURES	Product is very slippery in concentrate form.
METHODS AND MATERIALS FOR CONTAINMENT AND CLEAN UP	Contain large spills and pump out into containers; soak up remainder with absorbent material. Small spills can be flushed away with copious amounts of water for effluent treatment only. Dispose of wastewater correctly. Clean up personnel should wear protective overalls with goggles and gloves. Place waste in labelled containers for disposal. Must be disposed to approved landfill or incineration in accordance with local regulations.

7. HANDLING AND STORAGE

PRECAUTIONS FOR SAFE HANDLING	Product is very slippery in concentrate form. Hands and face should be washed before breaks and at the end of the shift.
CONDITIONS FOR SAFE STORAGE	Handle in accordance with good industrial hygiene and safety practice.
INCOMPATIBILITIES	Not available.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

NATIONAL EXPOSURE STANDARDS	No exposure standard allocated.
BIOLOGICAL LIMIT VALUES	No biological limit allocated.
ENGINEERING CONTROLS	Ensure workplace is well ventilated.
PERSONAL PROTECTION	Protective Goggles, Protective Gloves, Protective Overalls

9. PHYSICAL AND CHEMICAL PROPERTIES

APPEARANCE:	Varies

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MATERIAL SAFETY DATA SHEET

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ODOUR:	None
pH:	6.5-7.0 (at 200g/L, 20°C)
VAPOUR PRESSURE:	No Data
VAPOUR DENSITY:	No Data
BOILING POINT/RANGE:	No Data
FREEZING/MELTING POINT:	No Data
SOLUBILITY:	Soluble
SPECIFIC GRAVITY OR DENSITY	ca. 1.01 (23°C)
FLAMMABILITY:	Not Flammable
OTHER PROPERTIES	
SOLIDIFICATION TEMPERATURE:	ca. -5°C
VISCOSITY(23°C):	ca. 1000 mPa.s [Brookfield]

10. STABILITY AND REACTIVITY

CHEMICAL STABILITY	Stable under normal conditions of use.
CONDITIONS TO AVOID	None expected.
INCOMPATIBLE MATERIALS	Strong oxidising agents (may degrade polymer).
HAZARDOUS DECOMPOSITION PRODUCTS	No decomposition expected under normal storage conditions.
HAZARDOUS REACTIONS	Will not occur.

11. TOXICOLOGICAL INFORMATION

TOXICITY DATA FOR SIMILAR PRODUCT:

Acute Oral Toxicity > 5000 - LD50 . mg/kg (rat)

ACUTE & CHRONIC HEALTH EFFECTS

SWALLOWED	Adverse effects are not expected.
EYE	Eye contact with product is not expected to cause irritation.
SKIN	Skin contact with product is not expected to cause irritation.
INHALED	Inhalation overexposure is not expected at ambient temperatures.
CHRONIC EFFECTS	Chronic effects are not known.

12. ECOLOGICAL INFORMATION

ECOTOXICITY	
Oral Toxicity LD50 (Rat):	Undetectable
Fish Toxicity LC50 (Golden Orfes):	Undetectable

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Bacteria Toxicity EC50:	Undetectable
Daphnia Toxicity EC50:	Undetectable
Algae Toxicity:	Undetectable
PERSISTANCE & DEGRADABILITY	Not Available
MOBILITY	Not Available

13. DISPOSAL CONSIDERATIONS

DISPOSAL METHODS	Refer to appropriate authority in your State. Dispose of material through a licensed waste contractor. Advise of combustible nature.
SPECIAL REQUIREMENTS FOR LANDFILL OR INCINERATION	Normally disposable through a licensed waste contractor.

14. TRANSPORT INFORMATION

UN No: None Allocated	**D.G. Class:** None Allocated	**CAS No.:** None Allocated
Hazchem: None Allocated	**Sub. Risk:** None Allocated	**Susdp.:** None Allocated
G.T.EPG: None Allocated	**Spec.EPG:** None Allocated	**Pack.Grp:** None Allocated

Not classified as a dangerous good for transport.
No special transport requirements necessary.

15. REGULATORY INFORMATION

POISONS SCHEDULE	No Poisons schedule number allocated
OTHER	None

16. OTHER INFORMATION

PREPARATIONS AND REVISIONS	This MSDS was last revised 16/02/2010 to bring up to date with the National Code of Practice for the Preparation of Material Safety Data Sheets 2nd Edition [NOHSC:2011(2003)] **Version 1.0 supersedes all other versions.**

This MSDS summarises our best knowledge of the health and safety hazard information of the product and how to safely handle and use the product in the workplace. It should be read taking into account how the product is handled in your particular situation and how it is used in conjunction with other products.

This is the last page of the MSDS.

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Appendix G – Numerical modelling of rainfall redirection

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Evaluation of water and salinity dynamics in soil under grapevine in relation to different rainfall redirection techniques at different locations in South Australia

Soil salinity and water scarcity are twin problems in arid and semiarid regions around the world which hampers the sustainability and resilience of crop production. Availability of good quality water for irrigation is becoming inadequate and expansive commodity due to increase in the demand of fresh water for drinking, urbanization, industrial expansion, recreation and environmental needs. Consequently, use of poor quality water for irrigation especially drainage water, recycled municipal water and groundwater is explored to integrate it in irrigation scheduling to sustain the crops. However, indiscriminate or excessive use of saline water for irrigation, mostly in semi-arid and arid conditions potentially creates an alarming situation through accelerated salt deposition in the root zone of the crops. Therefore there is a need to explore possibilities of judicious use of saline water coupled with effective salt leaching strategies so that the soil profile can be maintained below a salinity threshold for sustainable production of different crops.

South Australia is a major grape and wine producing region in Australia contributing 48% of the total wine grape crush and 93% of vineyards uses supplementary drip irrigation (ABS, 2013; Gunning and Shafron, 2012). However, scarce good quality water resources, increased use of saline water for irrigation, frequent droughts and severe climate change predictions putting enormous pressure on the growers to maintain and sustain the production. Most regions in Australia now have restrictions on water allocated for irrigators, for instance the cap on water drawn from the Murray-Darling river and many other grape growing regions have imposed limits on both surface and underground water resources. In some areas groundwater is of poor quality and use of such waters can pose potential danger of soil salinization and can inflict serious impact on the sustainability of vineyards. These consequent dangers also hinder the opportunities for future vineyard expansion. There is need to assess the process of salt dynamics in soils under varied soil, climate and irrigation scheduling of vineyards existing in different vine growing regions.

Under saline water irrigation conditions it is imperative to leach the salts out of the root zone for sustainable crop production. Hence it is essential to maintain a leaching fraction which can push the salts out of the zone of interest. Earlier studies on leaching fractions were based on steady state flow conditions (Rhoades, 1974; Hoffman and van Genuchten, 1983; Ayers and Westcot, 1985; Rhoades, 1999) and may not be fully employed under drip irrigation where transient conditions prevail. Corwin et al. (2007) and Letey and Feng (2007) have shown that steady state models are conservative and overestimate the leaching fraction required for salinity control. Letey et al. (2011) reviewed the current recommended guidelines for leaching requirement (LR) and concluded that existing procedure overestimate the LR because these were based on steady state conditions. However, these studies ignored the importance of rainfall in leaching the salts from the root zone. In addition, pressurised irrigation systems such as drip has added new dimension to the complicity of the leaching of salts where water is applied within a localized zone to match the crop demand. Recent studies have shown that considerable (7.7- 33.5%) leaching is happening under the drippers in drip irrigation systems even when irrigation scheduling was based on crop evapotranspiration requirement (Hanson et al., 2008; Phogat et al., 2012, 2014). However, Hanson et al. (2008) investigated the impact of different localized leaching fraction (LLF) under subsurface drip ignoring the importance of rainfall in drainage and salt leaching. In fact, under saline supplementary irrigation salts are added through irrigation and leaching of these salts depends on the amount of rainfall (Stevens et al., 2012). Hence there is need to evaluate the process of salt leaching under drip irrigation systems considering all real water and salts inputs including rainfall under cropped conditions. The importance of rain under drip increased many folds as it is not possible to apply leaching fraction over the whole soil surface and salts deposited far from the localized zone due to the lateral salt migration remains in the system which could have immense impact on salinity development in the soil.

On-farm water harvesting techniques like mulching and rainfall redirection plays a key role under high efficiency drip irrigation. Drip irrigation coupled with plastic mulch (DIPM) has been introduced over a large area in arid environment in China to reduce evaporation and to optimise the efficiency of available water resources (Liu et al. 2013). Similarly, rainfall redirection techniques (removing under vine mound and mounding in mid-row with rainfall harvesting) has been found to reduce the soil salinity and Na^+ and Cl^- content in wine grapes (Stevens et al., 2013). However, rainfall amount and intensity, soil texture, structure and its hydraulic properties plays a key role in water and salt movement in the soils. Hence there is need to evaluate the impact of different rainfall harvesting and redirection techniques under varied soil and climatic conditions.

Conducting experiments involving numerous variables at different sites is time consuming and costly affair. Numerical models are excellent cost effective tools to study the impact of different climate, soil and crop variables on water and solute balance in soil provided that realistic input data is available. Hence, HYDRUS-2D was employed to evaluate the impact of different rainfall redirection and harvesting techniques on water and salt balance under grape vine at 3 locations having different soil, rainfall, irrigation scheduling and water quality conditions. The outcome would be helpful in devising guidelines for controlling soil salinization and salt leaching for sustainable wine grape production.

1. Study sites description

There are 3 broad grape vine producing regions in South Australia (SA) viz. Riverland, Fleurieu Peninsula and South East which are shown in Figure 1. These sites have different soil, crop, irrigation scheduling, water quality and rainfall conditions which can have a significant impact on water use, salinity distribution in soil and salt leaching. The water and salt balance modelling study was conducted for 3 consecutive seasons i.e. 2011-12, 2012-13 and 20013-14 at 3 locations representing all the three grape vine producing regions. The input data for modelling were obtained from ongoing and completed research trials at McLaren Vale (Fleurieu Peninsula) and Padthaway (South East), respectively. Input data for Riverland were obtained from the Loxton Research Centre of South Australian Research and Development Institute. Weather and soil characteristics of different site selected from these regions are described below.

Loxton

The SA Riverland vineyard region is located along the River Murray and includes Loxton. Loxton is warmer and receives less rainfall compared to other vineyard regions. The average maximum temperature, pan evaporation and rainfall for the last 100 years, estimated from SILO data (Jeffrey et al., 2001), is 23.8°C, 1823 mm and 265 mm, respectively. Most of the vineyards are irrigated with water from the River Murray which has very low salinity (0.1- 0.4 dS/m). Soils are predominately lighter in texture as compared to other regions. The hydraulic parameters were estimated from the van Genuchten- Mualem constitutive relationship (van Genuchten 1980) based on water content-pressure head measurements (Table 1). Hydraulic conductivity (*Ks*) and bulk density (*Db*) were measured in undisturbed core samples using standard procedures. The salinity data was not available for different locations under vines; hence a uniform salinity distribution was initially applied throughout the vine spacing. Similarly initial moisture content in the model was set at the field capacity value.

Table 1. Soil hydraulic parameters for Loxton.

Soil type	Soil depth (cm)	*ϑr*	*ϑs*	*α*	*n*	*Ks*	*l*	*Db*
			cm^3cm^{-3}	cm^{-1}		cm/day		kg/m3
Loamy sand	0-30	0.04	0.4	0.027	2.189	388.8	0.5	1.53
Loamy sand	30-65	0.05	0.38	0.04	1.702	259.2	0.5	1.48
Loam	65.100	0.05	0.37	0.04	1.62	172.8	0.5	1.43

ϑr is the residual water content, *ϑs* is the saturated water content of the soil, *Ks* is the saturated hydraulic conductivity of the soil, *Db* is the bulk density of the soil, *α*, *n* and *l* are the van Genuchten shape parameters.

McLaren Vale

McLaren Vale is a premium wine grape area on the Fleurieu Peninsula, south of Adelaide, and characterised by a Mediterranean climate. The average maximum temperature, pan evaporation (ET_0) and rainfall for the last 100 years (SILO data) is 20.9°C, 1568.5 mm and 555 mm, respectively.

The main issues identified for the McLaren Vale region's viticulture industry were the potential emergence of soil salinity and water insecurity (James and Liddicoat, 2008). Groundwater resources are the main supplementary source of irrigation in McLaren Vale. However, the use of groundwater for irrigation has declined in recent years due to its elevated salinity (Department of Water SA, 2012); particularly during drought periods which affects the sustainability of the vineyards. Hence, treated wastewater has emerged as an alternative secure water supply for irrigation due to scarcity of surface water resources in this region. It is distributed directly to growers in the region through a network of pipes and associated pumping stations. More than 40% of vineyards in McLaren Vale are irrigated with recycled water supplied by the Willunga Basin Water Network which supplies about 4 GL water per annum (www.oz**water**.org/sites/all/files/oz**water**/112%20CHeidenreich.pdf). However, its impact on salinity distribution and salt leaching in the soil has not been fully investigated.

Table 2. Soil hydraulic parameters for McLaren Vale (Under Vine, UV; Under Tree, UT and Mid Row, MR).

soil type	Soil depth (cm)	*ϑr*	*ϑs*	*α*	n	*Ks*	*l*	*Db*
			cm^3cm^{-3}	cm^{-1}		cm/day		kg/m3
Sandy clay loam (UV)	0-30	0.23	0.50	0.014	1.5	137.78	0.5	1.50
Sandy clay loam (UT)	0-30	0.23	0.46	0.013	1.5	57.43	0.5	1.55
Sandy clay loam (MR)	0-30	0.19	0.47	0.01	1.4	153.95	0.5	1.44
Clay (UV)	30-65	0.26	0.49	0.014	1.4	20.69	0.5	1.55
Clay (UT)	30-65	0.31	0.49	0.03	1.38	33.19	0.5	1.55
Clay (MR)	30-65	0.27	0.50	0.01	1.4	87.74	0.5	1.40
Clay (UV)	65-100	0.26	0.49	0.114	1.2	58.73	0.5	1.49
Clay (UT)	65-100	0.27	0.46	0.1	1.2	13.77	0.5	1.49
Clay (MR)	65-100	0.25	0.43	0.014	1.4	35.09	0.5	1.32

ϑr is the residual water content, *ϑs* is the saturated water content of the soil, *Ks* is the saturated hydraulic conductivity of the soil, *Db* is the bulk density of the soil, *α*, *n* and *l* are the van Genuchten shape parameters.

There are a wide variety of soil types including red brown sandy loams, grey brown loamy sands with yellow clay sub-soils interspersed with lime, distinctly sandy soils and patches of red or black friable loams in McLaren Vale. However, soils at the site used in the modelling are generally heavy textured but extensive sampling was carried out to examine the variability in soil characteristics. For modelling purpose, average hydraulic parameters were considered; however, vertical variation in soil texture and hydraulic parameters were assumed under vine (UV), under track (UT) and in the mid-row (MR). The van Genuchten parameters were estimated from the ROSETTA software using particle size analysis, *Db* and water content at 33 and 150 kPa suctions. The *Ks* was measured in the undisturbed core samples taken from the study site from different depths from the UV, UT and MR. The estimated parameters are shown in Table 2. Hence input parameters represent a complex cocktail of variability existing at different depths and laterally and across the vine rows.

Padthaway

Padthaway, in the South East of SA, is characterized by the presence of medium textured soils underlain with limestone rocks popularly known as *Terra rossa* soils. Padthaway has a warm climate with good rainfall. The average climatic parameters for the last 100 years show average rainfall 523.3 mm, pan evaporation 1553.4 mm, ET_0 1108.4 mm, maximum temperature 21.1°C and average minimum temperature 8.5 °C. However, due to scarce surface water resources, groundwater is used to supplement rainfall for vine production. The soil hydraulic parameters (Table 3) employed in the modelling study were estimated from water content-pressure head relationship from two soil depths (Stevens et al., 2012). Details of irrigation system design, and irrigation amount and quality were also taken from this trial (Stevens et al., 2012). Weather parameters were assessed from SILO data and a nearby Bureau of Meteorology observatory. These parameters were utilized to estimate potential transpiration and potential evaporation under field conditions using FAO 56 dual crop coefficient approach. The measured UV soil salinity (*ECe*) to 80 cm depth varied from 4 to 4.5 dS/m at the start of modelling simulation. The MR and UT salinity (1.2 to 2.0 dS/m) was less than half of the values measured under the vine.

In Padthaway, vines used 21% of the volume of water applied in irrigation from the Padthaway Prescribed Wells Area (Department of Water, 2012). Groundwater levels in the unconfined aquifer on the Padthaway Flat show a very close correlation with rainfall. Although groundwater salinity trends in the shallow unconfined aquifer on the Padthaway Flat are quite variable and are influenced by rainfall patterns and the types of various irrigation practices.

Table 3. Soil hydraulic parameters for Padthaway.

soil type	Soil depth (cm)	ϑr	ϑs	α	n	*Ks* cm/day	*l*	*Db* kg/m3
Sandy clay loam	0-30	0.07	0.48	0.020	1.247	26	0.5	1.3
Clay loam	30-100	0.17	0.44	0.058	1.323	11	0.5	1.435

ϑr is the residual water content, ϑs is the saturated water content of the soil, *Ks* is the saturated hydraulic conductivity of the soil, *Db* is the bulk density of the soil, α, *n* and *l* are the van Genuchten shape parameters.

2. Irrigation details

Surface drip is the most prevalent irrigation method for vineyard irrigation in SA. However different dripper discharge rates were used in the modelling simulations for each location [2 L/h (Riverland), 1.6 L/h (McLaren Vale), and 1.2 L/h (Padthaway)] with a uniform dripper distance (60 cm). Seasonal irrigation and annual rainfall for three seasons (2011-2014) at all locations is shown in Table 4. Irrigation application was much higher at Loxton as compared to the other two locations due to less rainfall and low water retention capacity of light textured soils. The average rainfall for the 3 seasons was 281.7, 525 and 496.6 mm for Loxton, McLaren Vale and Padthaway, respectively. A common vine spacing (2.75 m x 1.80 m) was considered for the modelling study to maintain uniformity for comparison of results.

The average annual rainfall over 3 seasons at Padthaway was quite similar to the rainfall received at McLaren Vale. However, irrigation application (242.5 mm) at Padthaway was more than double as compared to McLaren Vale. Irrigation application data was available for 2011-12 growing season only at Padthaway. Hence similar irrigation was assumed for 2012-13 and 2013-14 as almost similar rainfall occurred during the following seasons. This amount of irrigation also represents a typical average amount of water generally applied in that region.

Table 4. Amount of annual rainfall and seasonal irrigation of vineyards during 2011-2014 at three locations in SA.

Location	2011-12		2012-13		2013-14		Average	
	Rain (mm)	Irrig (mm)	Rain (mm)	Irrig (mm)	Rain (mm)	Irrig (mm)	Rain (mm)	Irrig (mm)
Loxton	298.20	322.50	198.70	435.00	348.30	377.00	281.73	378.17
McLaren	614.30	86.60	437.10	129.50	524.00	135.30	525.13	117.13
Padthaway	466.40	242.50	446.40	242.50	576.90	242.50	496.57	242.50

The salinity of the irrigation water was measured and average values were considered for modelling as there was low variability in the water quality. The average measured ECw values at Loxton, McLaren Vale and Padthaway were 0.35, 1.2 and 1.38 dS/m, respectively.

3. Rainfall harvesting and redirection treatments

Four treatments have been tested for the impact of rainfall harvesting and redirection on water and salt balance in the soil. These treatments were a) control, B) mid-row mound C) mid-row mound covered with plastic and E) buried plastic in the mid-row region as shown in Figure 1. These treatments were selected based on our earlier experience of similar study in the field (Stevens et al., 2013).

4. Modelling description

The HYDRUS-2D software package (Šimůnek et al., 2011) was used to simulate the transient two-dimensional movement of water and solutes in the soil. This program numerically solves the Richards' equation for variably-saturated water flow, and advection-dispersion equations for both heat and solute transport. The model additionally allows specification of root water uptake, which affects the spatial distribution of water and salts between irrigation cycles. The solute transport equation considers the advective-dispersive transport in the liquid phase, as well as diffusion in the gaseous phase. The theoretical part of the model is described in detail in the technical manual (Šimůnek et al., 2011) and in Šimůnek et al., (2008).

The modelling domain was constructed based on the vine spacing and drip design parameters (Figure 2). The vine row was assumed to be present at the centre of the domain which was extended equally on both sides across the row. Vertical distance was equal to 100 cm of soil depth. A time-variable flux boundary condition was applied to a 20 cm long boundary directly below the dripper, centred on 137.5 cm from the top left corner of the soil domain (Figure 1). The length of the boundary was selected to ensure that all water could infiltrate into the soil without producing positive surface pressure heads, because positive pressure heads at the flux boundary could make the numerical code unstable. During irrigation, the drip line boundary was held at a constant water flux, *q*. The atmospheric boundary condition was assumed for the remainder of the soil surface during periods of irrigation, and for the entire soil surface during periods between irrigation. A no-flow boundary condition was established at the left and right edges of the soil profile, to account for flow and transport symmetry. A free drainage boundary condition was assumed at the bottom of the soil profile. All these boundary conditions are illustrated in Figure 3. A special boundary with no evaporation was imposed for surface plastic cover. A free draining sandy soil was assumed over the plastic to facilitate water flow form plastic covered mid-row mound. The mathematical details of applying the boundary conditions to a domain similar to the current one can be obtained from Phogat et al. (2012).

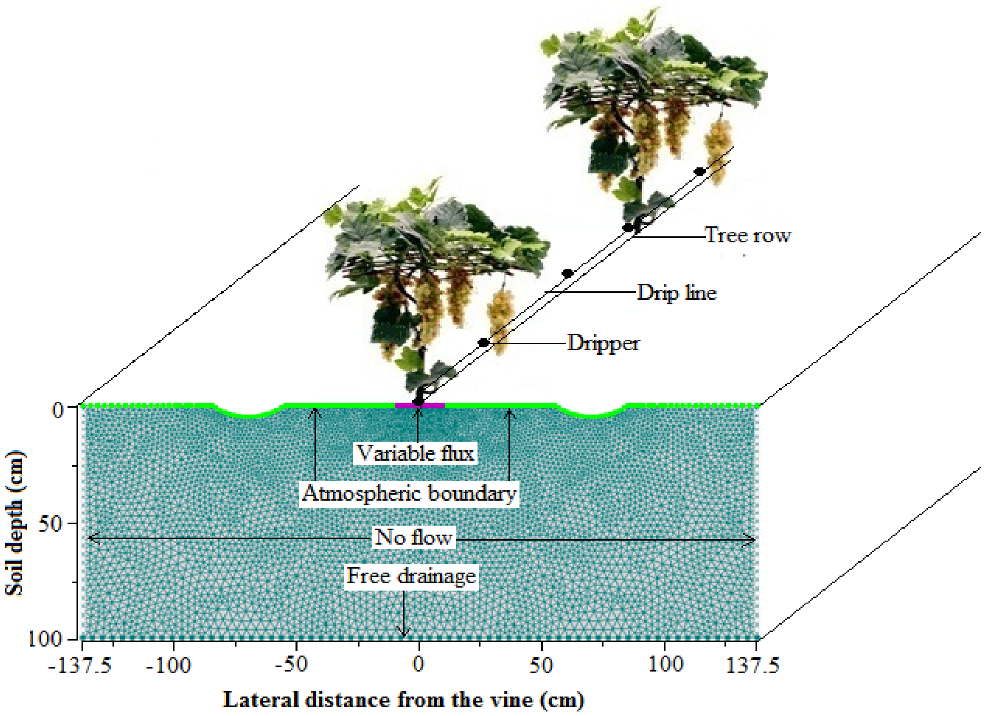

Figure 1. Schematic view of the 2D spatial modelling domain based on vine and drip spacing showing applied boundary conditions.

The initial water content distribution was set at the soils field capacity for all locations. Measured values of *ECe* in the soil were converted into EC_{sw} (salinity of the soil water) to be used as initial conditions in the model based on the initial and saturated moisture content following Phogat *et al.* (2012).

Estimation of salt balance and leaching efficiency

Estimation of salt leaching is an important criterion to judge the efficiency of different rainfall redirection techniques in maintaining the salt free rootzone. Modelling simulation estimates the leaching fraction and also the amount of salts flushed out of the soil with the fraction of water passing out of the root zone. Calculation of rootzone salinity is based on the following assumptions: the irrigation water mixes completely with the soil water; the exchange processes and chemical reactions which take place in the soil are not taken into consideration; the amount of salts supplied by rainfall and fertilizers and exported by crops are negligible; and a zone of shallow groundwater is created with the same average salinity concentration as the percolation water. Salt leaching efficiency is the measure of effectiveness of various rainfall redirection techniques. There are different ways to define the leaching efficiency e.g. fraction of added salts leached and amount of salts leached per volume of water drained. Hence both variants were estimated to compare the salts leaching efficiency.

5. Results

5.1. Loxton

5.1.1. Water balance

Rainfall redirection had little impact on vine water uptake as the transpiration remained almost similar in all treatments (Table 5). The mean water balance showed that transpiration accounts for 49% of the applied water, and 26% of irrigation and rainfall contributes towards evaporation losses leaving 25% water draining out of the soil profile; which is significant. However, evaporation was reduced to 16% of the applied water in treatment D (where the mid-row mound was covered with plastic).

Table 5. Model simulated annual water balance for vineyards under different rainfall redirection treatments for three consecutive seasons at Loxton (2011-2014).

Year/ Treatment	Irrigation	Rainfall	Transpiration	Evaporation	Drainage	Soil storage/ depletion
	-------------------------------------mm---					
A) Control						
2011-12	402.44	298.2	384.57	222.76	108.32	-9.81
2012-13	536.44	198.7	326.49	225.28	171.32	26.18
2013-14	477.60	348.3	405.30	231.00	200.75	-18.15
B) Mid-row mound						
2011-12	402.44	298.2	384.80	232.44	112.75	-10.09
2012-13	536.44	198.7	327.61	235.60	190.29	19.81
2013-14	477.60	348.3	405.60	228.67	203.22	-18.35
D) Mid-row mound+plastic						
2011-12	402.44	298.2	385.94	114.73	217.97	-14.83
2012-13	536.44	198.7	329.66	118.09	278.61	20.06
2013-14	477.60	348.3	406.81	119.40	328.69	-21.22
E) Buried plastic						
2011-12	402.44	298.2	383.71	224.97	106.14	-9.42
2012-13	536.44	198.7	325.15	227.29	169.87	25.52
2013-14	477.60	348.3	402.11	230.70	203.05	-17.01

Consequently, this intervention almost doubled the drainage/leaching losses (36%) which are responsible for transporting the salts and other dissolved chemicals to the deeper layers in the soil or to the groundwater under shallow water table situations. The mean reduction in evaporation under treatment D over 3 seasons was 48.5% as compared to the control.

This increased drainage losses by 73% as compared to the control. This could have massive impact on salt leaching in this treatment (D) from the under vine (UV) as the mid row rain was directed to move towards the vine row area. The impact of this profound leaching event has been clearly visible in the *ECe* distribution (Figure 2) in the following section as well. Interestingly in treatment E, placing the plastic at 10 cm depth in the soil could not control the evaporation losses because most of the evaporation in stage 1 is influenced by the water availability in the upper 10-15 cm of soil depth (Allen et al., 1998). Hence this treatment resembles more or less the control in terms of the water balance.

5.1.2. EC distribution

The *ECe* distribution with depth in the soil at the end of the 2011-12, 2012-13 and 2013-14 seasons for the treatments at Loxton is shown in Figure 2. All treatments had tremendous impact on reducing *ECe* by leaching salts out of the root zone. Salinity remained lower in the under vine region irrespective of the rainfall redirection treatments. However, the presence of buried plastic in treatment E encourages salt deposition just below it, as it blocks the vertical drainage of water and encourages lateral salt migration to the area underneath the plastic. However, in the mid-row mound with plastic cover (treatment D), the low salinity zone (<0.5 dS/m) extended further under the vine compared to other treatments. In the subsequent season (2012-13), a similar extent of *ECe* distribution was noticed as observed at the end of previous season. However, the low *ECe* zone under the vine stretched over a larger area in all the treatments as compared to the previous season.

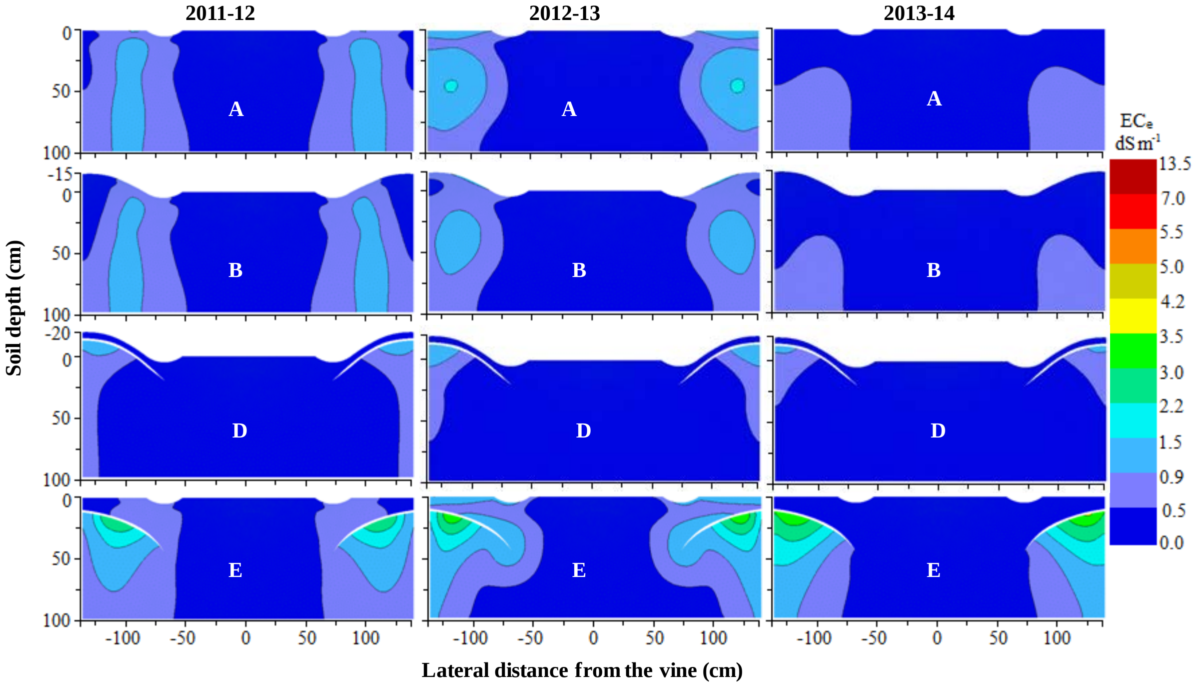

Figure 2. Electrical conductivity (*ECe*) distribution in the soil in different treatments (A- control, B- MR mound, D- MR mound+ plastic, E- Buried plastic) during 3 seasons at Loxton.

The mid-row region (MR) showed slightly high salinity distribution than under the vine region. At the end of 3rd season (2013-14) low *ECe* zone (<0.5 dS/m) increased laterally in all treatments. Hence, the current irrigation amount and quality of water doesn't pose any threat of salinity in the rootzone of the vine irrespective of treatments. It is also evident that most of the irrigation induced salts were leached out of the zone of interest and a small portion of salts may be pushed laterally in the mid row zone especially in treatment E. Occurrence of highly permeable light textured soils, low salinity of irrigation water and almost double irrigation application than other sites facilitated the rapid flushing of salts from the root zone at Loxton.

Similarly, the average daily salinity (*ECe*) distribution for 3 seasons under different treatments remained below threshold tolerance level of 2.2 dS/m (Zhang et al., 2002) for grapevines in Australia (Figure 3). However, the magnitude of average *ECe* under MR remained higher than under vine (UV) and under track (UT) regions in all the treatments. Treatment E D had slightly higher *ECe* than other treatments and a continuous increasing trend in *ECe* was observed at MR region in the domain. It shows that buried plastic cover (E) encourages salt deposition under the mid-row region and increasing salinity trend is visible even at the end of the 2013-14 season. Hence there is no perceptible impact of rainfall redirection techniques at Loxton where light textured soils and good quality irrigation water help in flushing of salts out of the root zone. Christen et al. (2007) showed similar impact on the salinity distribution when using good quality irrigation water on a loam.

5.1.3. Salt balance

Irrigation water quality in the Riverland is very good as salinity of the River Murray is quite low (0.3 to 0.4 dS/m). Hence, despite the high volume of irrigation applied at Loxton, the amount of salts added to the soil is low (Figure 4). The annual amount of salts added through irrigation varied from 900 to 1200 kg/ha during 2011 to 2014 depending on the volume of water applied annually. Additionally the amount of salts added through rain (136 to 247 kg/ha) were much lower as compared to salts added through irrigation during the same period because Loxton receives less precipitation as compared to other grapevine growing regions in SA (Table 4). Hence Loxton seems to be in a privileged location for managing potential salinity issues in irrigated horticulture. However, occurrences of drought and scarcity of good quality irrigation water may pose a serious danger on the long term sustainability of vineyards in this region.

On the other hand salt leaching was very rapid and higher amount of leaching of salts occurred vis-a-vis the amount of addition through irrigation and rainfall (Table 6). There was a net depletion of salts from the soil at the end of 2013-14 grapevine growing season in all the treatments. However, mid-row mound with plastic cover (D) had higher leaching of salts (4769 kg/ha) from the soil as compared to other treatments due to substantially higher drainage flux as compared to other treatments. High amounts of salt leaching in D is also reflected in the higher salt leaching efficiency per amount of seasonal salts added (LE_s; 1.74 kg salts/kg salts applied) as compared to other rainfall redirection techniques especially during 2011-12. However, overall leaching of salts in this treatment was less efficient in respect of leaching fraction (LE_w) as it could have been achieved with less leaching fraction experienced in other treatments especially under control treatment where leaching efficiency varied from 0.78 to 1.33 kg/m^3. The efficiency during 2012-13 was lower than the preceding season despite there was higher drainage during 2012-13. This happens because there were higher amounts of salts stored in the soil during 2011-12 especially under the vine but they were flushed out of the soil during the first season. Hence, during subsequent season (2012-13) the quantity of salts under the vine reduced drastically, however, high irrigation water (536 mm) was added which lead to high drainage and low amount of salt leaching. In contrast, in the mid-row region salt leaching was mostly governed by the rainfall. Hence low rainfall during 2012-13 encouraged salt storage. Therefore the overall balance showed salt storage in spite of higher drainage as compared to the preceding season. During 2013-14 salt leaching again increased due to increased mid-row leaching of salts which also increased the salt leaching efficiency.

These results showed that at Loxton there was no appreciable advantage of rainfall redirection techniques on overall salt leaching in the soils as the leaching fraction under control treatment was sufficient to flush the salts out of the soil profile. Hence these techniques should be adopted cautiously depending upon the soil, climate and irrigation water quality available for irrigation at a particular location.

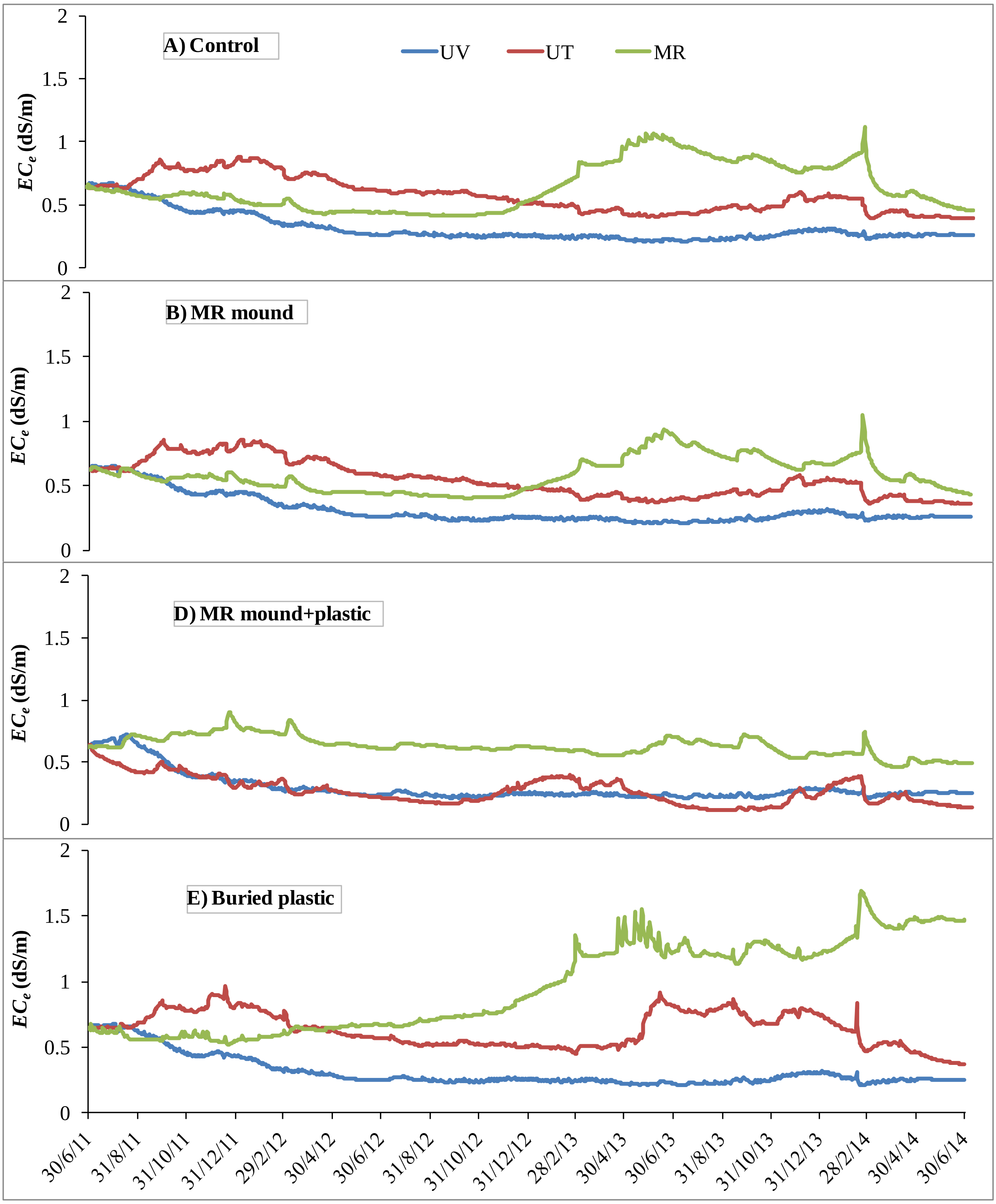

Figure 3. Average *ECe* (dS/m) distribution under vine (UV), under traffic (UT) and at mid-row (MR) in different rainfall redirection treatments (A- control, B- MR mound, D- MR mound+ plastic, E- Buried plastic) at Loxton during 2011 to 2014.

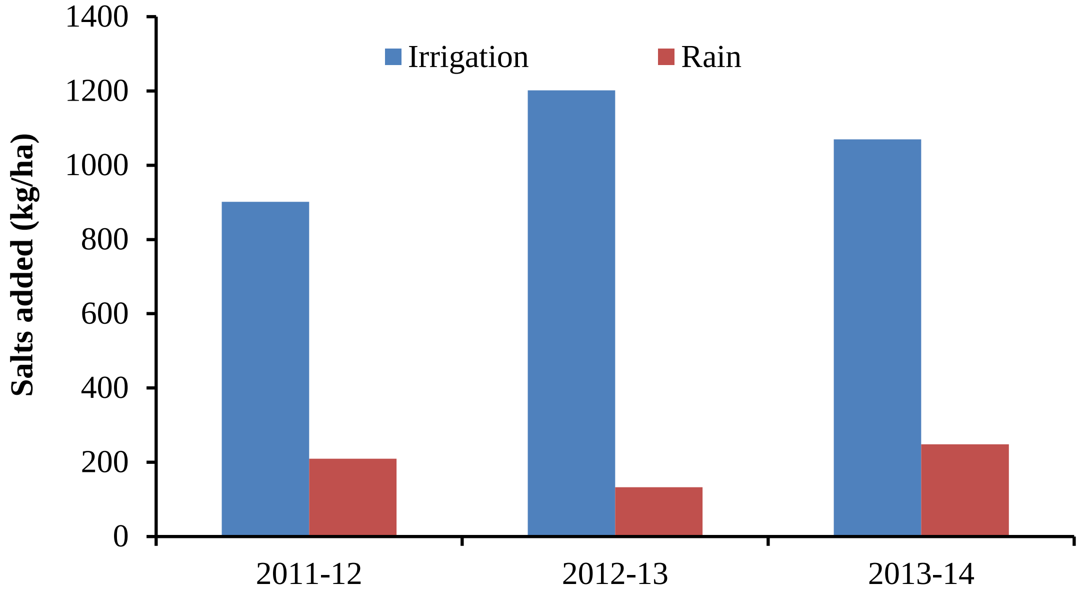

Figure 4. Amount of salts added in the soil through rainfall and irrigation applications to grapevine during three seasons (2011-14) at Loxton.

Table 6. Drainage flux, salt leaching and storage and salt leaching efficiency in different treatments during 3 seasons (2011-14) at Loxton.

Treatments/ seasons	Drainage flux (m^3/ha)	Amount of Salts leached (kg/ha)	Salt storage/ depletion (kg/ha)	Salt leaching efficiency	
				LE_s (kg leached/ kg applied)	LE_w (kg leached/ m^3 water)
A) Control					
2011-12	1048.00	1396.58	-262.33	1.26	1.33
2012-13	1677.82	1315.82	182.33	0.98	0.78
2013-14	1942.91	1857.42	-561.45	1.41	0.96
B) MR mound					
2011-12	1041.38	1381.93	-250.84	1.25	1.33
2012-13	1767.09	1366.47	71.64	1.01	0.77
2013-14	1966.80	1763.23	-487.02	1.34	0.90
D) MR mound+plastic					
2011-12	2109.02	1957.34	-835.78	1.74	0.93
2012-13	2728.44	1370.18	5.24	1.02	0.50
2013-14	3181.09	1441.56	-177.67	1.08	0.45
E) Buried plastic					
2011-12	1026.95	1208.76	-76.84	1.09	1.18
2012-13	1663.60	1146.29	252.15	0.86	0.69
2013-14	1965.09	1558.03	-184.87	1.18	0.79

5.2. McLaren Vale

5.2.1. Water balance

The rainfall redirection treatments had varied impact on water balance under grapevine at the McLaren Vale site. Mid-row mound covered with plastic (D) brought about higher water uptake by the vine followed by buried plastic (E) as compared to other treatments. At the same time there was drastic reduction in the evaporation flux which encouraged higher drainage especially during second and third season. The average reduction in evaporation flux over three seasons was 54% as compared to the control. Plastic treatment (D) also increased soil water storage as compared to other treatments and average soil storage increased by about 4 times as compared to the control. At the same time there was a 3 times increase in leaching fraction and total drainage flux in D compared with the other treatments. This could have a significant impact on removal of salts out of the soil profile providing an effective salinity control for sustainable vineyard production. The overall water balance irrespective of seasons and treatments showed that transpiration accounts for 39% of the water application, evaporation 44% and 17% leaching fraction at McLaren vale. Plastic cover in treatment D reduces the average evaporation to 23% and leaching fraction (LF) increases to 33% which is approximately twice than the overall average LF. While the mean LF in other treatments amounts to 10-13% and evaporation accounts for 51% of water application.

Table 7. Model simulated annual water balance for vineyards under different rainfall redirection treatments for three consecutive seasons at McLaren Vale (2011-2014).

Year/ Treatment	Irrigation	Rainfall	Transpiration	Evaporation	Drainage	Soil storage / depletion
	--------------------------------------mm--					
A) Control						
2011-12	82.16	614.3	245.14	340.90	65.91	51.21
2012-13	129.44	437.1	196.37	317.20	85.53	-25.00
2013-14	135.20	524.0	261.66	309.28	93.96	-14.40
B) Mid-row mound						
2011-12	82.16	614.3	245.94	341.79	63.96	52.21
2012-13	129.44	437.1	195.04	318.78	86.31	-26.47
2013-14	135.20	524.0	259.14	310.05	94.73	-13.43
D) Mid-row mound+plastic						
2011-12	82.16	614.3	289.89	155.31	183.98	79.97
2012-13	129.44	437.1	231.11	147.53	219.92	-25.89
2013-14	135.20	524.0	295.07	142.07	219.55	-6.98
E) Buried plastic						
2011-12	82.16	614.3	264.68	343.43	28.57	58.14
2012-13	129.44	437.1	207.57	319.17	65.69	-14.41
2013-14	135.20	524.0	277.11	307.34	90.17	-18.47

The mean increase in transpiration in treatment D is about 3-6% higher than other treatments. In summary, mid-row mound with plastic cover has the best impact in reducing salinity and improving soil water storage and plant water uptake in McLaren Vale.

5.2.2. EC distribution

At McLaren Vale high concentration of salts were present under the vine region as compared to the mid row (MR) in all the treatments (Figure 5). In drip irrigated vineyards the irrigation is applied under the vine region and the salts present in the irrigation water are deposited in the region just below the dripper. If insufficient water is applied for leaching, there is a tendency of salt deposition within this region. Moreover, plant water uptake is much higher from this region due to the high intensity of roots, leaving less water for leaching the salts. Additionally, in heavy clay soils as present at McLaren Vale water movement is very slow which delays the leaching of salts from the soil. On the other hand, in the MR lesser amounts of salts are added coupled with high rainfall induced salt flushing encourages low salt deposition as compared to UV region. However, higher *ECe* "pockets" were present in the control compared to other treatments. Contrary to Loxton, an increasing trend in *ECe* distribution occurred especially under the vine at the end of successive seasons which is correlated with proportionally higher addition of salts through irrigation coupled with less localised drainage within this region. Among the treatments buried plastic (E) showed less *ECe* distribution under the vine as compared to other treatments. Whereas treatment D showed higher proportion of low salinity region within the mid-row and under track region as compared to rest of the treatments. At the end of 2013-14 season the maximum *ECe* in the under vine region was 4.2, 3.5, 3.5 and 3.0, respectively in A, B, D and E treatments. However, MR region salinity remained below 0.5 dS/m in D whereas it was <0.9 dS/m in A and B treatments and much higher in E (0.9-1.5 dS/m). The results showed that at McLaren vale predominance of heavy textured soils, high irrigation water salinity encouraged salt deposition in the vicinity of vine.

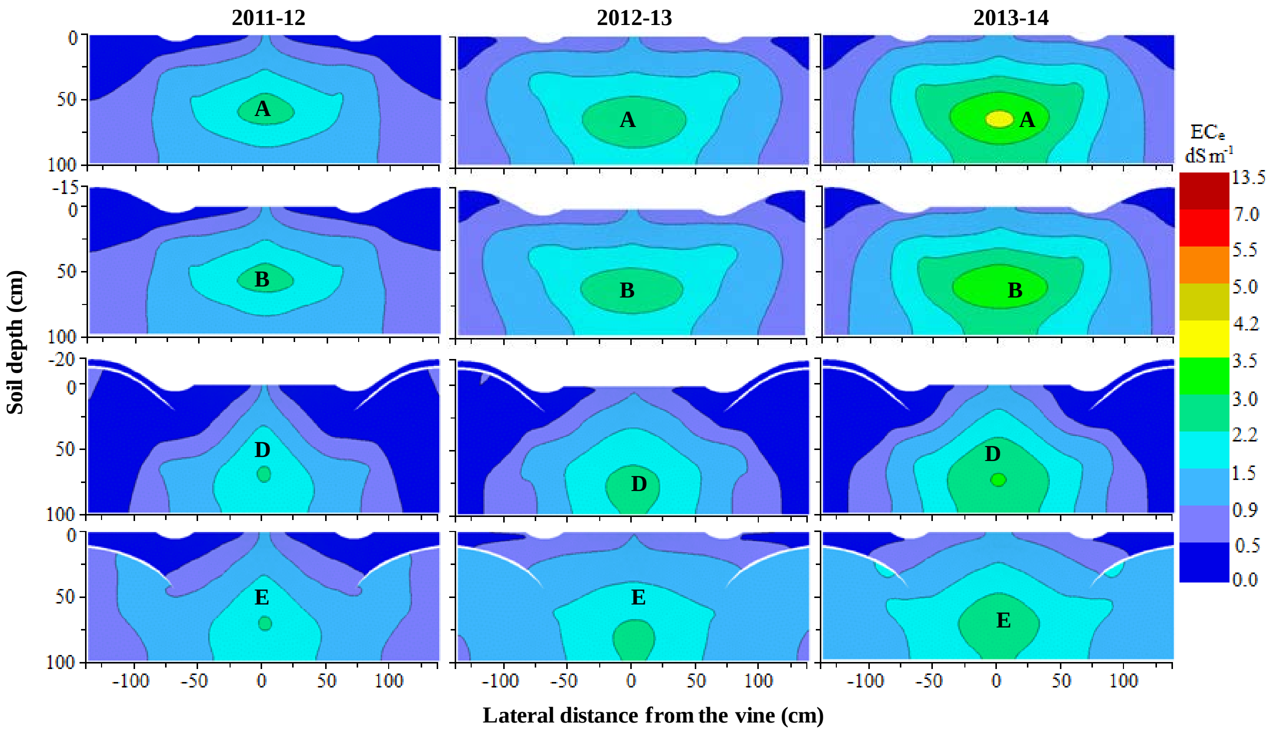

Figure 5. Electrical conductivity (*ECe*) distribution in the soil in different treatments (A- control, B- MR mound, D- MR mound+ plastic, E- Buried plastic) during 3 seasons at McLaren vale.

Daily profile average salinity distribution under vine (UV), under track (UT) and in the mid-row (MR) region at McLaren vale is shown in Figure 6. A progressive increase in *ECe* was found in all the treatments over the 3 seasons at all locations except in treatment D under MR and UT where the *ECe* remained almost constant over 3 seasons. However, the *ECe* remained below threshold under MR and UT region in all the treatments. On the other hand, it increased above threshold under the vine (UV) during the latter half of 2013-14 in all the treatments. There were sharp decreases in *ECe* under the UV region during winter and spring especially in treatment D and E due to rainfall redirection towards the vine row. *ECe* increased again during the summer season due to less rain. Hence treatment D and E are best at removing salt during the growing season at McLaren Vale compared to other treatments; however, the impact on average salinity seems marginal.

5.2.3. Salt balance

Quantitative salt balance is important to know the relative importance of different rainfall redirection techniques in reducing the salinity hazard and maintaining a suitable environment for vineyard growth. Mostly the salts are added to the soil either through irrigation water or through rainfall. Model estimated salt addition at McLaren vale for three seasons is shown in Figure 7. Irrigation added 631, 994 and 1038 kg salts per hectare during 2011-12, 2012-13 and 2013-14 season, respectively. Similarly high rainfall amount during 2011-12 added more salts (434 kg/ha) to the soil as compared to following seasons.

Salt deposition in the soil was similar in all the treatments, however, salt storage and leaching was modified due to rainfall redirection techniques (Table 8). Drainage flux and amount of salts leached during 2011-14 remained almost similar in treatments A and B. However the mid row mound with plastic cover treatment (D) resulted in more than twice the average salt removed (884 kg/ha) as compared to the control (406 kg/ha). This was due to the increased leaching fraction of the two-pronged strategy of redirection of rainfall and reduction in evaporation losses due to surface cover. Buried plastic treatment also recorded higher average salts leaching (563 kg/ha) than control and mid-row mound. Interestingly all treatments showed enormous salt storage during all the 3 seasons which is also supported by continuous increase in the *ECe* of the soil under all the treatments (Figure 6). However, average salt storage in treatment D reduced by half as compared to other treatments due to increased drainage flux but it was not enough to flush all added salts out of the soil profile. Salt storage in the soil drastically reduced during 2013-14 especially in treatment E which was almost equal to the storage recorded in treatment D with lower leaching volume as compared to D. Hence treatment E showed maximum leaching efficiency per drainage flux (LE_w) not only during 2013-14 but also during preceding seasons (2011-12 and 2012-13) as well. Treatment D was the worst in terms of LE_w as it has the lowest efficiency among all the treatments. On the other hand it had maximum efficiency per amount of seasonal salts (LE_s) added which varied from 0.63- 0.77 kg/kg salts added.

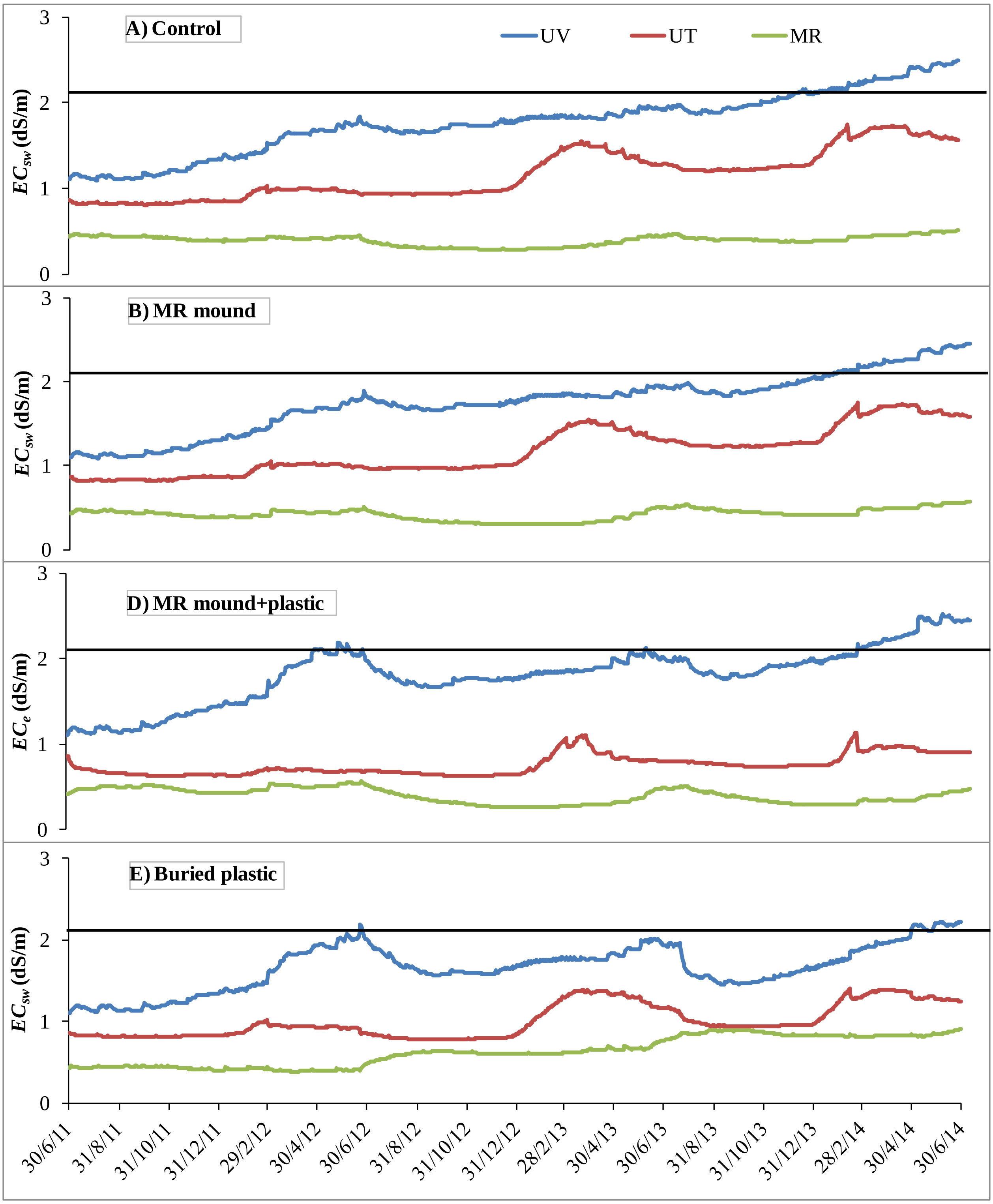

Figure 6. Average ECe (dS/m) distribution under vine (UV), under traffic (UT) and at mid-row (MR) in different rainfall redirection treatments (A- control, B- MR mound, D- MR mound+ plastic, E- Buried plastic) at McLaren vale during 2011 to 2014.

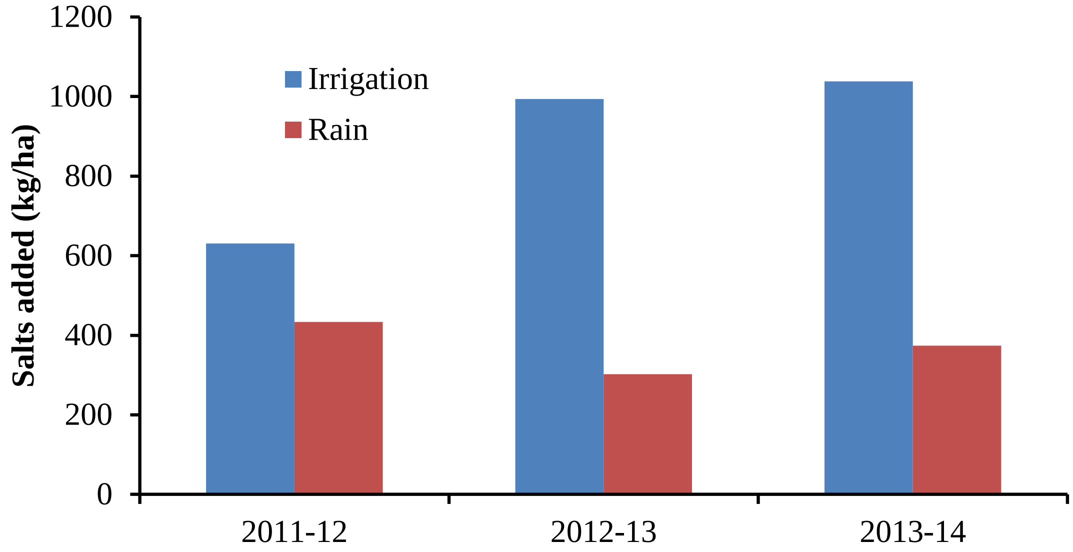

Figure 7. Amount of salts added in the soil through rainfall and irrigation applications to grapevine during three seasons (2011-14) at McLaren vale.

Table 8. Drainage flux, salt leaching and storage and salt leaching efficiency in different treatments during 3 seasons (2011-14) at McLaren Vale.

Treatments/ seasons	Drainage flux (m^3/ha)	Amount of Salts leached (kg/ha)	Salt storage/ depletion (kg/ha)	Salt leaching efficiency	
				LE_s (kg leached/ kg applied)	LE_w (kg leached/ m^3 water)
A) Control					
2011-12	614.73	292.68	818.84	0.27	0.48
2012-13	804.87	377.65	869.31	0.29	0.47
2013-14	882.55	548.04	807.64	0.39	0.62
B) MR mound					
2011-12	596.47	287.87	831.71	0.27	0.48
2012-13	812.25	408.93	842.04	0.32	0.50
2013-14	889.78	591.09	764.73	0.42	0.66
D) MR mound+plastic					
2011-12	1786.95	840.22	403.96	0.77	0.47
2012-13	2143.96	839.67	466.14	0.63	0.39
2013-14	2138.55	971.60	433.67	0.68	0.45
E) Buried plastic					
2011-12	266.41	246.60	876.11	0.23	0.93
2012-13	618.17	495.08	758.22	0.38	0.80
2013-14	846.95	948.07	453.09	0.67	1.12

5.3. Padthaway

5.3.1. Water balance

The water balance at Padthaway was similar to McLaren Vale. The average transpiration accounts for 39% of the total water applied whereas evaporation contributes 37%. Mean drainage flux (17%) was similar to that at McLaren Vale. The major difference was the soil storage which represented about 6% at Padthaway due to lower hydraulic flow. However, in treatment D the amount of evaporation reduced to 20% which consequently increased the drainage flux by 14% over the mean value. Whereas drainage flux in other treatments was 4-5% lower than the mean values and evaporation accounted for 43%. However, in treatment D, transpiration increased by 7.5%, evaporation reduced by half and drainage increased 3 times as compared to the control; which is highly significant. Hence treatment D has emerged as the most favourable treatment with increased plant water uptake and more of the evaporative flux diverted towards leaching; which can help in maintaining the favourable environment by transporting salts out of the root zone.

Table 9. Model simulated annual water balance for vineyards under different rainfall redirection treatments for three consecutive seasons at Padthaway (2011-2014).

Year/ Treatment	Irrigation	Rainfall	Transpiration	Evaporation	Drainage	Soil storage/ depletion
	-------------------------------------	----------	----------mm----------	----------	----------	----------
A) Control						
2011-12	242.54	466.4	259.43	311.08	14.34	111.58
2012-13	242.55	446.4	267.57	312.79	101.31	35.74
2013-14	242.51	576.9	325.58	331.58	165.58	-18.91
B) Mid-row mound						
2011-12	242.54	466.4	265.73	311.94	15.61	103.44
2012-13	242.55	446.4	270.38	313.85	94.00	35.81
2013-14	242.51	576.9	328.77	333.34	164.15	-19.45
C) Mid-row mound+plastic						
2011-12	242.54	466.4	296.07	144.77	112.76	152.36
2012-13	242.55	446.4	286.99	148.58	275.61	-11.34
2013-14	242.51	576.9	333.03	153.37	297.50	13.19
D) Buried plastic						
2011-12	242.54	466.4	260.73	312.72	18.64	107.33
2012-13	242.55	446.4	267.15	306.79	125.45	13.85
2013-14	242.51	576.9	328.62	326.50	143.22	4.71

5.3.2. EC distribution

The initial salinity at Padthaway was very high compared to the other sites because irrigation water is groundwater which has EC_w from 2.0-2.35 dS/m. The initial *ECe* of the soil varied from 4-4.5 dS/m under vine and from 1.2-1.8 dS/m in the mid-row region. Heavier texture and low hydraulic conductivity (11-26 cm/day) is conducive to salt deposition within the soil profile in the immediate vicinity of the vine, where irrigation is being applied through drippers. Therefore, pockets of high *ECe* (5.5-7.0 dS/m) still exist under the vine below 50 cm depth in A, B and E treatments at the end of 2011-12 vine growing season (Figure 8). Salinity decreased in the following seasons in all these treatments however, the higher salinity zones (higher than grape vine threshold salinity) were still present in the UV region. The maximum salinity zone had *ECe* from 3.5-4.0 dS/m at the end of 2013-14. However, this zone spread over a large area in A and B treatments as compared to E where it was restricted within a small region mostly in the deeper zone of the profile.

Treatment D was very different to the other treatments. Due to rainfall redirection towards the vine row, a significant volume of water passed through the zone of high salinity carrying salt out of the profile. Consequently the salinity reduced within the first season (Figure 8). During the following season (2012-13) the soil profile salinity reduced below threshold (2.2 dS/m) in almost the entire UT and MR region whereas pockets of higher salinity existed in the UV region below 30 cm soil depth. A similar salinity distribution was maintained during 2013-14. Thus the mid-row mound covered with plastic maintained relatively lower salinity within the vine root zone as compared to other treatments, providing a better growing environment for vine and a superior salt leaching intervention as compared to other techniques.

Hence, the salinity distribution in treatment D at Padthaway at the end of 2013-14 resembles with the kind of responses received at McLaren vale at the end of first season. The salinity remained always higher under the vine as compared to mid-row region; however, treatment D had pronounced impact on flushing the salts vertically and laterally away from the vine region. Hence, treatment D continued to have tremendous impact on salt removal, whereas, buried plastic showed marginally higher salt removal from the UV region at McLaren vale at the end of 3rd season. These results indicate that the treatments behaved different at different locations and impact on salt removal due to rainfall redirection technique depends on soil, water and weather parameters.

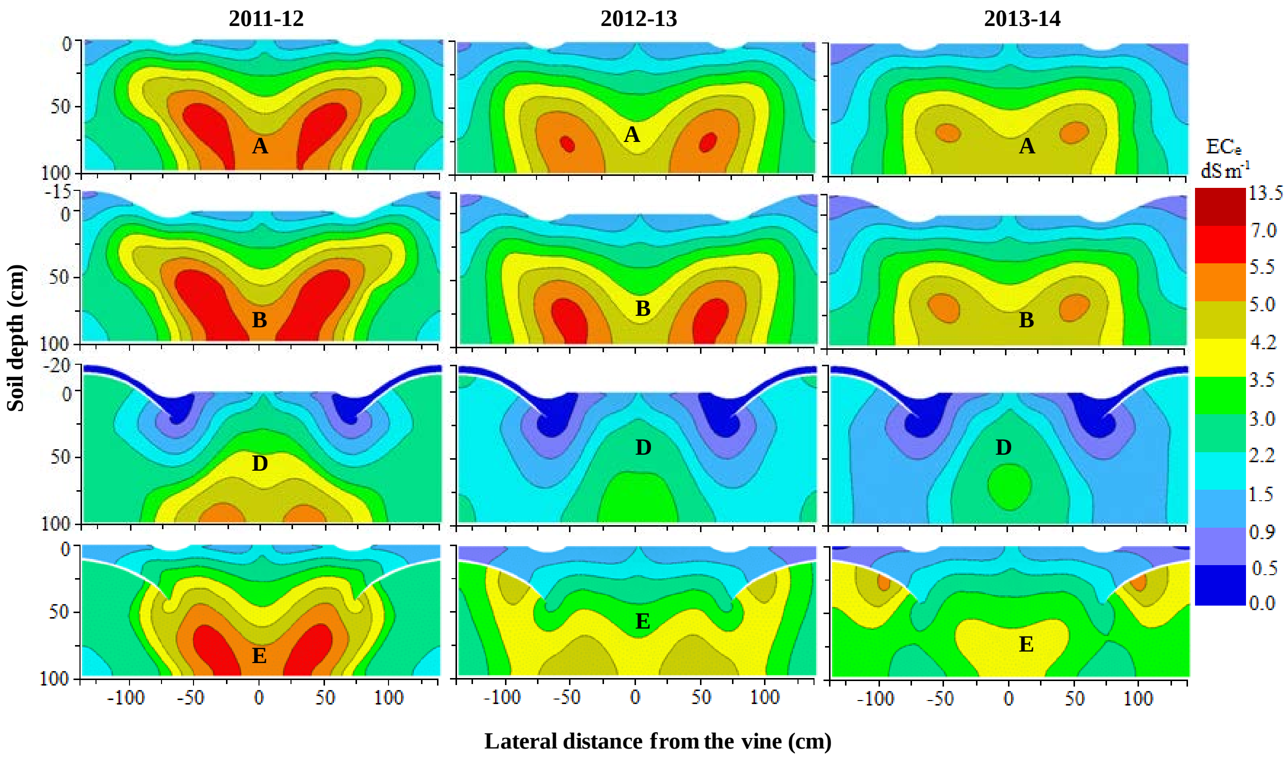

Figure 8. Electrical conductivity (*ECe*) distribution in the soil in different treatments (A- control, B- MR mound, D- MR mound+ plastic, E- Buried plastic) during 3 seasons at Padthaway.

Temporal salinity dynamics under UV, UT and MR regions of the soil profile during 2011-2014 at Padthaway is shown in Figure 9. Daily average salinity of the control profile was almost similar to the mid row mound without plastic (B). The average *ECe* under vine and under track was higher than the threshold salinity (2.2 dS/m) for grape vine whereas the *ECe* in the MR region remained below threshold. It means that mid row mound only is unable to reduce the *ECe* of the soil under vine in all regions. However tremendous impact of mid-row mound with plastic cover (D) occurred especially in UV and UT regions where *ECe* reduced drastically. As the redirected rain water moves in the depression made by the machinery and infiltrates down in the soil, hence maximum impact of salinity reduction was observed under tract region. Consequently, the mean salinity under UT initially increased during the summer of 2011-12 and rapidly comes down below threshold after the onset of rainfall season during 2012 autumn and winter season. Thereafter the *ECe* under UT remained below threshold. Similarly, profile average *ECe* under UV also decreased gradually after initial shoot up during 2011-12 summers. However, it remained higher than threshold and impact of rainfall redirection was not as rapid as obtained under UT region. The mean *ECe* in treatment E falls in between the values obtained in control and D treatment especially under UV and UT regions. Interestingly *ECe* under MR region increased above threshold in E treatment during 2013-14 growing season. Buried plastic probably harbour more salts due to blockage of vertical drainage and encourage gradual lateral movement of salt underneath which is also visible in Figure 8.

5.3.3. Salt balance

The salinity of irrigation water (EC_w) at Padthaway varied from 2.0-2.35 dS/m which is adding huge amount of salts in the soil. The irrigation schedule for all 3 seasons is same. Hence similar amount of salts are added in the soil which amounts to 3352 kg/ha. Salts added through rainfall (330-408 kg/ha) are much less in comparison to the amount added through irrigation. Over the three seasons irrigation added about 10 tons salts/ha while rain topped up this amount with a little higher than 1 ton salts/ ha which is enormous amount. Ignoring biosalt harvest through plant uptake and adsorption of these salts in soil which is very less, most are bound to be transported in the groundwater potentially increasing the salinity of the groundwater.

Due to low intensity of flushing caused by low hydraulic conductivity of the heavier textured soil at Padthaway, salt leaching was very slow. Hence there was a net deposition of salts during 2011-12 and 2012-13 in the control and mid-row mound treatment (Table 10). However these treatments had a net depletion during 2013-14 due to high rainfall as compared to previous seasons. While plastic cover (D) and buried plastic (E) had a net depletion during second and third season which was much higher in treatment D than E particularly during 2012-13 (3298 kg/ha). The overall depletion over 3 seasons was 3578 kg salts/ha in D as compared to a much lower range of 1076-1515kg/ha in other treatments. Hence, treatment D had a tremendous effect on salt leaching from the soil under grape vine. A total of 14.6 t/ha salts were leached during 2011-14 in treatment D which is 57% higher than control. Total salt leaching in other treatments ranged from 9.3-9.7 t/ha. The higher leaching in D was achieved due to more than double drainage flux (6.7 ML/ha) occurred in this treatment as compared to other treatments (2.6-2.7 ML/ha). Monitoring has shown an increase in groundwater salinity in parts of Padthaway of about 600 mg/L in the last 25 years, from around 800 mg/L to 1400 mg/L (Cleugh, 2006).

Salt leaching efficiency in terms of salts leached/ amount of salts added (LE_s) was influenced by the amount of salts leached during a particular period as the amount of salts application is similar in all the treatments. Hence, during 2011-12, the LE_s was very low (0.12-0.13 kg/kg salts added) in treatments A, B and E as compared to treatment B (1.04 kg/kg salts added).

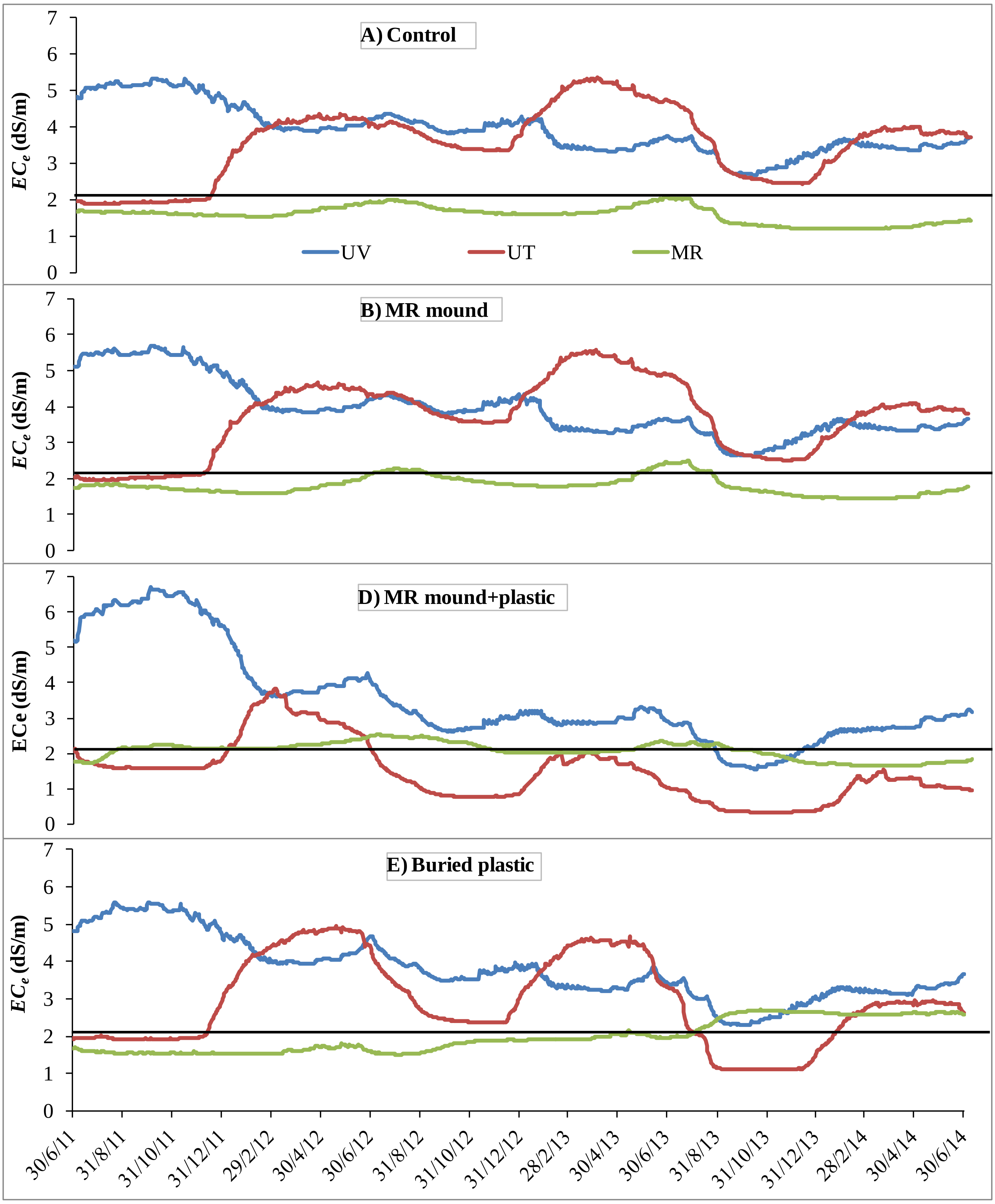

Figure 9. Average *ECe* (dS/m) distribution under vine (UV), under traffic (UT) and at mid-row (MR) in different rainfall redirection treatments (A- control, B- MR mound, D- MR mound+ plastic, E- Buried plastic) at Padthaway during 2011 to 2014.

However, leaching efficiency in terms of salts leached/volume of drainage flux (LE_w) in treatment D was almost similar to A and B because increased amount of drainage flux in D proportionally increased the amount of salts leaching from the soil. Likewise, the LE_s was maximum (1.81 kg/kg added salts) in D during the following season 2012-13 due to enormous amount of salt leaching whereas LE_w was reduced as compared to A and B treatments because the drainage flux was much higher in D than others. Maximum LE_w (4.19 kg/m^3) was recorded in treatment E during 2012-13 where ratio of salts leached/volume of drainage flux was greatest as compared to other treatments. This is also visible in Figure 8 which showed drastic reduction in *ECe* of soil in E as compared to control. Hence this treatment is the most efficient while treatment D is least efficient during 2013-14 which had LE_w of 1.41 kg/m^3. However, in terms of overall salt removal mid-row mound covered with plastic (D) was the most efficient technique bringing drastic change in the salt distribution in the soil.

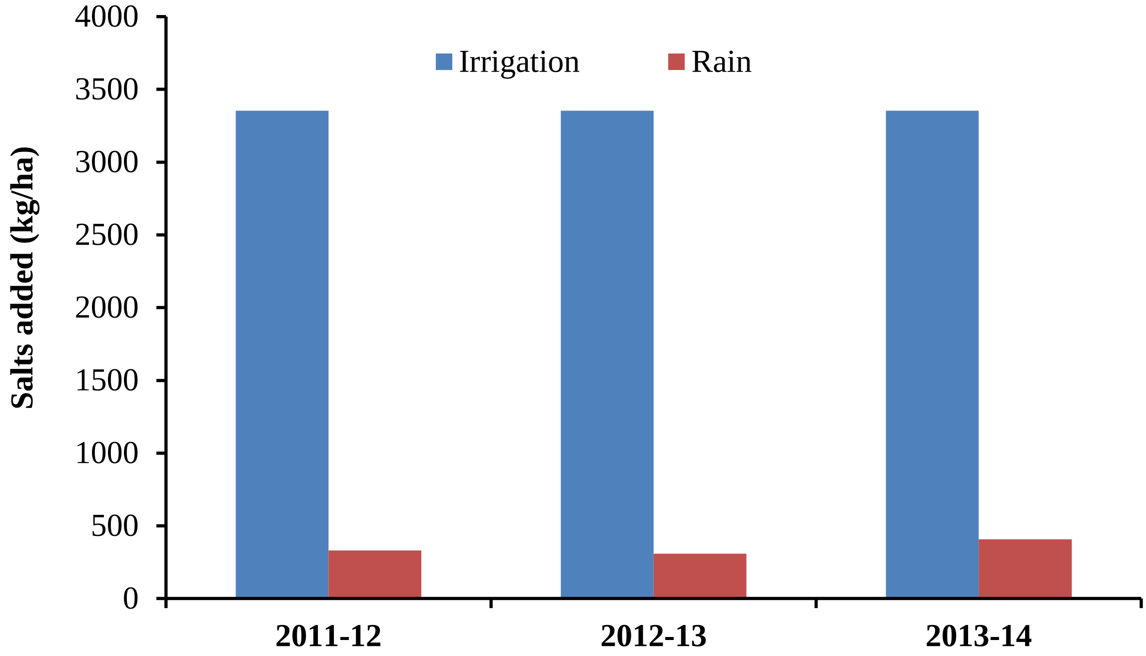

Figure 10. Amount of salts added in the soil through rainfall and irrigation applications to grapevine during three seasons (2011-14) at Padthaway.

Excessive transport of root zone salts and chemicals under grapevine may pose a potential danger for the groundwater pollution. Hence there is a kind of trade off exist between the extent of leaching and imminent danger of groundwater degradation. Hence judicious decisions are required for sustainable salinity management and controlling the pollution of groundwater.

Table 10. Drainage flux, salt leaching and storage and salt leaching efficiency in different treatments during 3 seasons (2011-14) at Padthaway.

Treatments/ seasons	Drainage flux (m^3/ha)	Amount of Salts leached (kg/ha)	Salt storage/ depletion (kg/ha)	Salt leaching efficiency	
				LE_s (kg leached/ kg applied)	LE_w (kg leached/ m^3 water)
A) Control					
2011-12	136.16	427.35	3090.18	0.12	3.14
2012-13	962.93	3158.03	566.91	0.86	3.28
2013-14	1566.73	5671.34	-2142.18	1.51	3.62
B) MR mound					
2011-12	148.25	464.98	3052.36	0.13	3.14
2012-13	893.49	3012.83	642.18	0.82	3.37
2013-14	1553.20	5848.36	-2242.18	1.55	3.77
D) MR mound+plastic					
2011-12	1102.36	3828.00	369.45	1.04	3.47
2012-13	2695.09	6647.99	-3297.81	1.81	2.47
2013-14	2904.36	4104.72	-649.45	1.08	1.41
E) Buried plastic					
2011-12	177.07	440.33	3075.63	0.12	2.49
2012-13	1192.42	4999.67	-1067.64	1.37	4.19
2013-14	1355.16	4306.90	-932.00	1.15	3.18

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Appendix H – A review of recycled wastewater in irrigated horticulture

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1. Recycled water for irrigated agriculture in Australia

Most of Australia's population is found on the relatively dry south eastern and south western seaboards. Major water resources, however, are in the north of the continent (Anderson 1996). The Australia's dry climate is exacerbated by large year-to-year variations in rainfall. This means that water storage strategies are needed to buffer against the drier years. In fact, Australia stores more water than any other country (NHT 2001). The uneven distribution of rainfall and population - both spatially and temporally - is typical of Mediterranean environments which often have difficulty matching water supply with demand (Angelakis *et al.* 1999). Given the distribution of population in Australia and the shortage of water resources, reclamation of sewage (reclaimed water) or more generally wastewater (recycled water) can be critical to the protection of fresh and near shore water resources and contribute significant volumes of water to agriculture or industry (Unkovich *et al.* 2004).

In Australia, the regulation of water recycling is a State responsibility. With Australia experiencing regular drought periods in recent decades, its public policy on environmental and water resource management has changed and is actively encouraging water conservation and recycling. In recent years, large schemes have been established to reuse treated wastewater for agricultural, industrial and urban use. In fact, since the late 1990s wastewater reuse has grown from less than 3% to around 16% in 2011 (van Leeuwen *et al.* 2012). Developments in recycling of water in Australia have been discussed by Stevens (2006), Radcliffe (2010) and van Leeuwen *et al.* (2012).

Impacts on agriculture (soils and crops) from irrigation with recycled domestic wastewaters have been extensively reported. These impacts included soil salinity, soil structure and boron toxicity. The fact that they are so well studied is likely due to a focus on ensuring the sustainability and productivity of agricultural lands. Other areas well reported in the international scientific literature are the presence, transport and fate of nutrients, metals and heavy metals in agricultural soils but less so in associated ground waters (van Leeuwen *et al.* 2012).

2. Sources of water for recycling

Sewage

Sewage refers to all material collected from internal household drains. It contains all the contaminants of greywater (discussed below) and urine, as well as waste material from toilets. Sewage can therefore contain human pathogens, plus wastes from industrial and commercial premises. Discharge of trade wastes to sewer can introduce a range of contaminants, particularly chemicals. Sewage also contains nutrients, particularly phosphorus and nitrogen, which have been identified as environmental hazards.

Greywater

Greywater refers to water from kitchen, laundry and bathroom drains, but not from toilets (note: some guidelines exclude water from the kitchen because of food scraps and other undesirable wastes). Greywater may contain human waste from nappy washing and showering, as well as soil, hair, detergents, cleaning products, personal-care products, sunscreens, fats and oils. Cleaning products discharged in greywater can contain boron and phosphates, and the water is often alkaline and saline.

These attributes pose potential risks to the receiving environment if not removed by water treatment. Greywater quality can be affected by inappropriate disposal of domestic wastes.

Stormwater

Stormwater refers to rain which reaches the stormwater system from roofs, roads, footpaths and other ground surfaces. It is usually channelled into local waterways. Stormwater carries rubbish, animal wastes, motor oil, petrol, tyre rubber, soil and debris (EPHC 2006).

3. Recycled water in South Australia

Development of recycled water in South Australia has been driven by environmental, economic and social factors (Unkovich *et al.* 2004). Adelaide's Metropolitan Wastewater Treatment Plants (WWTP) are located at Bolivar, Glenelg, Christies Beach, and Aldinga.

The Bolivar WWTP treats approximately 45 GL/yr of wastewater by the activated sludge process. The wastewater receives tertiary treatment at the St Kilda coagulation and dissolved air flotation and filtration (DAFF) plant followed by disinfection (chlorination). The wastewater recycling scheme supplies Class A (see Figure 1) reclaimed water to the horticultural districts of the Northern Adelaide Plains (NAP). The reclaimed water is distributed to farmers of the NAP through the Virginia Pipeline Scheme, where it is used to irrigate greenhouse crops (tomatoes, cucumbers, and capsicum) and field production of potatoes, carrots, brassica, almonds, olives and wine grapes. Around 250 growers use reclaimed water from the scheme. The piping infrastructure allows transport of recycled water across an area of around 200 km^2 (van Leeuwen *et al.* 2012). Around 16% of South Australia's horticulture production is on the NAP, or $92m farm gate value (Laurenson *et al.* 2011). The scheme also supplies non-potable water to the residential development at Mawson Lakes (Laurenson 2010). Currently, approximately 18 GL/yr of wastewater from the Bolivar WWTP is recycled for irrigation, reducing discharge of nutrients and salts to the Gulf of St Vincent by around 40%. Benefits of recycling of reclaimed waters include reduction in reliance and demand on groundwater resources of the NAP region (Laurenson *et al.* 2011).

Recycled water from the Glenelg WWTP is used to irrigate the Adelaide Parklands. The project supplies a minimum of 1.3 GL/yr, with capacity of up to 3.8 GL/yr (SA Water website www.sawater.com.au, accessed 20 June 2015).

The Willunga Basin Water Company (WBWC) Reuse Scheme is privately funded, owned and operated by growers of the McLaren Vale region. Most of the recycled water comes from the Christies Beach WWTP, 10 km north of the Willunga Basin. It produces around 10 GL/yr of treated wastewater. About 55% of this is used by WBWC, which has a current demand of over 5.4 GL to provide recycled water to the McLaren Vale region. (http://www.wbwc.com.au/index.php/about-us/our-profile, viewed 15th April 2015). The WBWC has more than 180 users and provides recycled water for irrigation of more than 2,000 hectares for vines, fruit trees, nut crops and flowers.

The Aldinga WWTP supplies some recycled water to the WBWC Reuse Scheme as well as an aquifer storage and recovery (ASR) scheme operated by the WBWC and SA Water. Recycled water is stored in an aquifer at 30-70m depth during winter (when irrigation demand is low) and is retrieved in the summer for use by irrigators (van Leeuwen *et al.* 2012).

4. Uses of recycled water

Common uses of recycled water include:

- Agriculture, such as irrigation of crops, pastures for animal feed, and nurseries,
- Landscape irrigation of golf courses, parks, sports fields,
- Industrial uses such as for cooling, laundries, car washing facilities,
- Emergency use in dust suppression and fire-fighting,
- Use in office buildings for toilet flushing,

- Aquaculture and groundwater recharge (Australian Parliamentary Research Anonymous 2005).

It is widely recognised that the benefits of water recycling may include the following:

- Improvement of water quality where recycled water has a better quality than existing alternative water supplies,
- Displacement of reliance on potable water supplies for primary production (e.g. food crops, pasture, nursery production, and horticulture) by irrigation with recycled water,
- Substitution of potable water with recycled water for non-potable fit-for-purpose industry applications,
- Boosting the reliability of water supplies in drought periods,
- Reducing detrimental impacts on receiving environments by reducing wastewaters discharged to it,
- Provision of new supplies for environmental enhancement and aquifer recharge,
- Providing a supply of nutrients useful when irrigating crops.

Compared to the traditional storage-based approach, water recycling is one of the most effective ways of improving efficiencies in cities where water resources are constrained. Risks associated with irrigation utilising recycle water vary according to:

- the quality and the quantity of water used,
- physical characteristics of the site being irrigated,
- the irrigation system used, the types of plants being irrigated and
- the management system in place (Kelliher 2005).

Environmental risks from wastewaters can generally be managed by the level and type of treatment, and the intended use of the water. Potential disadvantages of water recycling include the costs of treatment and supply, and community perceptions of risk that may arise from its use. These mostly relate to food quality, health of natural resources and the long-term sustainability of such schemes as well as the costly management of salinity, sodicity, nutrients, microorganisms and organics (Australian Parliament Research Anonymous 2005).

5. Guidelines and regulations for use of recycled water

Most states and territories have developed their own guidelines for water recycling in Australia. Others use the Australian Recycled Water Guidelines, e.g. Northern Territory. Some states have moved towards adoption of the Australian Recycled Water Guidelines (NSW, Vic and SA) while others have maintained their own guidelines (ACT).

In 2010, an Australian Government National Water Commission report on guidelines and regulations for recycled water use in Australia was released (Power 2010). The report overviews guidelines and regulation requirements for on-site wastewater management. These apply to sites ranging in scale from single-household effluent disposal in sewered and unsewered areas, to regulation of effluent disposal and recycled water use from large schemes. In that report, guidelines, codes and standards used in each Australian state and territory are detailed and discussed (van Leeuwen *et al.* 2012).

6. Characteristics, classifications & management of recycled water

The quality of recycled water varies depending on the source of the water and the recycling process used. The quality of recycled water required for irrigation depends on the specific use, irrigation method and restrictions applied during and after irrigation, e.g. withholding period. The class of water (i.e. class

A, B, C or D) usually refers to the level of treatment to remove pathogens from the water. It does not guarantee the water is suitable for a specific use.

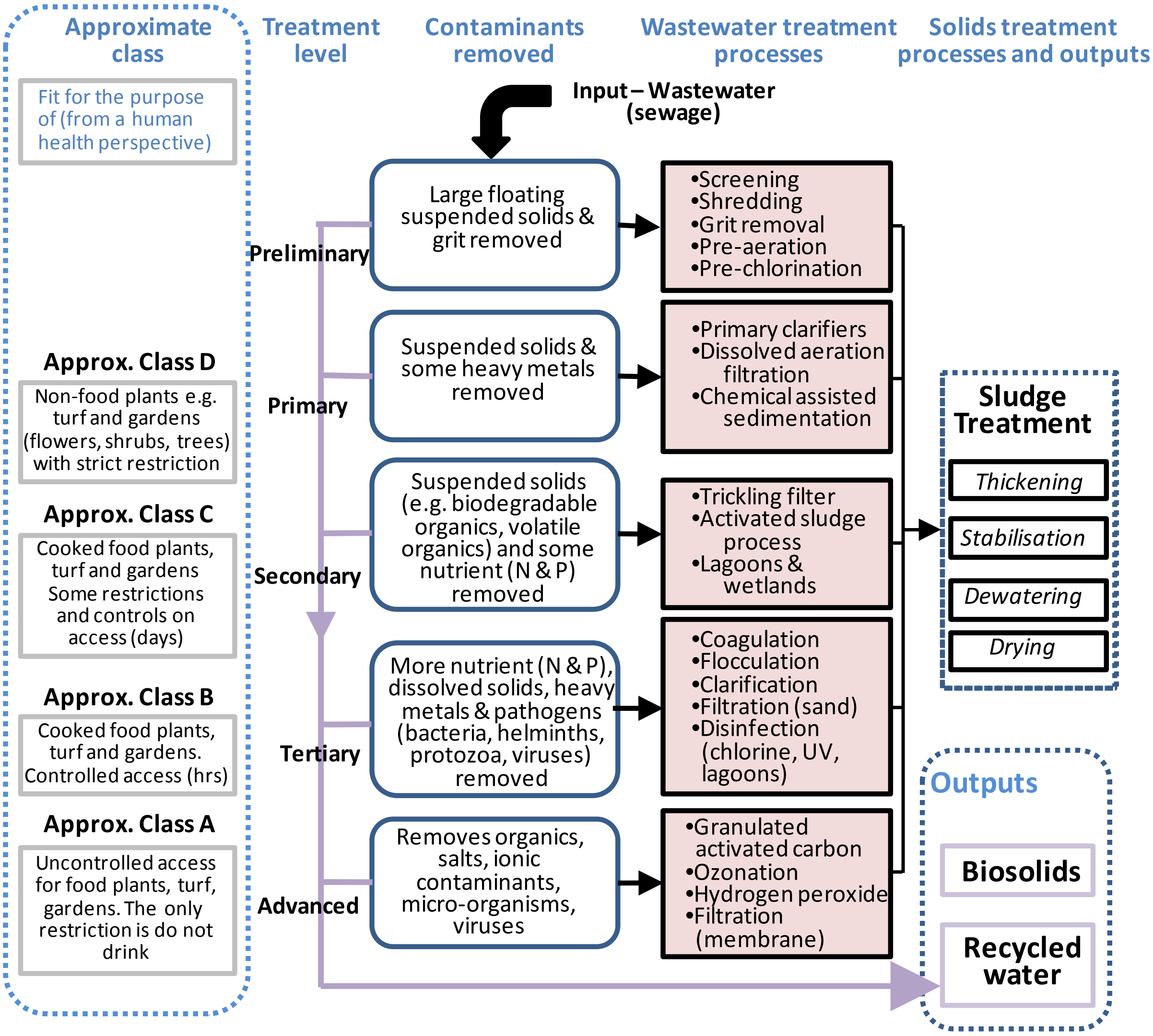

Figure 1. Treatment levels and processes typically used to treat wastewater. This diagram gives a general indication of parameters, it is not a substitute for specific guidelines and verification processes (Preliminary treated = limited treatment, Advanced = extensive treatment. Note: wastewater can be treated to a level where it is fit for the purpose of drinking. Stevens *et al.* (2008).

The physical and chemical properties of recycled water also need to be checked to ensure that the water is suitable for the plant species to be irrigated. South Australian guidelines previously specified four classes of recycled water, A, B, C and D. Recycled water can be produced using different degrees of treatment to produce a defined quality of water which will be fit for the intended purpose as described in Figure 1.

The new Australian Guidelines for Water Recycling (AGWR) replace the previous Class system. Recycled water is now referred to as being “Fit for Purpose”. This means that the user must ensure the quality of water they receive is fit for the purpose they intend to use it for, from a human health, horticultural and environmental perspective. This overcomes the limitations of the class terminology (classes A to D).

The risk management approach used in the AGWR involves identifying and managing risks proactively, rather than just reacting when problems arise. The first step in applying this approach is to look at all the hazards in the recycled water which could potentially affect human or environmental health (i.e.

what might happen and how). Once these hazards are identified, the risk from each hazard is assessed. This is done by estimating the likelihood that the event will happen and the consequences if it did. That is, 'How likely is it that something will happen?' and 'How serious will it be if it does happen?'. This approach allows identification of hazards which represent significant risks for the proposed end use. The next step is to identify preventive measures for control of such hazards, and to set up monitoring programs, to ensure that the preventive measures operate effectively. The final step is to verify that the management system consistently provides recycled water which is fit for the intended use (i.e. 'fit for purpose').

The framework of AGWR is based on, and follows the same principles as, that used in the 2004 *Australian Drinking Water Guidelines* (NHMRC 2011). It describes a generic process for developing and implementing preventive risk management systems for recycled water use. Such systems can be applied to all combinations of water source and end use, including applications not specifically addressed in the document. For example, stormwater recycling and use of recycled water to augment drinking water sources. The aim of AGWR is to provide a measurable and ongoing assurance that performance requirements are met. This will allow the best possible detection of faults before recycled water is supplied, discharged or applied; so that corrective action can be applied to prevent problems arising.

7. Irrigation with recycled water

A common characteristic of recycled water is elevated salt content. Salts that are contained in irrigation water, regardless of their source, can salinize agricultural land if the mass of salts that moves out of the root zone is less than the mass of salts entering the root zone. A favourable salt balance within the root zone must be maintained by adequate leaching, and disposal of drainage effluents must accompany adequate leaching (Maas and Grattan 1999).

In closed basins, salts may have been present in the soil long before irrigation was introduced to a region. Upon irrigation, saline water tables can develop in poorly drained areas in relatively short time periods (i.e., years). Even if good quality water is used for irrigation, salinization may occur from rising saline water tables. Rising water tables are a result of excessive leaching and are often associated with poor water-management practices.

The two processes described above: (i) salinization from irrigation with saline water and (ii) salinization from shallow saline water tables, are the most common cause of large-scale soil salinization in irrigated agriculture. They are, of course, not mutually exclusive and often highly saline water tables can occur from or in association with saline irrigation water.

Other common risks from irrigating crops (which can be exacerbated when using reclaimed water) are:

- Sodicity: can cause soil dispersion and swelling, reducing water infiltration on heavier textured soils leading to excessive runoff or waterlogging, and restrict root growth.
- Sodium/chloride: can be toxic to plants if sprayed directly on leaves and if accumulated in soil from ongoing irrigation.
- Nitrogen: a major nutrient required by plants. However excess nitrogen can cause excessive growth, which can affect fruit yield and quality.
- Boron: can cause plant toxicity in some sensitive plant species in some soils.
- Increased hydraulic loading: excess water can result in high groundwater recharge, water logging and secondary salinity.

Differences between reclaimed and other irrigation waters

Almost any quality of water can be produced from wastewater, with treatment being tailored to intended use. While there is great variability in the quality of "fresh" irrigation waters, there is a strong tendency for reclaimed water to have higher salinity and higher concentrations of sodium (Na) relative to other cations than other irrigation waters. The salinity in reclaimed water comes mainly from groundwater intrusion into leaky sewerage systems and from domestic and industrial water softeners

(EPHC 2006). Increased salinity also results from evaporative concentration during consecutive lagoon treatments. However, the quality of surface and groundwater can range from very good quality, to unacceptable quality for irrigation (Kelly *et al.* 2001). This encompasses the quality range of reclaimed water. In an audit of Australia's water resources (National Land and Water Resources NHT 2001) it was found that 61% of river basins examined exceeded nutrient quality standards, 32% exceeded acceptable salinity levels, and 61% exceeded turbidity criteria.

A comparison of reclaimed water and other irrigation waters was made by Kelly *et al.* (2001) on the NAP. They found that while total N and P were invariably higher for reclaimed water than for groundwater irrigation sources (Table 1), differences between other parameters measured were not consistent.

Table 1. Quality of Class A reclaimed water (CARW) and two major groundwater aquifers on the Northern Adelaide Plains, South Australia (Kelly *et al.* 2001).

		CARW	**T1 Aquifer**		**T2 Aquifer**	
Parameter	Unit	Average	Min	Max	Min	Max
pH	-	7.4	7.4	8.1	7.0	8.1
Total dissolved salts (TDS)	mg/L	1097	715	4033	556	2322
Electrical conductivity (calc.)	dS/m	~1.7	1.19	6.71	0.93	3.86
Total N	mg/L	10.3	0	0	0	2
Total P	mg/L	1.2	0	0	0	0
E. coli	/100ml	0[a]	na	na	na	na
Sodium absorption ratio (SAR)	-	7.95	3.8	7.7	2.9	12.6
Chloride	mg/L	382	170	485	190	736

[a]is median value; na indicates not analysed

Grower management of reclaimed water for irrigation

Differences between reclaimed water and other irrigation waters mean that use of reclaimed water requires a higher level of irrigator knowledge and skills, along with some modification of farming practices. For example, control of weeds may be more difficult under irrigation with reclaimed water if nutrients are applied at a higher rate than with other waters. This is because weed growth may be increased by higher N and P levels. With careful attention to crop nutrition, however, weed management issues should not be greater than for other irrigation systems (Unkovich *et al.* 2004). As well as weeds and fertilisers, growers need to be able to assess risks of salinity and toxic boron to crop growth and quality. There are also the health risks to workers and consumers from irrigation waters and contaminated produce. Provided that information is communicated to growers in a clear and simple way, these issues should not be too difficult to manage. They are no more complex than issues dealt with by farmers in a range of farming activities. Farming today is a complex business, regardless of the enterprise. The challenge is to ensure that growers are aware of the issues and are provided with cost effective avenues for seeking out available solutions (Unkovich *et al.* 2004).

Salinity

There are two main causes of salinity damage in plants:

1. The osmotic effect, which adversely affects energy expenditure and water uptake by plants. This creates a condition referred to as "chemical drought" – plants wilt because of a shortage of water, even though the soil remains moist.

2. Direct toxicity of salts – particularly from Na and Cl ions, though boron toxicity can also be an issue.

Crops may be affected by either the osmotic effect or salt toxicity or by both. At low salt concentrations toxic ions play a dominant role; at high salt concentrations, it is the osmotic effect that plays a major role.

Figure 2 from Lanyon (2011) shows the osmotic effect in plants. Water moving into roots is slowed down as the concentration of salt in the soil water increases. This reduces the water available to plants for growth and yield. Soil moisture content can also change dramatically between rainfall events. This variation in soil moisture directly affects the salt concentration of the soil water. The higher the soil moisture content (wetter the soil), the lower the concentration of salts, and conversely, the lower the soil moisture content (drier the soil) the higher concentration of salts. As soils become drier there is less water accessible for plants. In addition, the soil water becomes increasingly difficult to extract due to increasing matric potential. In saline soils there is the added complexity that as salt concentration increases during the drying process, then the plant's ability to 'suck' water from the soil is further reduced (osmotic effect) (Unkovich *et al.* 2004).

Ionic toxicity

Sodium, chloride and boron are specific components of soil and water salinity that can negatively impact on vine growth. These ions can reduce growth in two ways:

- direct toxicity, or
- indirect effects on nutrient uptake and balance.

Many of the effects of Na and Cl are difficult to tell apart and these two elements are commonly found together in soil and water. Sodium is not an essential element - most plants are natrophobic (Na hating) and have mechanisms to exclude Na from uptake by the roots. The use of rootstocks that limit the uptake of Na can form an effective Na management strategy.

While "fresh" irrigation waters can be of variable quality, reclaimed water usually has higher salinity and higher concentrations of Na relative to other cations than other irrigation waters. However, quality of surface and groundwater can range from very good quality, to unacceptable quality for irrigation, encompassing reclaimed water quality (Unkovich *et al.* 2004).

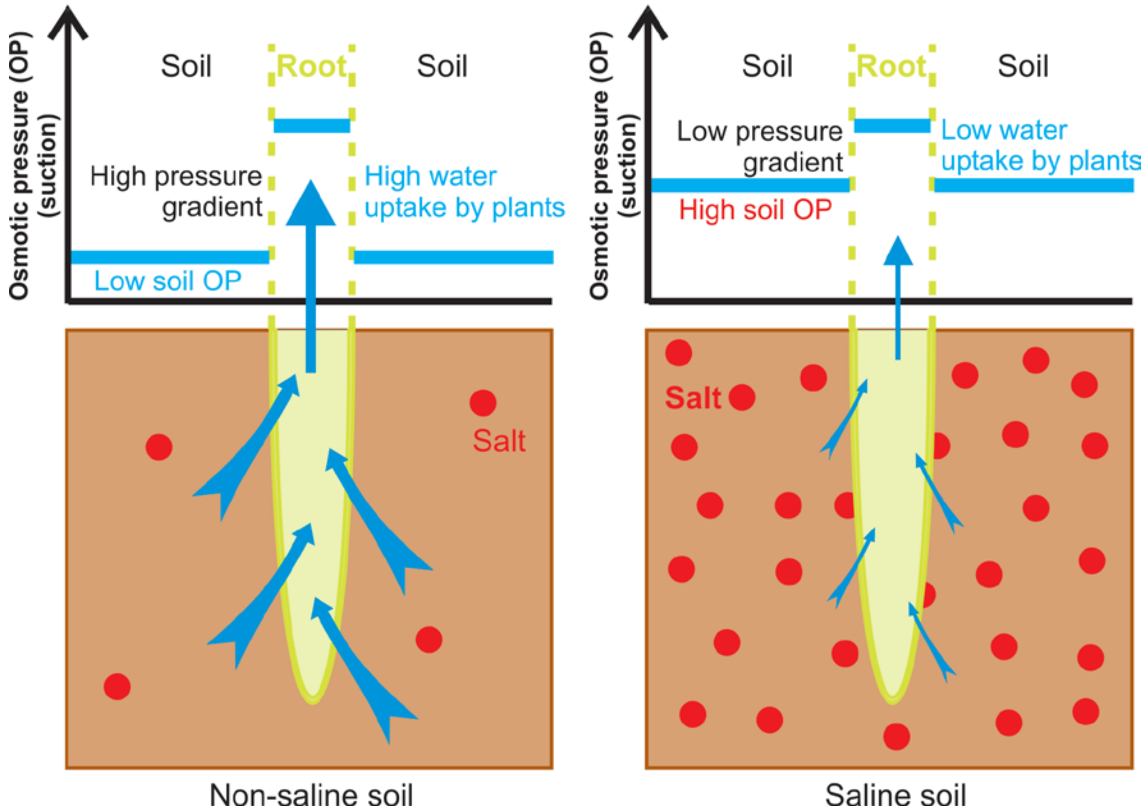

Figure 2. The relative water uptake by plants in saline and non-saline soils. In the saline soil the osmotic pressure associated with the salt reduces the pressure gradient between the soil and the root, reducing the flow of water into the root. This reduces the water available to the plant for growth and yield (Lanyon 2011).

Plant response to soil salinity

The most common whole-plant response to salt stress is a general stunting of growth. As salt concentrations increase above a threshold level, both the growth rate and ultimate size of crop plants progressively decrease. However, the threshold and the rate of growth reduction vary widely among different crop species. Some crops, like the common bean or strawberry, are highly sensitive and begin to exhibit injury symptoms and growth reductions at salt concentrations only twice that present in non-saline soils. Other crops like barley, cotton, and sugarbeet, are nearly as tolerant as some halophytes which actually grow better in moderately saline environments (Maas and Grattan 1999).

Although salinity affects plants in many ways physiologically, overt injury symptoms seldom appear except under extreme levels of salt stress. Salt-affected plants usually appear normal, although they are stunted and may have darker green leaves which, on some plant species, are thicker and more succulent.

Growth suppression seems to be a nonspecific salt effect that is directly related to the total concentration of soluble salts or osmotic potential of the soil water. In contrast, woody fruit and nut crops such as grape and almond can accumulate Cl^- and/or Na^+ to toxic levels which cause leaf burn, necrosis, and defoliation. The onset and severity of injury is related to the rate of foliar accumulation.

When specific ion toxicities occur, the effects on yield are generally additive with the growth suppressive effects of osmotic stress; yet the growth-reducing contributions of each are difficult to quantify. The additive effect can be attributed to leaf damage and defoliation which further reduces the photosynthesizing area of a salt-stunted plant canopy. In some woody species, like grape, toxic effects may be dominant; in others, such as stone fruits, yield losses caused by toxicity may be comparable to those caused by osmotic stress (Bernstein *et al.* 1956).

With most crops, including tree species, yield losses from osmotic stress can be significant before foliar injury is apparent. However, salts tend to accumulate in woody tissues over several years before toxic symptoms appear. Consequently, the effects of leaf injury and loss can occur dramatically when the salts reach the leaves. In these instances, tree or vine tolerance to salinity may decrease over the years as injury caused by specific-ion toxicities becomes more acute (Maas and Grattan 1999).

The onset and timing of foliar injury may determine the extent of damage to crop yields. With tree crops that develop fruit yields over a 2-year period, foliar injury and leaf loss during both years will be more detrimental than injury that occurs only the 2nd year. Of course, continued salt stress will eventually damage the tree itself. Salinity stress imposed one year may have physiological and/or morphological effects on subsequent years. It is also difficult to evaluate tree or vine response to salinity and account for dormant periods, changing climate throughout the year, and temporal and spatial changes in the salinity profile (Maas and Grattan 1999).

Leaching of salts

Leaching of salts from the root-zone is the most effective technique for salt management. Irrigation scheduling strategies such as RDI and PRD minimise deep leaching and tend to accumulate imported salts in the root-zone. The leaching fraction refers to the amount of water that needs to be applied in excess of vine evapotranspiration requirements to flush out accumulated salt. The extra water applied can come from irrigation or by rainfall. Low leaching fractions, caused by little rainfall or low irrigation allocations, increase the net salinity retained in the root zone. This leads to a potential requirement to use salt tolerant rootstocks (Lanyon 2011).

Application of leaching irrigation events has commonly been used for the management of root zone salinity. The use of leaching events during periods of high transpiration demand is less effective and efficient as leaching events during low transpiration demand, as shown in Figure 3 from Lanyon (2011). The best leaching of salts from the topsoil occurs when the soil profile is near saturation and the water applied has little salt and water is applied slowly and evenly, either by rainfall or irrigation (Lanyon 2011).

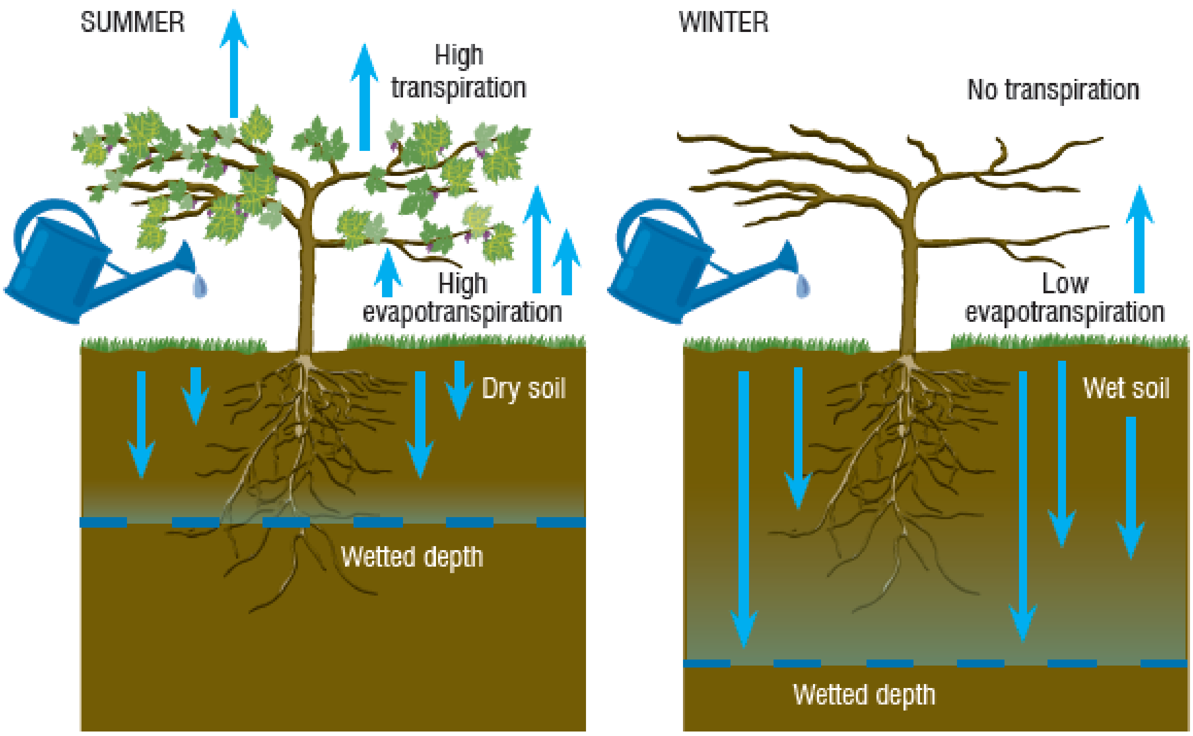

Figure 3. Difference in water movement through the soil profile for the same quantity of water applied during summer and winter, either through irrigation or rainfall (Lanyon 2011).

Recent research has shown that the leaching process is not always completely efficient. This is thought to be due to the presence of preferred pathways of water movement through the soil, resulting in salt build-up in other parts of the root-zone. In some situations where shrinkage cracks form in saline clay soil, salt crystals form on the crack faces in response to evaporation losses. If runoff water can be directed down these cracks before they close up, substantial amounts of salt can be leached quickly and deeply (Lanyon 2011).

Rainfall is important to the salt leaching process. As rainfall increases, there is a decrease in the number of leaching irrigation events which need to be applied to prevent salt build-up in the root zone of grapevines. Application of leaching fractions is only effective if the water table is deep enough to receive the extra water without adversely affecting vine growth. Hence, monitoring the water table using test wells and/or piezometers is recommended. Subsoil drains may have to be installed if the water table is high enough to adversely affect vine performance.

Sodicity

It is widely recognised that the biggest problem to deal with when using reclaimed water is the management of salt (which can cause sodicity as well as salinity). Na, Cl, HCO_3 and SO_4 are key elements or compounds that contribute substantially to salinity in recycled waters and in soils irrigated with recycled waters. The effects of salinity in soils are a function of the relative amounts of Na to other exchangeable cations (sodium absorption ratio, SAR) such as Ca and Mg. Where Na represents more than 6% of exchangeable cations in the soil, soil sodicity may occur. This leads to poor water infiltration, waterlogging and hard surface crusting. Recycled water can contain high concentrations of Na compared to other cations like calcium and magnesium leading to high SAR's (average SAR = 6 dS/m, ranging from 3 – 12 dS/m) (Stevens 2009).

High SAR in soil with low electrical conductivity leads to sodicity. This lowers hydraulic conductivity which then decreases the potential for further leaching of salts and increases the potential of anoxia in soils. High Na can increase clay dispersion, which can lead to low soil porosity, reducing hydraulic conductivity and increasing soil strength. This in turn, reduces plant root penetration. Loading of salts and other elements in soils in agricultural practices is an effect of reclaimed water application. This is, in itself, a function of crop type and concentrations in the reclaimed water. As described by Stevens *et al.* (2004), there is much information on the sensitivities of crops to salinity. Variation in what constitutes the salinity, however, (e.g. Ca concentration as well as anion concentration), and the plant responses to salinity can then be different. Amendment of soil with a cation source such as gypsum can counter the effects of sodicity under agricultural practice.

Sodicity can be controlled by continued use of high saline effluents, where the electro-osmotic effects of total salts tends to counter the repulsive forces that result from hydration of Na^+ on the exchange complex (Stevens *et al.* 2004). Hence soil structure can decline with use of fresh water or rainfall that leaches out the salts.

Although it could be assumed that salinity and SAR might increase with domestic wastewater reuse, this is based on initial soil conditions and comparison of the quality of alternative water sources. It is important to assess background levels where possible, as recycled water may, in fact, be replacing a more saline water source (van Leeuwen *et al.* 2012).

Nutrients in reclaimed irrigation water

Although around 50% of N and 60% of P is removed from sewage during treatment, N and P levels remain higher in reclaimed water than most other irrigation sources (Bahri 1998). Matching water and N supply can be difficult for crops irrigated with reclaimed water, as growers lose some control over the timing of fertiliser application. If periods of peak crop water demand do not match peak N demand then N supply may be in excess of crop requirements. This could affect the yield or quality of produce, depending on the crop being grown. It could also cause environmental problems off site. These problems are complex and need to be addressed on a site by site basis, as nitrogen is probably the most variable component of reclaimed water (Westcot and Ayers 1984).

Sams (1999) summarised the effects of chemical fertility on a wide range of horticultural produce, indicating that excessive N, P and K can reduce fruit firmness. Excessive K, relative to Ca, can increase fruit textural disorders. Calcium was highlighted as being the element most critical to fruit quality as it contributes more to the maintenance of firmness than any other element. Thus the relatively high cation content (particularly Ca^{2+}) of reclaimed water might contribute to improved firmness and textural quality of fruits.

Baier and Fryer (1973) reviewed the principal concerns that relate to over-fertilisation of a wide range of horticultural crops with N. A *precis* of the major issues is as follows.

If too much N is applied yield can be reduced, particularly for perennial crops. The date of maturation of crops may also change (but not yield), or fruit size can decrease (e.g. peaches). Grape varieties respond differently to excess N, Malbec is very sensitive and Pinot Noir one of the least sensitive. The main problem for grapevines is caused by pre-flower bud shatter when tissue nitrate-N reaches 1%. Problems may persist for more than one year if cane wood quality declines and impacts on next year's growth and yield. Grapes can also accumulate phytotoxic levels of NO_3^-. In potatoes and sugar beets too much N results in excessive vegetative growth and thus fewer and smaller tubers. Navel and Valencia oranges - when fertilised during the summer with excessive N (>17g/m^2) produce grainy, pulpy oranges with less juice. Over-fertilised Valencia oranges can also re-green when ripe. Lemons are rarely affected by over-fertilisation. Most stone fruit suffer a delay in maturation from over-fertilisation rather than a direct decrease in quality. This is because high N levels keep the plants vegetative for longer and this uses up carbohydrates which are normally stored in the fruit. With melons and squash the excessive vegetative growth may maintain high moisture content around fruit, providing conditions conducive to development of rots. It is unlikely that over-fertilisation with P will occur from reclaimed water irrigation, since most of the P will be immobilised in the soil and not be readily available to plants (Ryden and Pratt 1980).

Irrigated horticulture and water productivity

Water used in irrigation is consumed via evaporation from crop or soil surfaces, and may also be lost to runoff and deep percolation. In many cases, such water losses may be recovered within the catchment basin and reused, albeit with some degradation in quality. Water conservation aimed at increased irrigation efficiency (by changing the method of irrigation, for example), may not lead to net water savings if the losses conserved were recoverable (Seckler 1996). Because of this uncertainty, water productivity (WP) is defined as the ratio of yield (measured as biological or economic output) to crop evapotranspiration (ET) (Seckler 1996). Unlike efficiency improvements, improving WP by increasing yield and/or reducing ET always results in net savings, thus reducing agricultural water requirements.

Water productivity in irrigated agriculture varies widely and depends on many factors. Because variations in ET among crops are within an order of magnitude apart, by far the most important factor influencing WP is the economic value of the product. Horticultural products are usually high value and thus WP normally exceeds that of field and row (agronomic) crops. For example, Fereres *et al.* (2003) using values for yield and ET characteristic of California agriculture, found the WP of corn was about 0.20 \$/m^3 compared to 0.70 \$/m^3 for almond, 5.00 \$/m^3 for strawberry, and even more for greenhouse and ornamental crops.

A secure recycled water source for irrigation has become the lifeblood for many horticultural growers, particularly those near major urban centres. Access to a water supply that is independent of rainfall and water restrictions makes an attractive proposition in terms of the long-term viability of a site (Connellan 2010).

In South Australia, where most of Australia's wine-grapes are produced, there are many water resource issues. Where water is available it is highly regulated and increasingly expensive. Heavy fines may be imposed in some regions (e.g. McLaren Vale) if water is seen to be applied excessively. Groundwater salinity is also an issue in many areas of South Australia. Given the pressures on supply, quality and cost of irrigation water, it is essential that good practices in soil and water management be used to optimise the available water to grapevines.

Scheduling water resources

Growing wine grapes under drip irrigation needs careful control of irrigation frequency to reduce salt uptake by the vine. Soils should not be allowed to become too dry - salts concentrate in the soil solution as the soil dries and vines may take up the salt. Frequent drip irrigations will keep the soils close to field capacity and move salts to the edge of the wetted zone, away from the bulk of the root system (Lanyon 2011). However, with limited water supply and DI techniques this may not be possible. In some areas, a range of water supplies is available that are of variable quality (i.e. level of salinity). In this case, it is helpful to schedule the use of these water resources according to growth stage, although our understanding of variable water quality applications within a growing season is still developing. Recent research suggests that Cl accumulation in grape berries is related more to the environmental conditions leading up to veraison than to those after veraison. This suggests that it may be best to use the better quality water early in the season to maintain low saline soil conditions during the period of rapid cell growth and division. Then apply the poorer quality water after veraison during fruit development and maturity. This is a topic that needs further research (Lanyon 2011).

Conclusions

Australia is well situated to make the most of reclaimed wastewater as a source of irrigation water. This has the dual benefit of addressing shortfalls during periods of water scarcity and reducing the environmental impact of wastewaters returned to the environment. However, reclaimed water frequently contains elevated concentrations of salt. In an irrigation environment of increasing water efficiency, the use of saline water requires careful management to avoid exacerbating soil salinity. This does not preclude reclaimed water from use in irrigation systems, but exposes a need for the development of irrigation management strategies that enable various crops, with their own suite of requirements, to make best use of the reclaimed water resource.

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Appendix I – University of Adelaide soil investigations

Final Report – August 2015

Methods to increase the use of recycled wastewater in the irrigation industry by overcoming the constraint of soil salinity

Sponsor: AWRCOE – SARDI – UofA: RD-4919 SARDI-AWRCOE
Chief Investigator: Dr Cam Grant, University of Adelaide, School of Agriculture, Food & Wine.

1. Introduction

This final report first summarizes the contributions made by the University of Adelaide (detail can be found in the progress report of April 2015), then focuses on interpretation and recommendations.

General

- Seek and appoint a student to the irrigated vine project
- Contribute to supervision of the student project
- Contribute to the development and set up of student project
- Attend and contribute to the overall project meetings
- Contribute to the writing and review of progress reports for the vine component of the overall project

Specific

- Contribute expertise in the movement of salts and water in soils as modified by variations in soil chemical and physical properties
- Provide expertise and experience in understanding and managing the interactions between recycled water and the physical properties of soils, and experience in supervising PhDs.

2. Seek and appoint a student to the irrigated vine project

As early as possible in the project we recruited a third-year undergraduate student, Shelley Cong, to conduct a small project (February to July 2014) on the "*Residual Effects of Soil Management on Saturated Hydraulic Conductivity*". Her work addressed the question: "*To what extent, if any, do the effects of deep ripping, organic mulching, and/or soluble calcium influence soil hydraulic properties 6-7 years after initial application?*" She measured saturated hydraulic conductivity and bulk density down the profile on undisturbed soil cores from a heavy textured soil in the McLaren Vale (TWE Vineyard). She found that aside from deep ripping, all residual effects of organic mulching and gypsum application were lost after 6-7 years. A copy of her report was attached as an Appendix to the Progress Report in April 2015.

No Australian postgraduate student could be found to work on this project so we recruited an international student, Mr Justice Frimpong, from Ghana who won a University of Adelaide International Scholarship. Although he started in late 2014 as a PhD student, he transferred to a Master of Philosophy (Agricultural Science) in accordance with his abilities and the nature of the project. We believe he will complete his degree by mid 2016.

3. **Contribute to the supervision of the student project**

The supervisory committee for Mr Frimpong consists of me (Dr Cameron Grant) as principal supervisor, Dr Jim Cox (SARDI) as co-supervisor, A/Prof Tim Cavagnaro (UA) as co-supervisor, plus an independent advisor (Dr Rob Murray, UA).

4. **Contribute to the development and set up of student project**

The undergraduate research project of Shelley Cong was organised and supervised by me, Jim Cox and Tim Pitt, with casual technical help (supported by the project) to assist with the intensive sampling program in the field during April and May 2014.

The Masters project of Justice Frimpong has progressed to the point where a literature review and project proposal is now completed and the initial laboratory experiments have begun (progress on this described below).

5. **Attend and contribute to overall project meetings and Contribute to the writing and review of progress reports for the vine component of the overall project**

The steering committee for this project is led by Drs John Radcliffe and Don Begbie, and I have attended and contributed to 4 progress meetings with Dr Jim Cox and Mr Tim Pitt. I submitted a draft progress report for Dr Cox in June 2014, a full progress report in April 2015, and this Final report.

6. **Contribute expertise in the movement of salts and water in soils as modified by variations in soil chemical and physical properties**

All measurements were conducted in my laboratory, which is equipped to measure soil chemical and physical properties, including: pH, electrical conductivity, and exchangeable cations on 1:5 and paste extracts, plus particle size distribution, particle- & bulk-densities, saturated hydraulic conductivity and water retention. (Methods were reported in the Progress Report of April 2015). Water retention measurements take up to 5 months to obtain, and these are still being completed so the current data must be considered preliminary until then.

Data

All data are stored on a CD in Excel and supplied to Dr Jim Cox by email. A summary and interpretation of the following data is provided in this report:

- Soil pH and EC.
- Soil texture (as clay content) down the profile.
- Soil particle density (specific gravity).

- Saturated hydraulic conductivity.
- Bulk density (saturated, moist and oven dry).
- Water retention curves.

Soil pH, EC and sodium (ESP)

The soil pH (determined on saturated soil paste extracts) was slightly alkaline down the profile but there was no effect of location relative to the irrigation (under vine); that is, pH was unaffected by the irrigation practices under the vine, under the wheel track, or in the mid-row (Figure 1). By contrast, the salt concentration down the soil profile (as measured in a saturated soil paste extract) was slightly elevated under the vines (where drip irrigation of the recycled water occurs), and this diminishes with distance from the dripper into the mid-row (Figure 1). The influence of the elevated salt concentration under the vine is expressed in greater exchangeable sodium percentages under the vines. In fact, the ESP is beginning to fall into the range of concern for soil structural stability (ESP>5%), especially under the vine and the tyre track in the root zone (40-45cm depth); swelling and dispersion will eventually generate problems with soil structural stability, which will lead to greater swelling and clay dispersion. The consequences of excessive clay swelling and dispersion are that the average pore size in the root zone will decline, and this has serious implications for increasing soil hardness (penetration resistance), reducing drainage and soil aeration, all of which reduce the availability of any water held in the soil (discussed below).

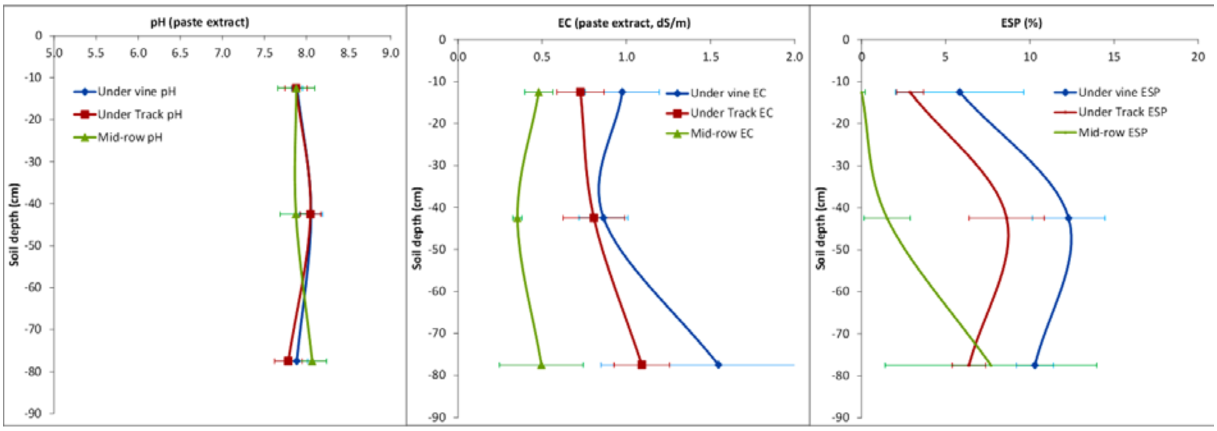


Figure 1. Soil pH, Soil electrical conductivity (EC), and soil exchangeable sodium percentage (ESP) as a function of depth and position in the vine row (under vine, under wheel track, or mid-row).

Particle size distribution (texture)

The soils were gradational in texture with increasing clay content down the soil profile. As Figure 2 shows, however, there was considerable variability in texture with depth (10-15cm, 40-45cm and 75-80cm) across the three sites (Block 2, Block 4 and Block 7). There was no expectation that particle size would vary across the vine row from under the vine, tyre track or mid-row, so the data were summarized only by block and depth in Figure 2. The primary implication of the increasing clay contents with depth is that the exchangeable sodium (ESP) also increases with depth. The combination of more clay and greater ESP with depth will lead to unstable soil structure in the long term, which has a negative impact on plant available water, primarily through poor soil drainage and aeration.

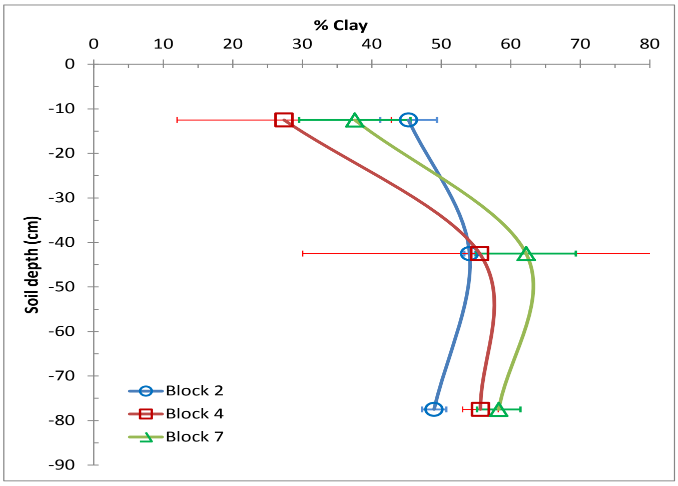


Figure 2. Clay content as a function of depth for the 3 blocks used in this study.

Particle density (specific gravity)

As might be expected, the specific gravity of the primary particles of soil varied significantly from block to block and depth to depth (dotted horizontal lines represent $\pm$ 1 standard deviation of the mean) but there were no obvious trends related to the position in the vine row (Figure 3). The overall mean particle density was 2.67 $\pm$ 0.12 g/cm^3 (95% CI = 2.55-2.79). A value for mean particle density of 2.67 g/cm^3 will be used in this report for all calculations requiring knowledge of the soil porosity.

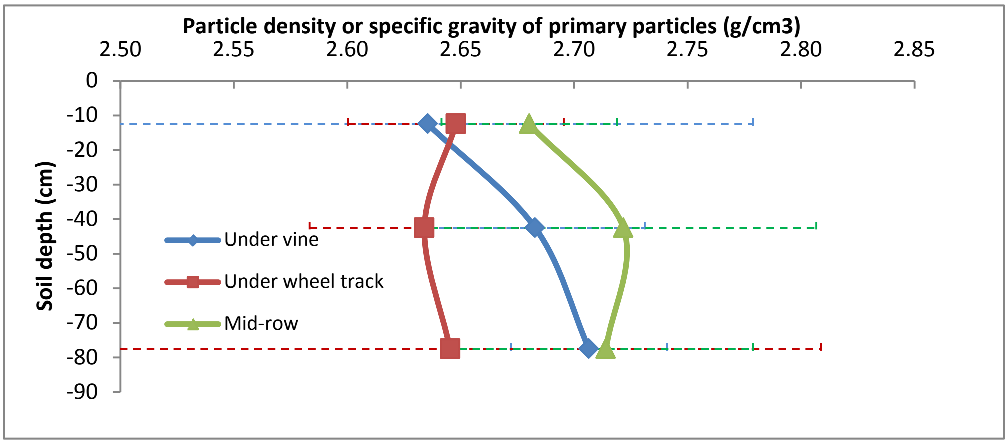


Figure 3. Primary particle density or specific gravity for soils used in the study.

Bulk density

Because the average clay content of the soil generally increased with depth, the degree of volume change in the soil samples between saturation and oven dry (swelling/shrinking) tended to increase with depth; swelling and shrinkage were greatest in the soil samples collected at 40-45 cm because they had the greatest clay content on average. Figure 4 shows the profiles of bulk density for soil samples in their fully saturated (swollen state), their moist state (5 bar, less swollen), and their oven dried state (105C, maximum shrinkage) for samples taken under the vine[1], under the wheel track, and in the mid-row. Variability was large because variation in the clay content was large (cf. Figure 2), so error bars are not shown here (they can be found in Appendix 7).

[1] Only samples from 10-15cm layer have been analysed so far; final samples are still coming to hydraulic equilibrium (30 July 2015).

The tendency for the soil at any depth to shrink is best illustrated by the differences in bulk density between the saturated and the oven dried states. For example, for the samples taken at 12.5 cm depth, the difference in bulk density is relatively small between the saturated state (open symbols, green, blue, red) and the oven dried state (closed, large symbols, **green**, **blue**, **red**). That is, the mean bulk density of the saturated mid-row soil at 12.5 cm depth was only 1.39 g/cm^3 and it increased to 1.49 g/cm^3 when oven dried (see black arrows, a difference of only 0.10 g/cm^3 or 7% increase). By contrast, the mean bulk density of the mid-row soil at 42.5 cm was quite low when fully saturated/swollen (1.23 g/cm^3) and it increased to 1.57 g/cm^3 when shrunk to is maximum density at oven dry (see black arrows: a difference of 0.34 g/cm^3 or 22% increase).

The changes in bulk density are relevant to the water retention data because the water retention data are presented on a volumetric basis (to enable water availability to be calculated). Thus, the bulk density needs to be taken into account to accurately convert the gravimetric water contents to volumetric water contents.

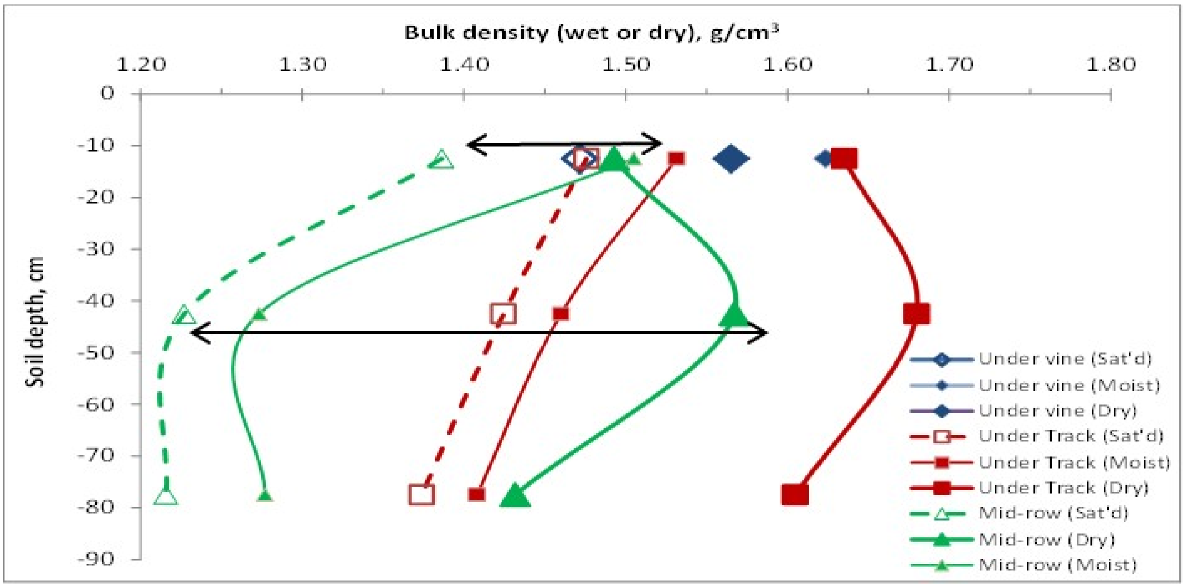


Figure 4. Profiles of soil bulk density across the vine row (under vine, under track and mid-row) in the fully saturated state (0 bar suction), the moist state (5 bar suction), and completely oven dried state (10,000 bar suction).

<u>Saturated hydraulic conductivity (Ks)</u>

The soil cores collected for water retention and bulk density were first used to measure the **saturated** hydraulic conductivity, K_s (m/s), to facilitate calculation of the (more important) **unsaturated** hydraulic conductivity K(h).

Sampling was conducted in the field to obtain undisturbed soil samples with both vertical and horizontal orientation to determine whether compaction under the wheel tracks might lead to greater lateral flow of irrigation water from under the vine row into the mid-row. Although sample orientation was expected to influence dynamic hydraulic properties (e.g. Ks), it was not expected to influence static hydraulic properties (e.g. water retention) so the sample orientation was only evaluated for the hydraulic conductivity data, not water retention. For the water retention data, results from different sample orientation were simply treated as replicates ignoring sample orientation. Figure 5 shows the effect of treatment (position in the row) on vertical and horizontal K_s down the soil profile.

In the mid-row (right hand figure), minimal traffic / compaction facilitates uninterrupted biological activity up / down profile (earthworms, invertebrates, etc), so there were more (and larger) continuous biopores, which created a greater average K_s throughout the profile, and slightly greater in the vertical direction than in horizontal direction at all depths. Under wheel traffic line, compaction reduced biological activity up and down the profile so fewer large and continuous pores existed, hence average K_s was one order of magnitude smaller in vertical direction than in horizontal direction at all depths.

The mean vertical K_s at the bottom of the trafficked profile was lowest of any K_s values anywhere in the vineyard. Interpretation of the mean Ks in the under vine regions is more complicated because several process were active: on the one hand there was significant root- and other biological-activity in all directions (at least in top 50 cm), so one would expect greater average K_s in both horizontal and vertical directions. However, the soil was exposed to recycled (saline) water under drip irrigation, so the effects of swelling and dispersion would be expected. Hence mean vertical K_s values were relatively large all the way down the profile, and the mean horizontal K_s values were large near soil surface but not at depth; the reason for the differences in horizontal v. vertical K_s under the vines is not clear.

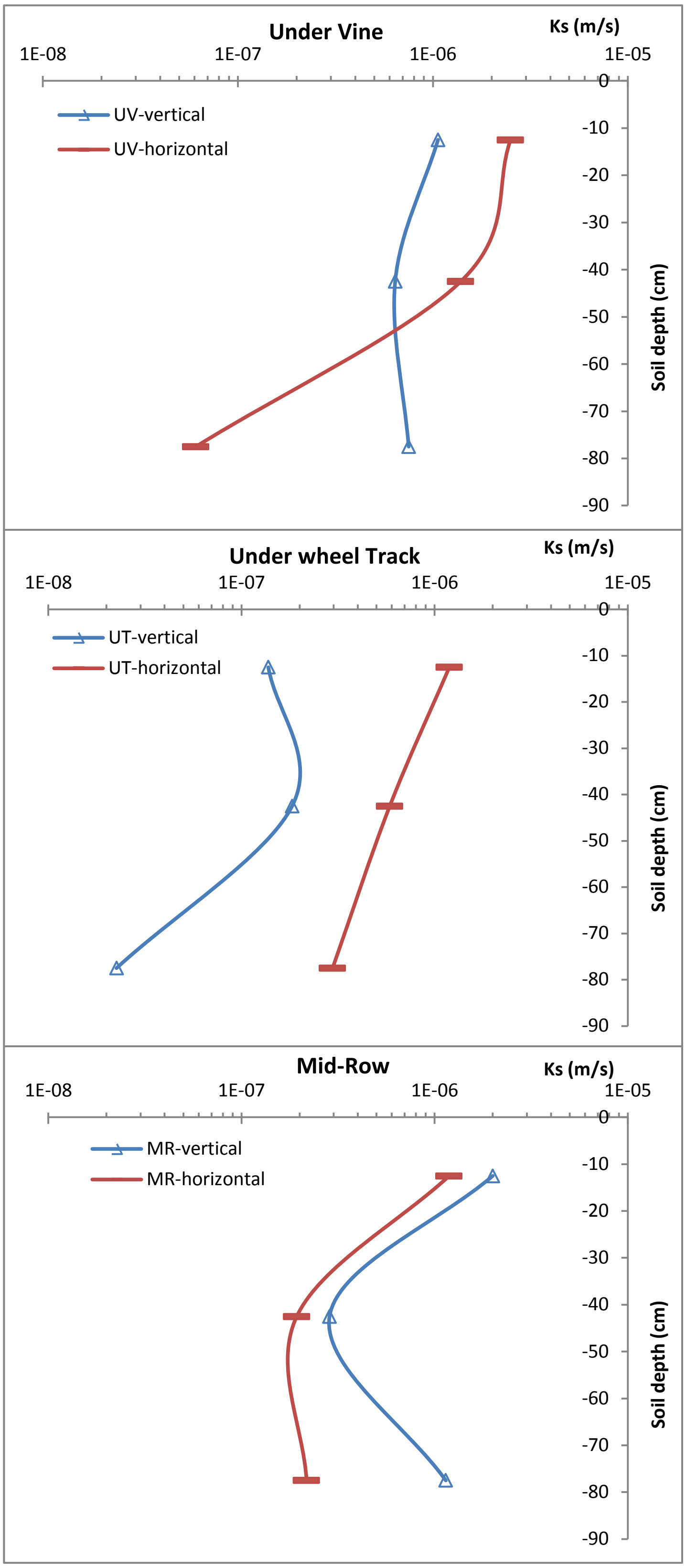


Figure 5. Profiles of saturated hydraulic conductivity, Ks (m/s) for samples taken in the vertical and horizontal orientation in different positions across the vine row.

Water retention curves, $\theta(h)$

The volumetric water retention curves for all locations in the vine row and all depths in the profile are shown in Figure 6. Error bars are not shown but it is evident from the points shown that there are two main groups: subsoil and topsoil. The subsoil data (40-45 cm and 75-80 cm) all fall in a relatively tight group, with greater water contents at all matric heads than for the topsoil samples.

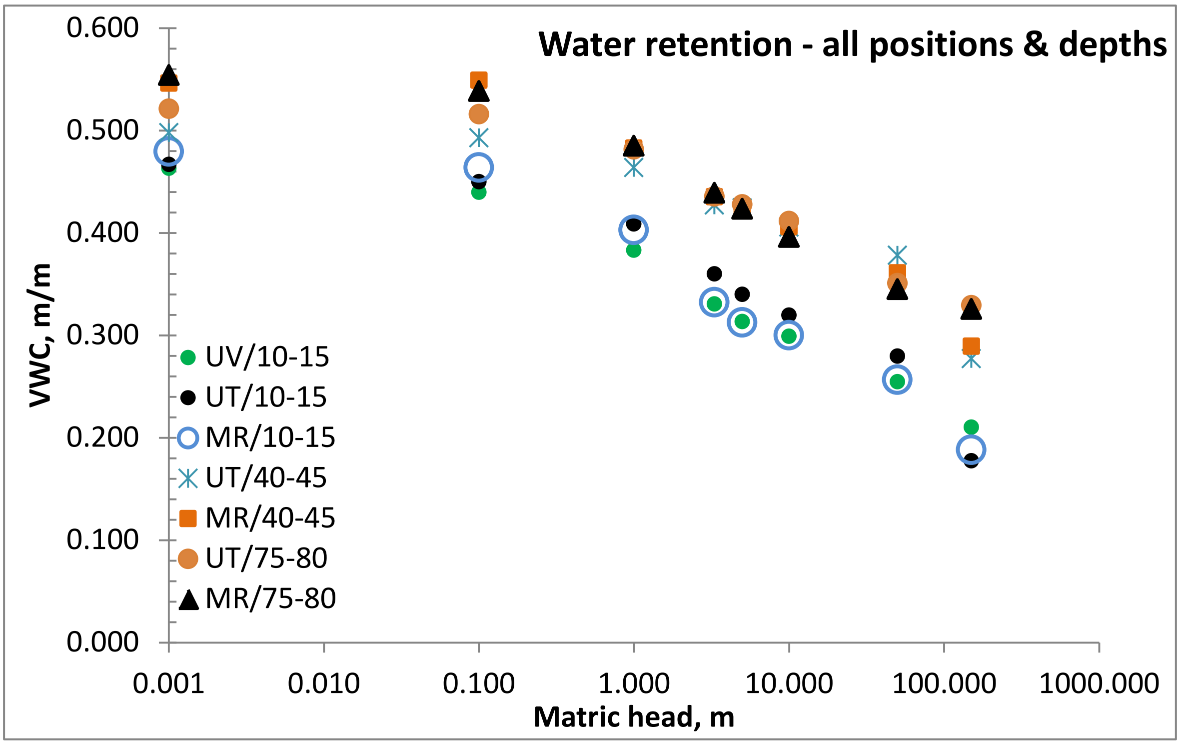


Figure 6. Water retention curves (on semi-log scale) for all locations in the vine row (i.e. under vine, under track, and mid-row) and all depths in the soil profile (10-15 cm, 40-45 cm and 75-80 cm). Most points represent the mean of at least 3 samples; some represent as many as 6 samples (horizontal and vertical orientation) and some represent only 1 sample because the rest of the results are not yet available.

Figures 7a, b and c show the water retention curves plotted separately (with error bars) for the topsoil (10-15 cm), the middle subsoil (40-45 cm) and the deeper subsoil (75-80 cm) respectively. It is clear that the standard error in the water contents is quite large and that no there are no significant effects of location in the vine row on water retention. Therefore separation of the data can only be justified in terms of topsoil and subsoil, and this is shown (with error bars) in Figure 8. The parameters to describe the water retention curves using the van Genuchten model are provided in a table at the bottom of Figure 8; the full set of van Genuchten parameters will be provided when the complete set of water retention data are available in September 2015.

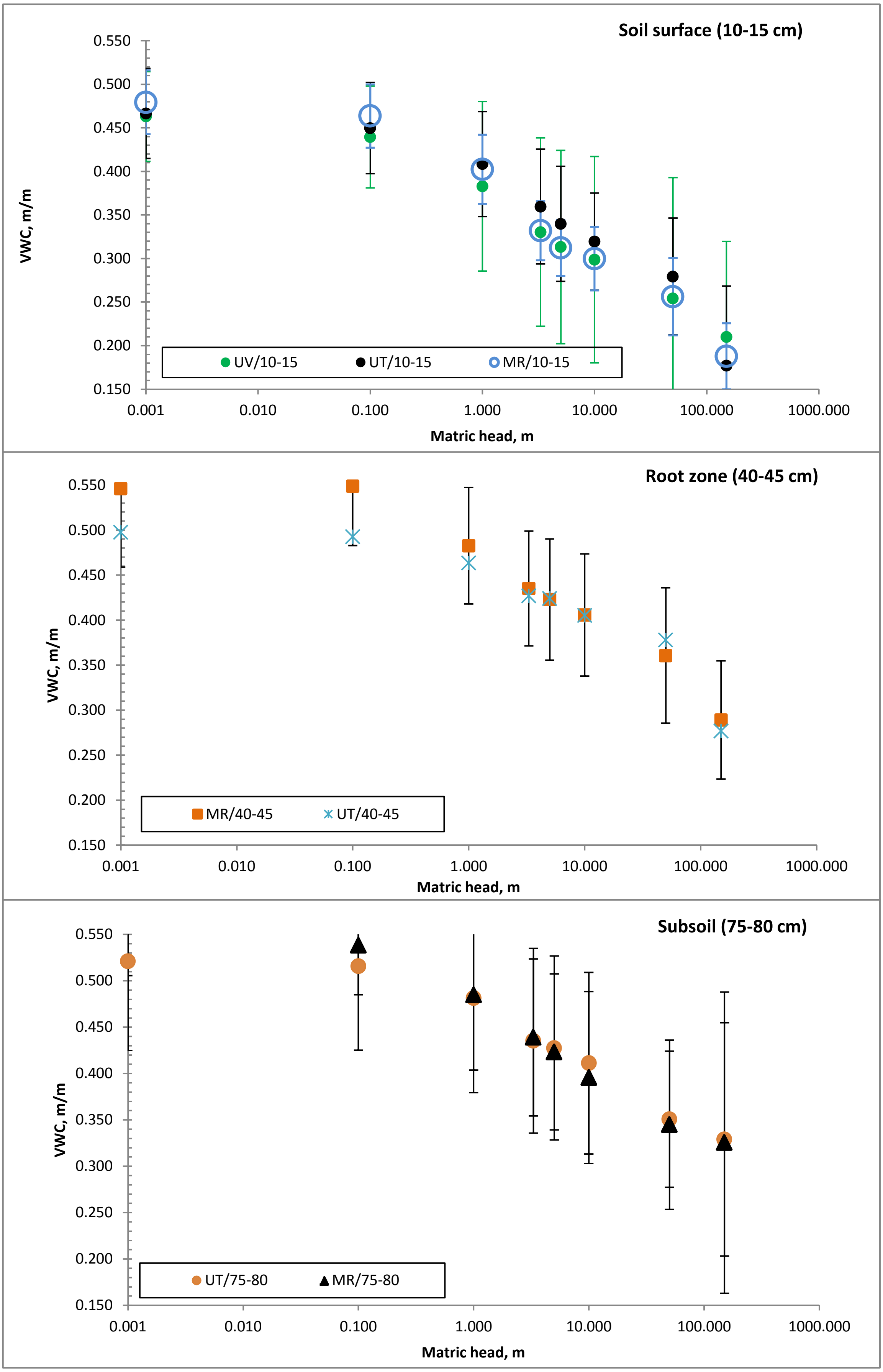
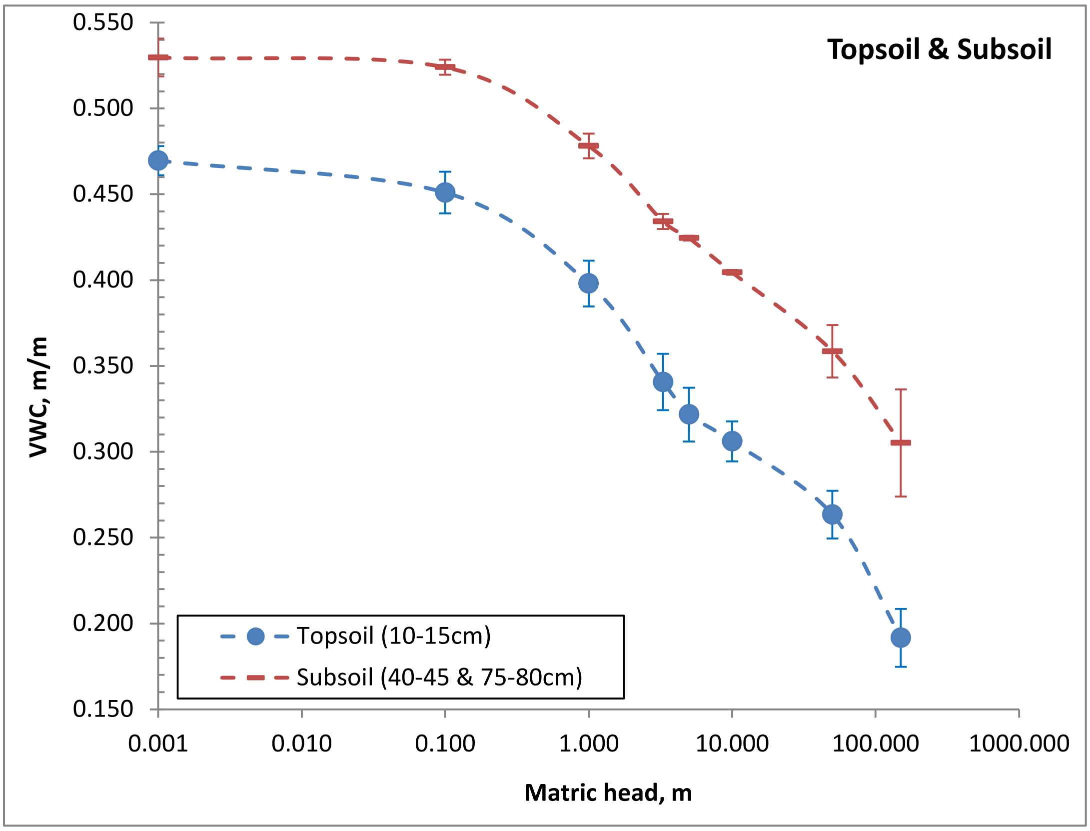


Figure 7. Water retention curves for **a)** 10-15 cm, **b)** 40-45 cm, and **c)** 75-80 cm, showing error bars as ± 1 standard deviation of the mean.



Position	θ_s	α	θ_{res}	N	M
Topsoil (10-15 cm)	0.470	7.001	42.198	0.999	-0.0009211
Subsoil (40-45 and 75-80cm)	0.530	3.931	9.121	0.996	-0.003965

Figure 8. Average water retention curves for topsoil (10-15 cm) and subsoil (40-45 and 75-80cm) with error bars representing ± 1 standard deviation of the mean. The modelling parameters for the two water retention curves are shown for the van Genuchten model immediately below.

7. **Provide expertise and experience in understanding and managing the interactions between recycled water and the physical properties of soils, and experience in supervising PhDs.**

This is ongoing and will develop as the Masters student, Mr Justice Frimpong, progresses. He has submitted his research proposal and literature review and has begun his experimental work in the laboratory. The section outlining his ***summary and conclusions*** from the literature survey is outlined below, and his research questions, hypotheses and experimental plans follow this.

Summary and conclusions from literature review (Justice Frimpong)

Restrictions to plant available water include pore size distribution (influenced by texture and structure), poor soil aeration, excessively large or small hydraulic conductivity, high soil strength, and osmotic stress caused by excessively high salt concentrations. Of these, the major restriction to plant available water when using recycled class A water to irrigate coarse textured soils are the unsaturated hydraulic conductivity and the osmotic stress caused by salinity.

To account for the rapid decline of the hydraulic conductivity function, Grant and Groenevelt (2015) proposed the relative diffusivity function to attenuate the measured water capacity, and furthermore that the attenuation should start at the matric head corresponding to the inflection point on the water retention curve (easily identified from the fitting parameter, k_0, in their water retention model). There are several problems with this proposal:

1) The weighting function proposed was found by Grant and Groenevelt (2015) to only attenuate the water capacity to about 50% and the only way to bring this down toward zero (as required in a true weighting function) was to introduce an artificial 'plant sensitivity' factor, ξ. The utility of the relative diffusivity and the ξ-factor as weighting functions therefore needs to be evaluated to determine whether a 50% attenuation is sufficient for many plants and whether plant sensitivity to hydraulic stress in soils can be matched to specific values of ξ.
2) Using the inflection point of the water retention curve at $h = k_0$ as the starting point for attenuating the water capacity was proposed by Grant and Groenevelt (2015) but this has never been properly evaluated for soil textures finer than very coarse sand. It is possible the approach may only apply to very coarse sands but not to finer textured soils (which are often used in horticultural production with recycled water, so the correlation between the magnitude of k_0 and the modal pore size distribution needs to be evaluated. One would expect the correlation to degrade as the modal pore size distribution declines in finer textured soils.
3) Salinity has a large impact on soil hydraulic properties but mainly in soils that contain significant amounts of clay and organic matter. In very coarse textured soils, where colloid dispersion is minimal, there may be little influence of salinity and sodicity. The link between k_0 and the modal pore size in soils that are saline and sodic has yet to be evaluated, as has the link between k_0 and the onset of plant stress.

These three problems can be reduced to the following three research questions, which form the basis for my research:

1) Is the matric head at the inflection point of the water retention curve $h = h_i = k_0$, really the best matric head to start weighting water capacity in calculating the plant available water in sandy soils as suggested by Grant and Groenevelt (2015)? Furthermore, if $h = k_0$ is indeed useful for sandy soils, is it also useful for finer textured soils?
2) Does the matric head, $h = h_i = k_0$, correspond with the matric head at which plants begin to suffer water stress in sandy soils?
3) If so, does the correlation hold under varying degree of salinity in sandy soils?

Hypotheses (Justice Frimpong)

The three questions above lead to the following testable hypotheses:

<u>Hypothesis 1</u>: Under controlled environmental conditions, the matric head, $h = h_i = k_0$, represents an unbiased point on the water retention curve (plotted on a semi-log scale) for all soils of sandy texture, and its location depends on (or can be related to) the single

dominant (e.g. modal) pore size of the soil. The value of k_0 will therefore shift in close (linear?) relation with some measure of particle size (or pore size) for sandy textured soils. A corollary to this would be that for soils of finer texture, where the pore size distribution may be multi-modal, the correlation between pore size and k_0 will become weaker and weaker in finer and finer textured soils.

Hypothesis 2: Under controlled environmental conditions, water stress in plants grown on soils (for which there is a strong correlation between k_0 and particle size) will only begin when the matric head of the soil water reaches $h = h_i = k_0$. The degree of correspondence will depend on the sensitivity of plant species to water stress; that is, highly sensitive plants will experience stress symptoms from $h = k_0$ while less sensitive plants will display symptoms only for $h >> k_0$.

Hypothesis 3: The degree of correlation between h_i (or k_0) and the matric head at which water stress begins (in applicable soils – see above) will depend on salt concentration; as salt concentration increases in the saturated soil, the correlation between k_0 and the onset of water stress will diminish.

Experiments to be conducted by Justice Frimpong

Experiment 1: Location of the inflection point in different textured soils.

Aim: To determine whether the inflection point ($h = k_0$) on the water retention curve varies in a predictable manner with some measure of particle and pore size in a range of different soils in the coarse-textured range.

Experimental design: the only factor that will be considered is soil texture. Twenty coarse textured soils will be sampled from a known site. In a split, ten (10) of these coarse textured soils will be pure sand with well-defined features of mono-modal particle size distribution and the other 10 extending relatively to the finer texture range. The sampling regime (i.e. random sampling) for collecting the soils will be based on a complete randomised design.

Procedures: Samples of 20 different soil textures (10 pure sands having well-defined and uni-modal particle size distributions) plus 10 other relatively coarse textured soils having at least bimodal or multimodal particle size distributions) will be placed in 50 mL cylinders to be saturated and drained at multiple different matric heads to prepare volumetric water retention curves across the plant available range of suctions, with a greater emphasis on the detail at the wet end of the retention curve. Detailed particle size distributions will be obtained by sedimentation. The water retention data will be fitted to the Groenevelt & Grant model to obtain an unbiased set of k_0 values. The particle size distribution data will be analysed to obtain a measure of the primary particle size (e.g. geometric mean diameter) and plotted against the magnitude of k_0 for the full range of soils characterized. The relationship will be evaluated to determine whether there is an obvious soil texture beyond which it deviates from linearity.

Experiment 2: Degree of correlation between the matric head at h = k_0 and the onset of water stress symptoms in plants.

Aim: to determine whether the theoretical inflection point on the water retention curve marks the point at which different plants begin to experience water stress.

Experimental design: Concern factors will be five selected coarse textures (mix of very sandy and finer textured soils), plant species, and predicted soil water availability at three different matric heads, $h = k_0$, $h < k_0$ and $h > k_0$. There will be five texture sub factors and up to two plant species sub factors (highly susceptible to water stress and moderately tolerant plants). The experimental design will be a 5 x 2 x 3 factorial experiment arranged in randomized complete blocks with three replications. Furthermore, 10 (5 x 2) control pots will be maintained wet with no restrictions imposed.

Procedures: Replicated pots for each of the relevant soils will be wetted to saturation then seeded to the various plant species, which will be allowed to germinate and grow under ideal conditions until they reach a critical leaf stage (e.g. 3 leaves or 6 leaves). Pots will then be exposed to one of three matric heads ($h = k_0$, $h < k_0$, and $h > k_0$) for a period of 2-3 weeks to allow symptoms of early water stress to be experienced and displayed in terms of tissue growth. Measurements will be taken on tissue dry mass (shoots and roots) at the allocated time. The correlation and regression technique will be used to establish the relationship between dry matter and k_0 with respect to soil and plant used in the experiment.

Experiment 3: Influence of salinity on the degree of correlation between the matric head at $h = k_0$ and the onset of water stress symptoms in plants.

Aim: to determine the extent to which the presence of salt in the soil solution will influence whether the theoretical inflection point on the water retention curve marks the point at which different plants begin to experience water stress.

Experimental design: concern factors will be selected soil textures, plant species, and salinity. There will be five soil texture sub factors, two plant-species sub factors and three salinity sub factors. The experimental design will be 5 x 2 x 3 factorial experiment arranged in randomized complete blocks with three replications. Furthermore, 10 (5 x 2) control pots will be maintained wet with no restrictions imposed till the desired growth stage.

Procedures: Replicated pots for each of the relevant soils will be wetted to saturation then seeded to the various plant species, which will be allowed to germinate and grow under ideal conditions until they reach a critical leaf stage (e.g. 3 leaves or 6 leaves). Pots will then be leached with one of 3 salt concentrations in the range typically found in recycled class A irrigation water and then exposed to one of three matric heads ($h = k_0$, $h < k_0$, and $h > k_0$) for a period of 2-3 weeks to allow symptoms of early water stress to be experienced and displayed in terms of tissue growth. Measurement will be taken for dry mass of tissue (shoots and roots) at the allocated time. The degree of correlation between dry matter and k_0 for each soil, plant and salt concentration will be evaluated to determine whether the salt effect influences the initial stress point.

Progress on postgraduate student work.

Mr Frimpong has started his laboratory experimental work for Experiment 1, and has several water retention curves completed. These each show very sharp declines in water content at critical matric heads ranging between 10 cm and 120 cm. The findings are ideal for evaluating whether or not the matric head at the inflection point in each soil corresponds with the onset of hydraulic stress in plants grown in these soils; the necessary glasshouse work required to obtain real plant response (Experiment 2) is currently being organised by Mr Frimpong. The mathematical modelling required to identify the location of the inflection point for each soil is also currently underway. In addition, the ideas are being tested on other data for sands published in the UNSODA database. A peer reviewed manuscript based on this work is currently underway as follows:

"Frimpong JO, Grant CD, Cox JW and Cavagnaro T (2016). Evaluation of the inflection point in the water retention curve as the initial hydraulic stress point for plants grown on sandy soils. Plant and Soil (DRAFT)."

A follow-up paper based on the effects of saline water on the onset of hydraulic stress surrounding the inflection point in sandy soils (Experiment 3) is also under construction, as follows:

"Frimpong JO, Grant CD, Cox JW and Cavagnaro T (2016). To what extent does the osmotic potential of soil water influence the onset of dynamic hydraulic stress of plants grown at matric heads beyond the inflection point of water retention in sandy soils? Plant and Soil (DRAFT)."

Note: As indicated in the Introduction, the experimental work is ongoing, and will proceed uninterrupted beyond the funding period until the student, Mr Frimpong, completes his thesis, and the work is published and extended for practical use. This was not anticipated initially but is not untypical of projects such as this, where the funding period is prescribed before the scientific work gets underway.

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Methods Appendix

Saturated hydraulic conductivity

The saturated soil cores that were prepared for measuring water retention curves (of length, L cm) were first saturated and set up to determine their saturated hydraulic conductivity using a falling head method as follows. A close-fitting tube of H = 10 cm height was attached to the top of each ring and allowed to fill with water by capillary action (at first) then under hydrostatic pressure until the water level came to the top of the tube. Samples were then fixed to a retort stand and allowed to drain, with the total hydraulic head (H+L) being monitored over time. The hydraulic head was then plotted as a function of time and the slope of the graph used to calculate the saturated hydraulic conductivity, K_s, using:

$\log_e (H+L) = \log_e (H_0 + L) – (K_s/L)\ t$

An example for one of the 108 soil cores on which K_s was measured is shown in Figure A2-1. For this sample, the slope of the line was $K_s/L = -7.93 \times 10^{-4}\ min^{-1}$, the soil sample length was L = 5 cm, so $|K_s| = 7.93 \times 10^{-4}\,\frac{1}{min} \times 5\,\frac{cm}{} \times \left(\frac{1\,m}{100\,cm}\right) \times \left(\frac{1\,min}{60\,s}\right) = 6.6 \times 10^{-7}\,\frac{m}{s}$. The values for Ks were collated and averaged according to depth in soil profile and location in the vine row, and these are reported in the main report.

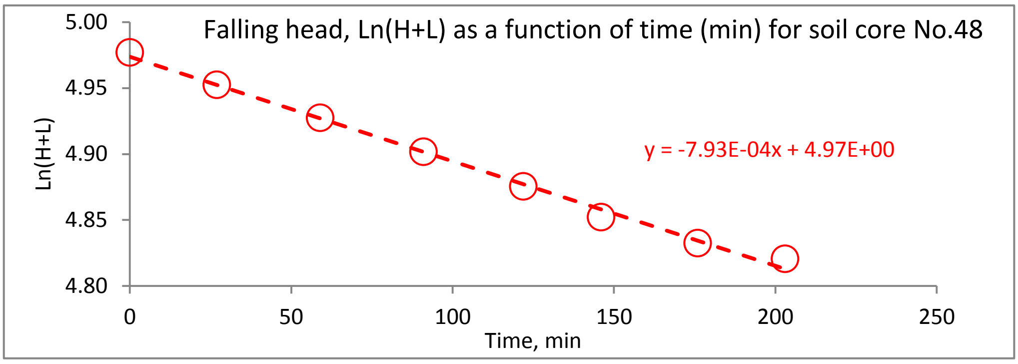

Figure A2-1. Typical plot of falling head for an undisturbed soil core (No.48) on which saturated hydraulic conductivity was measured.

Mean values of K_s for the soil cores are shown in Table A2-1 for all depths and locations.

Table A2-1. Mean saturated hydraulic conductivity for different depths and locations in the vineyard, showing the number of blocks from which sets of 3-replicate cores were taken for the measurements.

Location	Code	No. blocks involved	Soil depth (cm)	Mean K_s (m/s)	Std deviation of mean Ks (m/s)
Under vine	UV/10-15vertical	3	-12.5	1.1E-06	1.3E-06
	4/UV/10-15horizontal	1	-12.5	2.5E-06	1.7E-06
	UV/40-45vertical	3	-42.5	6.4E-07	4.6E-07
	4/UV/40-45horizontal	1	-42.5	1.4E-06	1.8E-06
	UV/75-80vertical	3	-77.5	7.5E-07	5.6E-07
	4/UV/75-80horizontal	1	-77.5	6.1E-08	7.9E-08
Under wheel track	UT/10-15vertical	3	-12.5	1.4E-07	7.9E-08
	4/UT/10-15horizontal	1	-12.5	1.2E-06	2.5E-07
	UT/40-45vertical	3	-42.5	1.8E-07	1.9E-07
	4/UT/40-45horizontal	1	-42.5	5.9E-07	3.3E-07
	UT/75-80vertcal	3	-77.5	2.3E-08	1.9E-08
	4/UT/75-80horizontal	1	-77.5	3.0E-07	2.4E-07
Mid row	MR/10-15vertical	3	-12.5	2.0E-06	2.4E-06
	4/MR/10-15horizontal	1	-12.5	1.2E-06	1.1E-06
	MR/40-45vertical	3	-42.5	2.9E-07	1.4E-07
	4/MR/40-45horizontal	1	-42.5	1.9E-07	1.7E-07
	MR/75-80vertical	3	-77.5	1.1E-06	1.7E-06
	4/MR/75-80horizontal	1	-77.5	2.2E-07	3.0E-07

Bulk density

As indicated in the body of the report the bulk density of the soil cores changed with water content because they contained significant quantities of clay (particularly those at depth). The variability in the data was large and so error bars were not shown in the figure presented in the main report. With the available information to date, the mean bulk densities and their standard deviations are shown in Table A2-2 below. The remaining data (shown as not yet available, nya) will be available in September 2015.

Table A2-2. Mean bulk density of soil cores (g/cm^3) in various states of soil water

Depth (cm)	Location	Under vine			Under Track			Mid-row		
	Water status	Saturated	5 bar	OD	Saturated	5 bar	OD	Saturated	5 bar	OD
-12.5	Mean	1.47	1.62	1.57	1.48	1.53	1.64	1.39	1.51	1.49
	Stdev	0.09	nya	0.09	0.11	0.09	0.09	0.10	0.11	0.09
-42.5	Mean	nya	nya	nya	1.42	1.46	1.68	1.23	1.27	1.57
	Stdev	nya	nya	nya	nya	nya	nya	0.31	0.33	0.15
-77.5	Mean	nya	nya	nya	1.37	1.41	1.60	1.22	1.28	1.43
	Stdev	nya	nya	nya	0.22	0.19	0.09	0.03	0.03	0.16

Water retention

Each of the 108 *in tact* soil cores was saturated over a period of days to weeks (depending on texture and rate of wetting) then placed on ceramic pressure plates connected to an elevated suction or N_2-gas pressure as indicated in Table A2-3.

Table A2-3. Methods use to measure soil water retention curves for the soils in this study.

Matric head (m)	Method
0.01	Wet by capillary action then place in standing pool of free water until saturated, then weigh.
0.1	After weighing for 0.01 m, place on a saturated porous ceramic plate connected to a hanging column of water 10 cm high. Leave for 48 h, weigh, return to ceramic plate for a further 24 h and re-weigh; if weight unchanged, proceed to greater suction (if not, repeat until weight does not change over 24 h period).
1	After weighing for 10 cm, place on a saturated porous ceramic plate connected to a hanging column of water 1 m high. Leave for 72 h, weigh, return to ceramic plate for a further 24 h and re-weigh; if weight unchanged, proceed to greater suction (if not, repeat until weight does not change over 24 h period).
3.3	After weighing for 1 m matric head, return to saturated porous ceramic plate (1 bar capacity), place into pressure chamber connected to atmospheric pressure, seal chamber and raise gas pressure to 33 kPa (using N_2 gas). Weigh as described above.
5	After weighing for 33 kPa matric head, return to saturated porous ceramic plate (1 bar capacity), place into pressure chamber connected to atmospheric pressure, seal chamber and raise gas pressure to 50 kPa (using N_2 gas). Weigh as described above.
10	After weighing for 50 kPa matric head, return to saturated porous ceramic plate (1 bar capacity), place into pressure chamber connected to atmospheric pressure, seal chamber and raise gas pressure to 100 kPa (using N_2 gas). Weigh as described above.
50	After weighing for 100 kPa matric head, transfer to saturated porous ceramic plate (5 bar capacity), place into pressure chamber connected to atmospheric pressure, seal chamber and raise gas pressure to 500 kPa (using N_2 gas). Weigh as described above, then place in oven to dry at 105C for at least 24 h. Weigh to obtain oven dry weight (to calculate bulk density).

At the same time that the 108 undisturbed soil cores were collected in the field, a set of duplicate undisturbed soil clods (roughly 2 cm diameter) was collected and brought to the laboratory. Each clod was placed on a 15 bar capacity ceramic pressure plate and wetted by capillarity to saturation on the plates. The plates were then placed into a high-pressure chamber capable of withstanding at least 1500 kPa N2-gas pressure and allowed to come to equilibrium. Samples were then weighed and dried to constant weight in an oven at 105C. Gravimetric water contents were calculated and converted to volumetric water contents using the bulk density of samples taken at 5 bar.