Risk Based Approach for Managing Salt Accumulation in Soil Irrigated with Recycled Water

by

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This thesis is dedicated to my son and other children suffering from severe Autism Spectrum Disorder (ASD). I hope, in the future, appropriate research will discover the treatment of this disease and help the children with ASD to live a normal life.

ABSTRACT

Recycling is one of the viable options to attain sustainable management of wastewater. The supply and reuse of recycled water may play an important role in enhancing urban water supplies in many water-scarce parts of industrialised countries because of its reduced treatment cost relative to seawater desalination and imported surface water. One such reuse option includes application of recycled water for irrigating urban open fields. Past literature suggests that the continuous use of recycled water over a long period of time may lead to the accumulation of salt in the root zone. Salt transport models to quantify salt accumulation in soil exist, but these do not consider the stochastic nature of the elements of salt accumulation process. Moreover, none of the past studies propose a framework to manage and control the salt accumulation process due to recycled water irrigation by considering stochastic nature of different components.

The study described in the thesis details a novel methodology adopted for the development and implementation of an integrated risk based approach to control sources of salinity and the level of treatment required to use recycled water in irrigation in a sustainable manner. The study included laboratory and field work and involved thorough investigation of site specific soil, data analysis, development of relationships among elements of salt accumulation process, and incorporated long-term prediction modelling result and scientific knowledge into a framework. One of the key investigations conducted was to understand and monitor salt accumulation process in columns using sensors in terms of depth of soil, type of soil and type of irrigation water. Data generated from these experiments and output from simulation were used to develop the framework. Therefore, the overall aim of this study was to develop a framework with the help of a probabilistic method, namely, Bayesian belief network (BBN) to manage the salinity in the root zone due to recycled water irrigation.

Results from the column study show that due to recycled water irrigation, soil water electrical conductivity (EC_{SW}) was higher in the upper part of the column (0-0.2 m) than the lower part. This is because only applied irrigation water could not leach the salt from upper part to downward. When simulated rainfall was applied

(once in a week) in a loamy sand column along with recycled water (twice in a week), the average EC_{SW} showed a decreasing pattern with time. In another column study with silty loam soil, average sodium adsorption ratio due to recycled water (EC = 0.8 dS/m) irrigation was 3.6 times more than the tap water (EC = 0.2 dS/m) irrigation and 1.4 times less than the synthetic saline water (EC = 2.0 dS/m) irrigation. In the same column study, it was observed that the ratio of soluble cations (Na^+: Mg^{2+}: Ca^{2+}: K^+) in the soil sample changed than its initial ratio at the beginning of the study. The change in the ration occurred because of exchanging cations between soil and the water added for irrigation. A salt transport model HYDRUS 1D was validated with experimental results and used to predict risk of salt accumulation in field condition. The salt transport modelling carried out in this study shows that in drought condition, yearly averages EC_{SW} exceeded the maximum salinity tolerance threshold of 5.0 dS/m for rye pasture due to recycled water irrigation in a loamy sand paddock. The EC_{SW} exceeded 1, 59, 79, 87 and 90% for the years from 1 to 5, respectively. In another modelling with future climate condition between years 2021 and 2040 shows that EC_{SW} was 24% higher in loamy soil paddock compared to loamy sand paddock. Amount of leachate in the loamy sand paddock was 27% more than the amount leached from loamy paddock, which may pose a salinity risk to the ground water if there is a perched aquifer in the field at a depth < 1 m.

BBN framework analyses identified that for root zone EC_{SW} of 2.25 dS/m, it is 92% probable that the Na^+ concentration of the root zone soil water would be in the range of 5 – 15 mmol(c)/L; for EC_{SW} of 16.5 dS/m, there is 86% probability that the Na^+ concentration of root zone soil water would be in the range of 30 – 35 mmol(c)/L. Furthermore, over the study period of 2021 to 2040, it was found that the reduction of the posterior mean of recycled water EC by 13% (from μ=0.92 to μ=0.8 dS/m), brings the average root zone EC_{SW} down from 6.5 dS/m to 4 dS/m, which is within the salinity threshold limit for rye pasture. The BBN framework also identified the most significant sources of salinity contributing to wastewater and proposed control strategy of those sources to minimise the salt accumulation in the soil for a sandy loam oval irrigated with recycled water. Results show that accumulation of salt in the root zone was largely due to the salt load in the wastewater stream from washing machines and the salt load in the wastewater from toilets was the second most influential source. It was found that by controlling multiple sources at the same time significantly reduces salt accumulation in the soil. It was observed that by using environmental friendly detergents reduce the TDS load in the laundry stream by 4 to 7 times and Na^+ load by 2 times than popular brand detergents.

Irrigation scheduling with recycled water is typically done while considering only the soil moisture levels. The study reported in this thesis proposes that besides considering the soil moisture levels, salt accumulation within the soil must be considered while irrigating open fields using recycled water. Proposed methods and outcome of this research would provide vital knowledge about the uncertainty associated with root zone salinisation of urban open fields, and better management and control of root zone salinity due to irrigation with recycled water. The study highlighted that any strategies that help in the reduction of salt in the recycled water will be beneficial in managing the soil salinity as a result of recycled water use for irrigating open fields. Hence, the proposed decision making tool for controlling the risk of soil salinisation can assist in developing recycled water irrigation schemes which are sustainable over the long-run.

STATEMENT OF AUTHENTICATION

I, Muhammad Muhitur Rahman, declare that all the materials presented in the PhD thesis entitled 'Risk based approach for managing salt accumulation in soil irrigated with recycled water' are of my own work, and that any work adopted from other sources is duly cited and referenced as such.

This thesis contains no material that has been submitted previously, in whole or in part, for any award or degree in other university or institution.

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Muhammad Muhitur Rahman

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PUBLICATION MADE FROM THIS RESEARCH

Journal papers

1. Rahman, M.M., Hagare, D. and Maheshwari, B. (2014) Framework to assess sources controlling soil salinity resulting from irrigation using recycled water: An application of Bayesian Belief Network. Journal of Cleaner Production, In Press (Impact factor 3.590).
2. Rahman, M.M., Hagare, D., Maheshwari, B. and Dillon, P. (2015) Impacts of prolonged drought on salt accumulation in the root zone due to recycled water irrigation. Water, air & soil pollution, 226:90 (Impact factor 1.685).
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Book Chapter

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ABBREVIATIONS AND SYMBOLS

AAS	Atomic Absorption Spectrophotometer
ASTM	American Society For Testing And Materials
BBN	Bayesian Belief Network
BC	Boundary Condition
BIAS	Percent Bias
BOD_5	Biochemical Oxygen Demand at 5^{th} Day
BS	Bathroom Sink
C5	Paddock name
CEC	Cation Exchange Capacity
COD	Chemical Oxygen Demand
CPT	Conditional Probability Table
CSIRO	Commonwealth Scientific and Industrial Research Organisation
D21	Paddock name
D33	Paddock name
DAG	Directed Acyclic Graph
DW	Dish Washer
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
EM	Electromagnetic method
ER	Electrical Resistivity method
FAO	Food and Agricultural Organization
GCM	Global Climate Model
GS3	Sensor name
HWRS	Hawkesbury Water Reuse Scheme
HYDRUS 1D	Salt transport modelling software
IDAL	Intermittently Decanted Aerated Lagoon
KS	Kitchen Sink
LAI	Leaf Area Index
LCA	Life Cycle Assessment
LF	Leaching Fraction

MAE	Mean Absolute Error
QMRA	Quantitative Microbial Risk Assessment
RE	Relative Error
RETC	Code for quantifying the hydraulic function of unsaturated soils
RIRA	Recycled Water Irrigation Risk Assessment
RMSE	Root Mean Square Error
RO	Reverse Osmosis
RW	Recycled Water
SAR	Sodium Adsorption Ratio
SOM	Soil Organic Matter
STP	Sewage Treatment Plant
SW	Synthetic Saline Water
SW	Shower Water
SWCC	Soil Water Characteristic Curve
TAFE	Technical and Further Education
TDR	Time Domain Reflectometry
TDS	Total Dissolved Solid
TF	Trickling Filter
TW	Tap Water
VG	van Genuchten
VWC	Volumetric Water Content
WM	Washing Machine
σ	Standard deviation
$\boldsymbol{\alpha_1}$	Longitudinal dispersivity (cm^{-1})
μ	Mean
a	Constant in transmission coefficient (-)
b	Constant in transmission coefficient (-)
BBN_{Field}	BBN model developed for field
BBN_{Lab}	BBN model developed with laboratory experimental result
BS_{Load}	TDS and Na^+ load from bathroom sink (gd^{-1})
c	Concentration of chemical in liquid phase (mgL^{-1})
c_0	Concentration of the irrigation water (mgL^{-1})
C_{sum}	Concentration of total cation ($meqL^{-1}$)

D_d	Molecular diffusion coefficient in free water (cm^2d^{-1})
DW_{Load}	TDS and Na^+ load from dish washer (gd^{-1})
D_z	Dispersion coefficient (cm^2d^{-1})
E_a	Actual evaporation (mm)
EC	Electrical conductivity (dS/m)
$EC_{1:5}$	Electrical conductivity of 1:5 soil water solution (dS/m)
EC_{25C}	Electrical conductivity converted at 25^0C (dS/m)
EC_{bulk}	Bulk electrical conductivity (dS/m)
EC_e	Electrical conductivity of saturated extract (dS/m)
$EC_{measured}$	Measured electrical conductivity (dS/m)
EC_{rw}	Recycled water electrical conductivity (dS/m)
EC_s	Electrical conductivity of dry soil (dS/m)
EC_{SW}	Electrical conductivity of soil water (dS/m)
$EC_{SW\ (in\ situ)}$	In-situ extracted electrical conductivity (dS/m)
$EC_{SW\ (sensor)}$	In-situ sensor measured electrical conductivity (dS/m)
ET_0	Reference or potential evapotranspiration (mm)
h	Pressure head (mm)
h_c	Crop height (m)
k	Extinction coefficient (-)
K_d	Distribution coefficient (cm^3g^{-1})
KS_{Load}	TDS and Na^+ load from kitchen sink (gd^{-1})
K_z	Saturated hydraulic conductivity (cmd^{-1})
l	Pore connectivity parameter (-)
m	Empirical parameters (-)
n	Empirical parameters (-)
N	Number of observations
O_i	Observed values
$pH_{1:5}$	pH of 1:5 soil water solution
pH_{SE}	pH of saturated extract
P_i	Predicted values
q_z	Volumetric flux density (cmd^{-1})
R^2	Correlation coefficient
RW_{TDS}	Recycled water TDS concentration (gL^{-1})

S	Sink term representing water uptake by plant roots (cm^3 $cm^{-3}d^{-1}$)
S_e	Effective saturation (-)
SW_{Load}	TDS and Na^+ load from shower water (gd^{-1})
T	Soil-specific transmission coefficient (-)
t	Time (d)
T_a	Actual transpiration (mm)
t_o	Time when the modelling begins (d)
T_p	Potential transpiration (mm)
WM_{Load}	TDS and Na^+ load from washing machine (gd^{-1})
WW_{TDS}	Wastewater TDS concentration (gL^{-1})
z	Depth in the vertical direction (positive upward) (cm)
α	Soil water retention function (cm^{-1})
β	Effect of solute distribution in the soil's mobile fraction of water
ε	Dielectric permittivity (-)
ε_o	Dielectric permittivity of vacuum ($C^2N^{-1}m^{-2}$)
θ	Volumetric moisture content (cm^3cm^{-3})
θ_r	Residual moisture content (cm^3cm^{-3})
θ_s	Volumetric solid content in the soil (cm^3cm^{-3})
θ_s	Saturated moisture content (cm^3cm^{-3})
ρ_b	Bulk density of soil (kgm^{-3})
ρ_s	Specific density of soil (-)
τ	Tortuosity factor (-)
κ	Dielectric constant (-)

CHAPTER 1

INTRODUCTION

1.1 Background of the research

Recycling is one of the viable options to attain sustainable management of wastewater. The merits of recycled water is diverse which include reducing pressure on existing fresh water supplies, minimising effluent disposal to surface or coastal waters and provisioning constant volume of water than rainfall-dependant sources (Chen et al. 2012). The supply and use of recycled water may play an important role in enhancing urban water supplies in many water-scarce parts of industrialised countries because of its reduced treatment cost relative to seawater desalination and imported surface water. The technological improvement and economic affordability of wastewater treatment has made wastewater recycling a reality and broadened the most sustainable use of recycled water. One such reuse option includes application of urban recycled water in open fields including paddocks and sporting ovals. In Australia, in 2004, approximately 67% of the total recycled water was used for agriculture; about half of this water was used by irrigation industries for pasture and fodder crops (Hamilton et al. 2005). In 2004-05 and 2008-09, state-wide average of recycled water use in urban irrigation was 30% of the total recycled water usage, which was 27.2% in 2009-10 (ABS 2006; ABS 2010; ABS 2012). In Sydney, in 2011, Sydney Water supplied about 3.8 billion litres of recycled water for irrigating farms, sporting ovals, golf courses, parks, landscapes and racecourses and by 2015, it is expected that the recycling water will meet 12% of total water demand in greater Sydney (Sydney Water 2011). Also, by 2015, Melbourne (another major city in Australia) is expected to achieve recycling of 23% of urban effluent and the national target for recycling water is set at 30% by the Australian Government (Lane and Ward 2010). Thus the use of urban effluent or recycled water particularly for irrigating urban open fields, in the place of fresh water, is one of the important goals of the local and national governments to achieve sustainable management of water.

However, the downside of using recycled water, particularly for irrigation, is due to its contaminants. One of the contaminants that is of concern for this study is salts. Salinity is the concentration of soluble salts in water that are measured as total dissolved salts (TDS) or electrical conductivity (EC) in soil solutions. From an environmental point of view, sodium and chloride are the two constituents of recycled water which are of most concern as they are more likely to remain as ions in soil solutions and contribute to the effects of salinity on plant growth (NRMMC-EPHC-AMC 2006). In the conventional wastewater treatment process, the majority of mineral salts pass through the wastewater treatment system unaffected, unless reverse osmosis is used as one of the treatment processes (Aiello et al. 2007; Rebhun 2004). As such, the recycled water contains elevated levels of salt, when the recycled water is used for irrigation, there is a potential risk of salt increase in the root zone.

The increase in salt concentration in the soil can adversely influence the amount of water a plant can uptake from the soil due to the osmotic effect. Several studies have reported increased salinity levels in soil due to the prolonged use of recycled water for irrigation. Distinct long-term effects of recycled water use in terms of salinity have been observed by Dikinya and Areola (2010). They observed that after three years of irrigation with recycled water, the electrical conductivity in soil increased from 0.11 to 0.24 dS/cm and Na^+ concentration increased from 2.95 to 5.75 meq/100g of soil. Jahantigh (2008) reported 95% increase of salinity levels for a field which used recycled water for irrigation over five years. Increase of salinity in terms of EC, Na^+ and Cl^- are also reported in a number of other studies (Xu et al. 2010; Klay et al. 2010; Adrover et al. 2012; Candela et al. 2007). Higher salt levels in the soil can adversely affect the soil potential for supporting plants and crops growth (Grewal and Maheshwari 2013; Bernstein 1975; Al-Hamaiedeh and Bino 2010). Hence, it is important to control the salt accumulation in the root zone through appropriate management options including controlling salt level in the irrigation water.

Controlling salt level in the irrigation water is possible by source management (Patterson 2004; Stevens et al. 2011). Source management includes the identification and monitoring of contaminants, with a view to reduce or eliminate these, before entering the sewer system. This is critical in order to protect the sewage collection infrastructure, workers at sewerage systems, efficiency of treatment processes, effluent quality, and the receiving environment. In addition, source management, in particular, is becoming important in the context of sustainable management of resources, as the potential pollutants are prevented from entering into the environment. Similarly, source control in the case of controlling the salt in the wastewater can yield more sustainable use of recycled water for irrigation purposes.

Generation of salts from its sources to the accumulation in the root zone incorporates a number of parameters and the associated uncertainty of those parameters, which include user pattern of domestic appliances in contributing salt in the wastewater stream, meteorological parameters, soil type, irrigation frequency and irrigation water salinity, to name a few. Since quantifying the magnitude as well as probability of occurrence of these parameters is essential for an efficient management of salinity in the irrigated field, a methodology is needed which is capable of incorporating uncertainty of associated variables by using marginal probability distributions. Hence, the thesis applies a risk based approach implemented in Bayesian belief network to assess the salt accumulation in open fields due to recycled water irrigation and devise management options to control it in a probabilistic manner. Bayesian belief network was applied in this study because this method can address multi nodal problem where one can determine the conditions at the source for the desired final effect. The network provides graphical representation of key factors, which portrays a better understanding of the inter-dependent relationships between the factors of the decision process (Jensen and Nielsen 2007). The study implements the methodology through the case study of four paddocks (D21, C5, D33 and Yarramundi under Hawkesbury Water Reuse Scheme) as well as a sporting oval (Greygums oval under Penrith Council). All of them use urban effluent from Western Sydney, Australia, as irrigation water.

1.2 Need for this research

Recycled water use, particularly in irrigation, has emerged as a realistic option out of new sources of water to meet water shortages (Tsagarakis 2005). Despite significant benefits, recycled water may deteriorate soil health in terms of increased salinity and sodicity. Although several studies in the past (Xu et al. 2010; Klay et al. 2010; Adrover et al. 2012; Candela et al. 2007) have highlighted the increase of soil salinity due to recycled water irrigation, yet the phenomenon depends on variability of soil characteristics. As salts are highly soluble, they infiltrate and accumulate in the deeper layer of the soil. When the soil EC is less than the EC of recycled water, a little portion of the residual dissolved solid is accumulated and most of the salt is leached from soil and accumulates in the groundwater (Klay et al. 2010). The movement of soil solution depends on soil type, specific to the study area, and different hydraulic properties of soil, which should be carefully considered when investigating salt accumulation due to recycled water irrigation. Conducting column study at laboratory provides useful information such as the impact of soil depth, irrigation frequency and irrigation water salinity on the extent of salt accumulation. Without having such information it is very difficult to say that soil condition is directly associated with application of recycled water (Aiken 2006; Stevens et al. 2003).

Modelling the salt accumulation helps to quantifying risk of salinisation by determining the magnitude of salt accumulation (Ragab 2002; Bahceci and Nacar 2007). A salt transport model validated and calibrated with data specific to the study area is an excellent tool to quantify salinity in the root zone. However, uncertainties associated with different parameters in salt accumulation process should be examined. An assessment framework based on probabilistic approach can properly deal with the parameter uncertainty related to the salt modelling.

Recycled water has been used as irrigation water in the Hawkesbury Water Reuse Scheme (HWRS) since 1960 (Aiken 2006). Due to this long history of using recycled water for irrigation, the HWRS has always been under the attention of the scientific community of the Western Sydney region and consequently several risk assessment studies related to recycled water irrigation have been carried out (Derry et al. 2006; Derry and Attwater 2006; Attwater et al. 2006; Aiken et al. 2010). However, none of the previous studies have attempted to model the salt accumulation in the soil of paddocks of HWRS due to applications of recycled water for irrigation under extreme climatic conditions (such as drought).

Bayesian belief networks have been successfully used to better understand and model different environmental problems, which include decision making on maintaining ecological health of river, framework to maintain sustainability of coastal lake-catchment system, and assessing sources of salinity in coastal aquifer (Ticehurst et al. 2007; Chan et al. 2012; Ghabayen et al. 2006) . In the case of recycled water, Bayesian belief network was used mainly for assessing health risk (Donald et al. 2009; Donald et al. 2011). However, none of the past studies applied Bayesian belief network for managing salinity associated with the use of recycled water for urban open field.

Hence, to overcome these knowledge gaps, soil from the study areas are analysed, and relationships among parameters associated with salt accumulation are evaluated using results from batch and continuous column studies. Moreover, a salt transport model is validated using results from a continuous column study and applied under field conditions to quantify root zone salinity under changing climatic conditions. In addition, a novel methodology incorporating Bayesian belief network is proposed to identify the sources that significantly influence the soil salinity and sodicity within the context of using recycled water for irrigation. The methodology is also used to identify the level of treatment needed for the recycled water, in order to reduce root zone salinity.

1.3 Research questions

After an extensive literature review, the following research questions were developed, which need to be answered to understand the salt accumulation in the soil due to recycled water irrigation:

- How parameters (i.e. soil moisture, permittivity, bulk EC and soil water EC) associated with salt accumulation in sensor based irrigation systems are related?
- How changing climatic conditions impact on salt accumulation?
- How the soil type and irrigation water salinity levels impact the soil salinity under transient irrigation system?
- How the elements (i.e. recycled water salinity, soil moisture, rainfall, evapotranspiration and leaching fraction) in the salt accumulation process can be assessed and quantified in a stochastic manner under a framework through the cause-effect relationship?

- How sources of salt can be assessed stochastically and included as a part of the management option to control salinity in the field, irrigated using recycled water?

1.4 Aim and objectives of current research

The main aim of this research is to develop a stochastic assessment framework for managing salinity in soil due to recycled water irrigation. The specific objectives are:

1. To understand the salt accumulation in soil, especially,
   a. To examine the impact of soil type and irrigation water salinity on the soil salinisation in a sensor based irrigation system under transient condition.
   b. To model salt accumulation in soil due to recycled water irrigation under changing climate condition.
2. To develop an integrated management framework implemented in Bayesian belief network,
   a. To investigate the degree of treatment recycled water needed to keep the soil salinity level within the salinity tolerance limit due to recycled water irrigation.
   b. To identify the salt sources which have maximum influence on the salinisation of the soil.

1.5 Research contribution

The study investigated the impact of recycled water irrigation in urban open fields including paddocks and a sporting oval. The extensive laboratory experimentation including batch and continuous column study with different types of soil as well as salt transport modelling in changing climate condition contributed to the increase of the knowledge as follows:

1. A stochastic assessment framework implemented in Bayesian belief network is proposed to identify the salinity level of recycled water needed to keep the root zone salinity of a paddock under sustainable limit.

2. Link between the domestic sources of salinity through user behavior for appliance use and the root zone salinity in a sporting oval is established, using Bayesian belief network.
3. Empirical parameters related to hydraulic modelling and soil water characteristic curve for soil specific to paddocks of the study area is evaluated. Moreover, regressed equations to determine soil water salinity from bulk salinity is proposed for sensor based irrigation system specific to paddocks of the study area.
4. Impact of drought in a loamy sand paddock is investigated in terms of root zone salt accumulation due to recycled water irrigation.
5. Impact of future climate condition such as rainfall, on the salt accumulation in paddocks of different soil types is investigated

The methodology proposed in the thesis along with its outcome provide vital knowledge about the possible root zone salinity in open fields using urban effluent; this also highlights management options to control the salinisation in a probabilistic manner. The methodology developed in this study is versatile in its application and can easily be updated with data from any open field in any part of the world.

1.6 Outline of the thesis

The research undertaken in this study is presented in ten chapters. Additional experimental data and modelling outputs are included in five appendices.

Chapter 1 presents brief background of this research followed by the need of this study. The research questions that need to be investigated and the objectives of this research are included. Moreover, significant contributions made by this research are also listed.

Chapter 2 presents a literature review on the characteristics and generation of recycled water and the impact of recycled water irrigation on soil properties. Sensor based irrigation system is discussed and different aspects of salinity measurement are reviewed. Importance of continuous column studies is identified to understand salt accumulation process in the laboratory environment. In addition, available salt transport models are reviewed for predicting salt accumulation in the field condition. Moreover, concept of Bayesian belief network is recognised and its applicability in solving environmental problems related to recycled water irrigation is reviewed. At the end, this chapter summarises the findings from the literature and identify the knowledge gap on the risk based approach for managing soil salinity due to recycled water irrigation and formulate the research problem that needs to be investigated in this research.

Chapter 3 presents the materials needed and methods followed during the laboratory experiments. The chapter includes a brief description of the study areas, soil sample collection from the study areas, and sample management in the laboratory. Protocols related to soil characterisation, batch study to establish relationships among parameters associated with a sensor based irrigation system, and continuous column study are discussed at length. Governing equations for salt transport and BBN modelling are also discussed.

Chapter 4 presents results of physico-chemical properties of soil samples collected from different paddocks in HWRS, which constitute the initial condition of the continuous column studies conducted with paddock soils. Proposed regressed equations to determine soil water salinity from sensor measured bulk salinity is presented in this chapter.

Chapter 5 presents the impact of drought condition on the salt accumulation in a loamy sand paddock (D21) of the study area. The chapter commences with presenting continuous column study result under no rain condition. Then, a salt transport model, HYDRUS 1D is validated with results from the continuous column study. This is followed by presenting results from HYDRUS 1D prediction of salt accumulation in field condition due to recycled water irrigation for the occurrence of drought for five consecutive years.

Chapter 6 presents impact of soil type on salt accumulation due to recycled water irrigation. The chapter commences with comparing results of continuous column study with soils from loamy sand (D21) and loam (C5) paddocks of the study area. Later, the chapter presents the salt accumulation modelling in field condition in these two paddocks due to recycled water irrigation using future climate data of 20 years. Impact of soil type on root zone salinisation is presented from different aspects including rainfall, leachate and seasonal variation.

Chapter 7 presents impact of irrigation water salinity on salt accumulation in a continuous column study with soils from loamy sand (Yarramundi) and silty loam (D33) paddocks of the study area. Three different types of irrigation water were used for the study comprising tap water (0.2 dS/m), recycled water (0.8 dS/m) and synthetic saline water (2.0 dS/m). The chapter commences by presenting the salt accumulation recorded by the sensor. This is followed by presenting results of spatial variation of salinity measured in soil samples collected from columns at the end of the continuous column study to find out the impact of variation of irrigation water salinity on soil salinisation.

Chapter 8 presents a methodology implemented in Bayesian belief network to manage salinity in the recycled water to control root zone salinity in a loamy sand (D21) paddock of the study area. The chapter commences with presenting relationships among different variables in salt accumulation process developed with the results of batch experiments and continuous column study with soil from the paddock. This is followed by the presentation of the results of the validation study as well as sensitivity analysis of the proposed network. Later, the chapter shows management options to be availed to control salinity in the recycled water to keep the root zone salinity within a sustainable limit, in a probabilistic manner.

Chapter 9 presents application of the methodology in BBN to assess sources controlling salinity in the root zone of a sandy loam sporting oval (Greygums oval). The chapter commences with presenting relationships among different parameters related to generation of the salt in the sewage, treatment of sewage, and application of treated sewage or recycled water in the oval. The relationships were evaluated based on data collected from literature and salt transport modelling conducted to predict salt accumulation in the oval for the irrigation scheduling practiced with recycled water. Later, results of the stochastic analyses for finding the most significant source contributing root zone salinity in the oval is presented.

Chapter 10 presents the summary and conclusions made from this research and suggest recommendations for further research.

Appendix A to **E** presents details of physico-chemical parameters determined in the laboratory for soil samples collected from fields and additional data related to Chapters 5 to 9.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In Chapter 1 background and necessity of this research are discussed. This chapter highlights issues relevant to the recycled water irrigation, its impact in terms of salt accumulation, available tool to model salinisation, and finally avenues to control salinisation in a probabilistic manner. In a risk based approach to solving a problem, the first step is hazard identification. Then, the hazard is quantified by analysing the exposure pathways. Lastly, the risk is assessed using an assessment methodology. In this chapter, literature related to all the above 3 steps is reviewed. Information is gathered to see how salinity hazard exists due to recycled water irrigation including sensor based irrigation system. In the next section, solute transport model capable of quantifying salinity is reviewed as part of assessing exposure pathways. Then, applications related to Bayesian belief network are reviewed as part of the literature related to risk assessment framework. Finally the research gaps identified in the existing literature are summarised.

2.2 Recycled water irrigation

Recycled water is the treated wastewater after removing solids and certain impurities. Characteristics of recycled water depend on its source, treatment level and geographic location. Recycled water characteristics can be classified according to its physical, chemical and biological aspects. Biological aspect is important when health effect is considered. Physical and chemical characteristics are crucial to understand the environmental effects of using recycled water. Important recycled water characteristics are pH, total dissolved solid (TDS), electrical conductivity (EC), sodium adsorption ratio (SAR), heavy metals, and specific salt concentrations. These parameters directly influence the salt accumulation in the soil and also the sodicity and its effect on soil.

2.2.1 Characteristics and generation of recycled water

Various domestic and commercial activities at the source of wastewater generation contribute towards the elevated levels of salt in the wastewater. In other words, composition of recycled water depends on the original composition of the municipal water supply and nature of residential and commercial communities contributing to the wastewater, and varies community to community. According to DEC (2004), recycled water for irrigation is classified as low, medium and high strength according to the concentrations of nitrogen, phosphorus, BOD_5, TDS and other potential contaminants (Table 2.1).

Table 2.1 Classification of recycled water for irrigation according to its strength (DEC 2004)

Parameters	Strength of recycled water		
	Low	Medium	High
Electrical conductivity (dS/m)	<0.9*	0.9-1.6*	1.6-3.9*
Total Nitrogen (mg/L)	<50	50-100	>100
Total Phosphorus (mg/L)	<10	10-20	>20
BOD_5 (mg/L)	<40	40-1500	>1500
Metals, pesticides (mg/L)	Five times the value mentioned in ANZECC and ARMCANZ (2000) is considered as high strength		
Grease and oil (mg/L)	>1500 mg/L is considered as high strength		

*Converted from TDS value as 1dS/m=640 mg/L

It is expected that for a certain class of recycled water strength, all the mentioned constituents in Table 2.1 typically fall within the given range for low, medium and high strengths. However, the strength of recycled water to be used in urban irrigation should also agree with the plant type, tolerance limit of the plants to contaminants, site characteristics, and management of the site such as water balance for the site, relevant environmental objectives for any receiving water, existing ambient water quality and the conditions under which a discharge is likely to occur.

In Australia, mostly, recycled water is tertiary treated before supplied for urban irrigation. Table 2.2 compares the characteristics of recycled water supplied by Sydney Water with the Australian and International standards. As shown in the table, recycled water characteristics are well within the range suggested in the Australian and International standards. Data presented in the table reveals the wide range of contaminants present in recycled water. This is because of the variability in community and water usage pattern based on geographical position, as discussed earlier. However, some contaminants (such as, EC and TDS) shown in the table are significantly higher than drinking water standard in Australia. According to NRMMC-EPHC-AMC (2006), the values of EC, TDS, Na^+ and Cl^- found in town water (drinking water) are 0.1 dS/m, <500 mg/L, 180 mg/L and 250 mg/L, respectively.

Sydney Water operates 17 recycled water schemes. These include:

- The residential dual reticulation scheme at Rouse Hill
- The Wollongong Recycled Water Scheme that supplies recycled water for industrial and irrigation use
- Other schemes that supply recycled water for use in paddocks and sport fields and golf courses

The amount of recycled water used in greater Sydney varies, depending on the weather and other factors. The application rates as well as number of years of irrigation of some of the open fields in Sydney are listed in Table 2.3.

Table 2.2 Key characteristics of recycled water for irrigation

Parameter	Unit	Recycled water Characteristics (International)[a]	Recycled water Characteristics (Australian)[b]	Recycled water standard for irrigation (Australian)[c]
Total Salinity, EC	dS/m	0.51-2.7	0.803	0.65-1.3*
Total dissolved solids (TDS)	mg/l	358-1800	495	600-1000**
Sodium adsorption ratio (SAR)		1.9-11	5.4	10-18**
BOD5	mg/l	6-13.2	<2	40-1500**
Aluminum	mg/l	0.0-0.17	0.033	5
Arsenic	mg/l	0.00062-0.005	<0.001	0.1
Boron	mg/l	0.0005-0.00118	0.048	0.5
Cadmium	mg/l	0-0.22	0	0.01
Cobalt	mg/l	0.001-4.8	0.001	0.05
Copper	mg/l	0.00273-5.76	0.001	0.2
Iron	mg/l	0.103-25.7	0.026	0.2
Lead	mg/l	0-0.2	<0.001	2
Manganese	mg/l	0.003-7.35	0.039	0.2
Molybdenum	mg/l	0.004-0.004	<0.001	0.01
Nickel	mg/l	0.003-3.05	0.003	0.2
Selenium	mg/l	0.053-0.053	<0.005	0.02
Zinc	mg/l	0.035-2.2	0.033	2
Sodium	mg/l	84.9-350	96	230-460**
Chloride	mg/l	43.9-564.4	113	350-700**
Total N	mg/l	8.6-11.71	5.8	5-50
Total P	mg/l	0.6-11.1	0.021	0.5-10***

[a]Adrover et al. (2012); Dikinya and Areola (2010)
[b] Treated by Sydney water (2011-2012); data collected by personal communication
[c]DEC (2004)
* water salinity rating:Low
**For moderately tolerant plant, e.g. lucerne
*** Total P loads in wastewater from intensive animal industries are likely to vary between 10 and 500 mg/L

Table 2.3 Application rate of recycled water for urban open field irrigation (Sydney Water 2010)

Name of the site/field	Number of years of irrigation	Application Rate (ML/ha/year)
Hawkesbury Campus, Western Sydney University	51	1.12
Richmond Golf Club	51	3.52
Ashlar Golf Club	37	4.50
Warwick farm racecourse	31	0.60
Castle Hill Golf Club	28	2.07
Nepean Rugby Park	17	2.50
Kiama Golf Club	13	5.11
Dunheved Golf Club	11	1.05
Liverpool Golf Club	7	2.53

2.3 Effect of recycled water irrigation on soil

One of the major concerns related to recycled water irrigation is the increase of salinity including sodicity and bicarbonate hazards in irrigated fields (Marcum 2006; Toze 2006). Salinity is the concentration of soluble salts in water that are measured as total dissolved solid (TDS) or electrical conductivity. Electrical conductivity is an indirect measurement of TDS in the irrigation water or soil extract. Electrical conductivity of soil extracts can be based on a 1:5 soil: water extract ($EC_{1:5}$) or saturation paste extract (EC_e). EC_e is commonly used as an indicator of plant tolerances. However, because $EC_{1:5}$ are much easier to obtain, conversion factors are often used to convert $EC_{1:5}$ to EC_e. Soils are considered to be saline when the $EC_e > 4$ dS/m measured at 25 ^{0}C (Richards 1954).

Irrigation salinity problems are often compounded by the effects of sodium (Na^+) on the dispersion of soil colloids, resulting in a loss of soil structure. This phenomenon decreases the leaching potential of the salt and accelerates the build-up of salts within the root zone. Na^+ also affects the saturated hydraulic conductivity. Soil colloid dispersion is affected by the ratio of Na^+ to the divalent cations calcium

(Ca^{2+}) and magnesium (Mg^{2+}) in the irrigation water, a ratio known as the sodium adsorption ratio (SAR), which is given by:

$$SAR = \frac{(Na^{+})}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}} \quad (2.1)$$

Where, Na^{+}, Ca^{2+} and Mg^{2+} are the cation concentrations in mmol (c)/L. It should be noted that millimol of charge per litre is an SI unit corresponding to milliequivalent per litre (meq/L).

From an environmental point of view, among different salts in recycled water such as sodium (Na^{+}), potassium (K^{+}), calcium (Ca^{2-}), chloride (Cl^{-}), magnesium (Mg^{2+}), sulphate (SO_4^{2-}) and bicarbonate (HCO_3^{-}), sodium and chloride are the most important salts. This is because they are more likely to remain as ions in soil solution and contribute to the effects of salinity. Plants are affected by salts via soil salinity irrigated by saline irrigation water (NRMMC-EPHC-AMC 2006; Escalona et al. 2014; Dag et al. 2014). As water evaporates from soils or is used by the plants, salts are left behind. This phenomenon along with evaporation increases the concentration of salts in the soil with time, until it influences the amount of water a plant can take up from the soil due to the osmotic effect it creates.

Accumulation of salt due to recycled water use has been investigated by many researchers. According to Al-Nakshabandi et al. (1997) salts accumulate on the soil surface and along the soil profile. Salt accumulates more when irrigation water salinity is higher and, particularly when evaporative demand is high (Marcum 2006). Aiken (2006) investigated the long term effect of recycled water use on soil properties for urban open field irrigation. Soil samples were collected from different paddocks (agricultural field) of Hawkesbury campus of Western Sydney University and from different locations of Richmond Golf Course situated in New South Wales, Australia. Soils were sampled as cores from the 30-40 cm and 60-70 cm depths, on two occasions. A replicated factorial experimental design was carried out for the testing sites having 0, 2, 35 and 40 years of irrigation history. Aiken (2006) concluded that soil salinity increased with years of effluent irrigation, but at a soil depth of 30-40 cm. In contrast, salts accumulated at 60-70 cm in the profile were not detectable. According to Rebhun (2004), some parts of salt from saline water remain at least temporarily in the upper soil with negative impact on crop production. Most of the saline soil solution penetrates to the subsurface (root zone) and eventually reach the groundwater; also, salinisation is felt on a time scale of tens of years. Miyamoto et al. (2005) and Miyamoto and Chacon (2006) examined spatial dependence of soil salinity in relation to soil profile characteristics and salinity variability over the length of selected fairways at five golf courses and at two public parks in west Texas and southern New Mexico. The results indicated that high level of salt accumulation in soils with a thick thatch layer restricted the drainage. Salt accumulation of up to 10 dS/m was observed in compacted clayey soil in the parks. Also, high soil salinity was observed near the tee box which might be because of soil compaction associated with foot traffic and at steep slopes which can cause high runoff. Some investigators (Estevez et al. 2010) reported less or no effect of soil salinisation due to recycled water application in urban open field except soil alkalisation (Chen et al. 2015). However, to be in a safe side, an intensive management and long term monitoring was recommended by some researchers to avoid mass loading of salt and nutrients in soil (Tanji 1997; Zhang et al. 2006).

2.3.1 Impact of soil type on soil salinisation

Soil type impacts the salt accumulation in soil although the effect is not direct (Bui 2013); water flow and evaporation is affected by different types of soil texture, which consequently affect salt accumulation. However, long term modelling shows coarse textured soil resulted in lower electrical conductivity (in terms of soil water EC) than the finer, as reported by Isidoro and Grattan (2011). According to Setia et al. (2011), soil texture is considered important in investigating impact of salinity on plant growth in terms of osmotic potential. Osmotic potential is calculated from the amount of salt present in the soil solution and depends on the water content of the soil; at a given EC of the soil solution, osmotic potential of the soil decreases with decreasing water content. In a fine textured soil, water retention capacity is higher than the coarse textured soil, thus, the osmotic potential of the soil solution is higher. According to Sumner et al. (1998), EC in the soil solution increases with the increased clay content in the soil texture (i.e. fine textured soil), which negatively affects the plant growth. Soil texture affects different transport parameters related to the salt transport mechanism including solute flux, hydrodynamic dispersion, tortuosity and longitudinal dispersivity (Bejat et al. 2000; Vanderborght et al. 2001; Buchter et al. 1995; Vanderborght and Vereecken 2007; Persson and Berndtsson

1998). Vanderborght et al. (1997) observed that in sandy soil solute transport is very heterogeneous, in silty loam soil the process is homogeneous for low flux but heterogeneous for high flux, and in sandy loam soil the process is relatively more homogeneous. Heterogeneity of solute transport can be defined as the horizontal variations of solute concentrations (in a plane transverse to the solute transport direction), which occurs due to the lack of solute mixing (in the soil water) at the time of solute transport. During homogeneous solute transport, solutes are mixed completely, which results no or less horizontal variation of solute concentration (Vanderborght et al. 1997). Dispersivity (which is the ratio of hydrodynamic dispersion and Darcy velocity) was found to be considerably higher in loam soil compared to sandy loam soil by Vanderborght et al. (2000).

2.3.2 Real-time monitoring system

Measurements of water content and salinity in soil by conventional methods require removing soil samples from a soil mass or soil profile. This is disadvantageous in some instances, such as bench scale column study conducted in laboratory, because of the small dimension of columns. An alternate to this is measuring water content and salinity in soil profile using non-destructive methods such as using sensors. This is also called *real-time monitoring system*. In an agricultural system, the real-time monitoring system helps to provide temporal information to determine “when” to irrigate the field on the basis of real-time measurements of soil conditions in terms of water content and salinity (Corwin and Lesch 2005).

In the last three decades, different sensors have been developed for the measurement of moisture and salinity in the soil, which are undergoing continuous improvement for achieving higher precision. In-situ measurement by sensors are based on mainly three techniques including (i) electrical resistivity (ER) method (ii) electromagnetic (EM) method and (iii) time domain reflectometry (TDR) method (Corwin and Lesch 2005). Electrical resistivity and electromagnetic techniques are appropriate for field scale applications because of its suitability for collecting data on spatial variability of average root zone soil electrical conductivity when it is mobile (i.e. mounted on a tractor) (Corwin and Lesch 2005). However, for more precision on the measurement of soil moisture and soil salinity, time domain reflectometry method is widely used both in the laboratory as well as in the field scale (Noborio

2001; Vogeler et al. 1996; Nadler 1997; Muñoz-Carpena et al. 2005). In a TDR technique, simultaneous measurement of water content and bulk electrical conductivity of soil is possible with a single probe and the measurement technique is relatively easy with nominal maintenance (Dalton et al. 1984; Herkelrath et al. 1991).

Sensors using the TDR technique are commonly known as dielectric sensors (Decagon 2011). The dielectric sensors quantify bulk electrical conductivity (EC_{bulk}), dielectric permittivity (ε) and temperature. The dielectric permittivity is usually normalised by the dielectric permittivity of vacuum (ε_0) [$8.85 \times 10^{-12} C^2/(Nm^2)$] and can be expressed as:

$$\varepsilon = \kappa \times \varepsilon_0 \qquad (2.2)$$

Where, κ is the dielectric constant. Some dielectric sensor, such as GS3 (Decagon Device, USA), reports the dielectric permittivity (ε) directly.

The dielectric permittivity is used to quantify volumetric water content (θ) by a calibration equation (Topp et al. 1980; Vogeler et al. 1996; Muñoz-Carpena et al. 2005). Topp et al. (1980) proposed a calibration equation to quantify θ from ε, which is:

$$\theta = A + B\varepsilon + C\varepsilon^2 + D\varepsilon^3 \qquad (2.3)$$

Where, $A = -5.3 \times 10^{-2}$, $B = +2.92 \times 10^{-2}$, $C = -5.5 \times 10^{-4}$, $D = +4.3 \times 10^{-6}$

Equation 2.3 is widely used for different textures of mineral soils; however, the effects of soil structure on Equation 2.3 have not been examined (Noborio et al. 1994). While some researchers used Equation 2.3 as its original form, some researchers proposed modifications suitable for the soil type specific to their study area, which is shown in Table 2.4. According to Dasberg and Hopmans (1992), Topp's calibration study (Equation 2.3) fit well for Sand compared to other textured soils including sandy loam (clay 13.2%, silt 8.0% and sand 78.8%), loam (clay 23.8%, silt 35.6% and sand 40.6%), clay loam (clay 31.0%, silt 49.0% and sand 20.0%) and clay (clay 55.0%, silt 20.5% and sand 24.5%) soil; the authors observed distinct instrument sensitivity to soil texture and recommended for site specific calibration. Jacobsen and Schjønning (1993) also observed deviations in the calibration equation proposed by Topp et al. (1980) (Equation 2.3); the authors proposed to improve the equation by adding the dry bulk density in the equation, which they found well suited for different soil types ranging from coarse sandy soil to a sandy clay loam soil. Similar modification of Equation 2.3 is also reported by other researchers (Jacobsen and Schjønning 1993; Dasberg and Hopmans 1992).

The bulk electrical conductivity measured by dielectric sensors may be affected by different factors including soil salinity, clay content and mineralogy of soil, water content, bulk density and temperature (Corwin and Lesch 2005). The magnitude and heterogeneity of these factors vary from one field to another, which make the sensor based irrigation system highly site-specific. Different studies on sensor based irrigation system have been conducted that identified the complexity of sensor based measurement of salinity and emphasised for site-specific calibration of the system (Noborio 2001; Mittelbach et al. 2012; Skaggs et al. 2012; Corwin and Lesch 2005; Kargas et al. 2013); the studies also highlighted using pore water electrical conductivity instead of bulk electrical conductivity as a representation of soil salinity.

Sensor measured apparent or bulk electrical conductivity (EC_{bulk}, the combined conductivity of the water, soil and air) can be converted to pore or soil water electrical conductivity (EC_{SW}, conductivity of the water to what the plant root is exposed to) using different model. Muñoz-Carpena et al. (2005) categorised the models into (i) linear (ii) non-linear and (iii) empirical. The linear model was proposed by Rhoades et al. (1976) as:

$$EC_{bulk} = EC_{SW} \times \theta \times T + EC_s \qquad (2.4)$$

Where, T is a soil-specific transmission coefficient to take into account the tortuosity of the flow path as water content changes ($= a \times \theta + b$, where a and b are constants), EC_s is the electrical conductivity of dry soil. Constants a and b can be determined by plotting $(EC_{bulk} - EC_s)/(EC_{SW} \times \theta)$ vs. θ (Rhoades et al. 1976). The non-linear model for estimating EC_{SW} was introduced by Rhoades et al. (1989) as a modification of Equation 2.4. According to Rhoades et al. (1989), at low value of EC_{SW} (< 4 dS/m) and at constant volumetric water content, the relation between EC_{bulk} and EC_{SW} was found to be curvilinear. Therefore, instead of assuming EC_s as constant in Equation 2.4, βEC_s was used, where the factor β includes the effect of solute distribution in the soil's mobile fraction of water. The non-linear equation proposed by Rhoades et al. (1989) is given by:

$$EC_{bulk} = [\theta - (a\theta + b)]EC_{SW} + \frac{(\theta_s + a\theta + b)^2}{\theta_s} \times EC_s \qquad (2.5)$$

Where, θ_s represents the volumetric solid content in the soil, and can be calculated as the ratio between soil's bulk density (ρ_b) and specific density (ρ_s). Although Equation 2.5 provides more accurate estimation, Equation 2.4 is used by different researchers due to its simplicity in application (Table 2.4). In addition to linear and non-linear relationships between EC_{SW} and EC_{bulk}, empirical relationships for site specific soils are proposed by some researchers, which are also shown in Table 2.4.

Besides bench scale calibration study, sensor based continuous column studies in the laboratory were reported by some researchers to observe salt accumulation in different soil texture and for different irrigation water salinity (Phogat et al. 2010; Inoue et al. 2000; Skaggs et al. 2012; Suarez et al. 2006; Devitt 1989). One of the reasons of conducting continuous column study instead of field study is the difficulty and uncertainty associated with monitoring and controlling of basic experimental parameters, and associated cost and manpower to conduct the study (Skaggs et al. 2002). Continuous column study provides greater control at low cost (Skaggs et al. 2012); however there are uncertainties associated to reproduce the bench scale study result to apply in the field condition. An appropriate approach to handle this scale-up of results may be adopting a methodology that is capable of replicating the salt accumulation process in the field in a probabilistic manner.

Table 2.4 Relationships used to obtain EC_{SW} from sensor measured EC_{bulk} in different studies

EC_{SW} – EC_{bulk} Model		Constants in θ - ϵ relationship (Equation 2.3)	Soil type	Sensor used	Reference
Linear	*a* = 1.2867 *b* = 0.1158 (Parameters of Equation 2.4)		Very fine sandy loam (sand 42.2%, silt 51.6%, clay 6.2%)	Four electrode resistivity device	Rhoades (1976)
	a = 2.635 *b* = 0.03184 (Parameters of Equation 2.4)	$A = -1.418 \times 10^{-2}$ $B = +1.258 \times 10^{-2}$ $C = -9.409 \times 10^{-5}$	Loamy sand (sand 84%, silt 7%, clay 9%)	TDR-three wire probe	Noborio et al. (1994)
	a = 1.876 *b* = -0.512 (Parameters of Equation 2.4)	$A = -11.2 \times 10^{-2}$ $B = +5.0 \times 10^{-2}$ $C = -16.0 \times 10^{-4}$ $D = +2.0 \times 10^{-5}$	Volcanic soil, Clay loam (Clay 13.0±6.2%)	TDR probe	Muñoz-Carpena et al. (2005)
Non-linear	*a* = -0.323 *b* = 0.435 (Parameters of Equation 2.5)				
Empirical	$EC_{SW}(Sm^{-1}) = \frac{EC_{bulk} - (0.547\theta - 0.153)}{(1.023\theta - 0.293)}$				
	$EC_{SW}(Sm^{-1}) = \frac{EC_{bulk} - (0.228\theta - 0.042)}{(0.804\theta - 0.217)}$	$A = +1.19 \times 10^{-1}$ $B = +1.7 \times 10^{-2}$ $C = -1.0 \times 10^{-4}$	Ramiha silt loam	TDR-three rod probe	Vogeler et al. (1996)

2.3.2.1 Variability in sensor types and column dimension

A number of low cost sensors were investigated instead of high cost TDR sensors by some researchers. According to Muñoz-Carpena et al. (2004), cost of sensors using TDR technique may vary between US$400 and 23,000. Mittelbach et al. (2012) investigated three low cost sensors, namely 10HS (Decagon Devices, United States), CS616 (Campbell Scientific, United States) and SISOMOP (SMG University of Karlsruhe, Germany), and compared their measurement accuracy in terms of soil moisture and salinity against the TDR sensor TRIME-IT/-EZ (IMKO GmbH, Germany); the authors concluded that the low cost sensors may be an alternative to high cost TDR sensors for certain environmental application, provided a site-specific calibration is established. Parsons and Bandaranayake (2009) tested TE-5 and EC-5 (Decagon Devices, United States) in a sandy soil; both the probes responded well to changes in soil water content in the field, however, the EC-5 probe output increased noticeably when bulk density was increased from 1.1 to 1.6 kg/m^3. The authors suggested that the response to the variations of bulk density may affect the estimation of field water content if appropriate correction factor is not utilised. Valdés et al. (2015) used GS3 sensor (Decagon 2011) to study the salt accumulation for a potted horticulture crop irrigated with recycled water. The pot was filled with a growing medium containing black peat (40%), coconut fibre (40%) and perlite (20%). The sensor was able to control irrigation scheduling based on soil electrical conductivity and moisture content. However, the manufacturer specified calibration formula to estimate pore water electrical conductivity from sensor measured bulk electrical conductivity provided poor result when compared with 1:2 soil water electrical conductivity.

Dimension of columns in a column study vary depending on its purpose of the experiment, precision of results needed and availability of funds. The bigger the dimension of the column the more it represents the field condition (Figure 2.1); however, for smaller dimension of columns, replication of the experiment is easier and cost effective. While the diameter of columns in different studies varied widely, some researchers (Alvarez-Benedi et al. 2005; Skaggs et al. 2012) have argued that availing a column of the dimension of a monolith for column experiment in the laboratory sufficiently represent field condition. Table 2.5 represents dimension of soil columns used by some researchers for conducting column study.

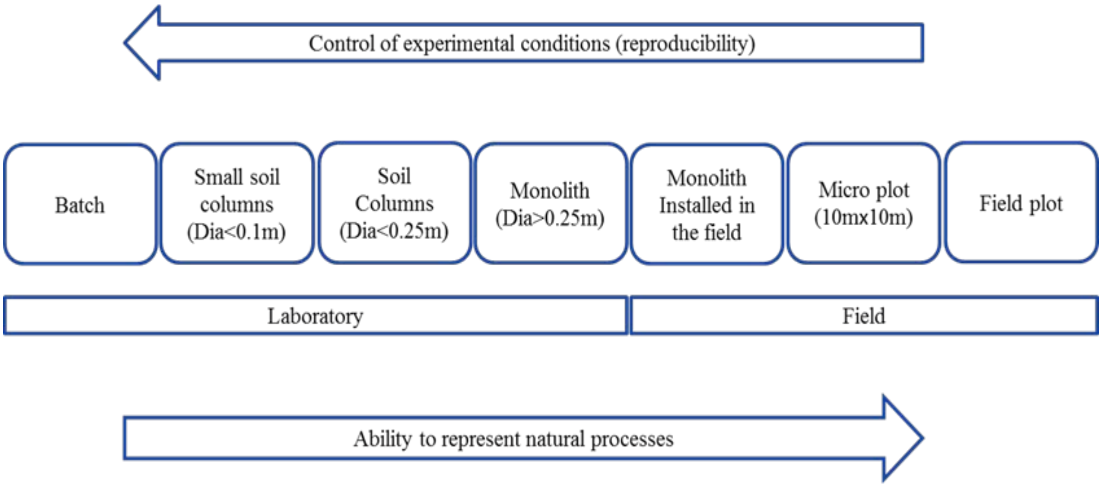


Figure 2.1 Basic scales of columns for soil-solute studies (Álvarez-Benedí et al. 2010)

Table 2.5 Dimension of soil column used in column studies

Purpose of the column study	Diameter (cm)	Height (cm)	Reference
Infiltration study	10.1 (outer) 8.8 (inner)	134	Freeze and Banner (1970)
Infiltration study	20.3	80	Stormont and Anderson (1999)
Infiltration study	10.8 (inner)	102.2	Choo and Yanful (2000)
Infiltration study	19 (inner)	100	Yang et al. (2004)
Soil salinity-Leaching fraction experiment	51	165	Devitt (1989)
Transport of sorbing contaminant	1	10	Grolimund et al. (1996)
Hydraulic conductivity with saline-sodic water	9 (Inner)	30	Ezlit (2009)
Infiltration, redistribution, evaporation and percolation study	19 (Inner)	100	Pfletschinger et al. (2012)
Rain-irrigation management study	19.4 (top) 25 cm (bottom)	29	Suarez et al. (2006)

2.4 Salt transport modelling in vadose zone

Salt transport modelling is one of the means to quantify salinity risk in vadose zone (the unsaturated earth located between the ground surface and water table). A number of investigations have been carried out to model the solute transport in vadose zone. Some of the models are commercially developed and widely used, namely MODFLOW (Modular Finite-Difference Ground-Water Flow Model), RT3D (Multi-Species Reactive Flow and Transport Simulation Software), SWAT (Soil and Water Assessment Tool) and HYDRUS (Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media) (Bear 1979). All these models are built upon the fundamental flow equation given by Richards' equation. A summary of different solute transport model is presented in Table 2.6.

Ragab (2002) reported a salt transport model in vadose zone called SALTMED. The model was designed to accommodate variety of irrigation systems, soil types, soil stratifications, crops and trees, leaching requirement and water quality. The model demonstrated the effect of the irrigation system, soil type and the salinity level of irrigation water on soil moisture and salinity distribution, leaching requirement and crop yield. The basic equations used in this model include evapotranspiration, plant water uptake, water and solute transport, drainage and the relationship between crop yield and water use. Richards' equation was used as moisture flow model and basic convection-dispersion solute transport model was used to demonstrate salt accumulation. One of the salient features of this model is to calculate leaching requirement at the time of irrigation scheduling. The model calculates additional depth of water needed to reduce excess salt concentration which might affect crop yield. The leaching requirement is calculated as a ratio of the salt concentration of the irrigation water to that of the drainage water. The data required to run this model includes plant characteristics (crop coefficient, root depth and lateral expansion, crop height, and maximum crop yield), soil characteristics (depth of soil horizon, moisture content, longitudinal and transverse dispersion coefficient, initial soil moisture and salinity profiles), meteorological data (minimum and maximum temperature, humidity, wind speed, rainfall), water management data and model parameters (number of discretisation, maximum time step). The code of this model is written in C/C^{++} for windows 95/98. The model has been calibrated with the data collected in Egypt and Syria over a period of 2 years for cultivation of a salt tolerant variety of tomato (Ragab et al. 2005) and in Brazil for the cultivation of carrot (Montenegro et al. 2010).

Another salt transport model used in agriculture is SaltMod. According to Bahceci and Nacar (2007), SaltMod is capable of simulating salinity of soil, and ground and drainage waters, the depth of the groundwater, and the quantity of drainage in irrigated agricultural lands using different hydrological and geo-hydrological conditions, varying water management options, and several crop rotation schedules. SaltMod assumes four reservoirs: surface reservoir, root zone, transition zone and aquifer. The model uses water balance components (i.e. rainfall, evaporation, irrigation, reuse of drainage water and runoff, upward seepage, natural drainage and pumping from well) as input data. As output, the model shows the variation of downward percolation, capillary rise and gravity drainage. The model is based on seasonal water balances of agricultural land and is designed to make long term simulation (Oosterbaan 2001). Bahceci and Nacar (2007) used this model to establish the effect of irrigation practices on root zone salinity. After three years of irrigation, the experimental values of root zone salinity conformed to the result predicted by SaltMod. This model was also used by Singh et al. (2002) in Andhra Pradesh of India and was capable of evaluating various drainage spacing of a subsurface drainage system and facilitated reasonable prediction of the reclamation period.

Kroes et al. (2000) reported a computer model for the simulation of vertical transport of water, solutes and thermal energy in unsaturated-saturated soils, named SWAP 2.0 (soil-water-atmosphere-plant). The model is used for an integrated modelling of soil, water, atmosphere and plant system in agriculture. More specifically, it coordinates among solute and heat transport, soil heterogeneity, detailed crop growth, regional drainage at various levels and surface water management and has been used by different researchers for the purpose of on-farm water management, irrigation management and leaching of pesticides (Kroes et al. 2000). SWAP applies Richards' equation in the saturated and unsaturated zone with the possible presence of transient and perched groundwater levels. A finite difference scheme is applied to solve the Richards' equation. For solute transport, it simulates convection, diffusion and dispersion, non-linear adsorption, first-order decomposition and root uptake of solutes, which is the basis to model the effect of salinity on crop growth. Kroes et al. (2000) applied the model to analyse the effects of water management alternatives on the water flow and salt transport in the soils along the sea shore in Netherlands. The model was calibrated by using groundwater level and soil salinity measurements during the period of 1971-1996. The calibrated model was used to simulate water flow and chloride transport for future scenarios for period of 10 years. Jiang et al. (2011) applied SWAP model to predict long term (up to 4 years) irrigation with saline water in an arid region of China and found the model output conforms the measured data in the field.

According to Xu and Shao (2002), one of the major factors in modelling salinisation in vadose zone depends on soil moisture and moisture fluxes which are influenced by hydrological parameter i.e. rainfall, evapotranspiration and runoff. So, inclusion of interaction among atmosphere, land surface and ground water in the model is essential. They coupled Richards' equation along with another model ALSIS (Atmosphere and land surface interaction scheme) to simulate the soil moisture and moisture fluxes in the vadose zone. Source and sink terms were included in the model to describe source of salt solution and soil solution taken up by the plants. Infiltration was determined by the availability of water on the land surface as the net contribution from precipitation, evaporation and runoff. In this salt transport model, absorbed salt concentration was described by linear distribution coefficient and a third type boundary condition was used at the soil surface. The numerical solution was achieved by finite difference scheme and the code was written in FORTRAN. The model was applied to rice irrigation field in the Murray-Darling Basin in Australia to investigate the effect of saline ground water table rise on the salt accumulation in root zone. For 1-D (one-dimensional) simulation, the model was applied to sites with three different irrigation practices, i.e. site with no irrigation, site with fresh water irrigation and site with saline water irrigation. Irrigation with saline water in comparison to the fresh water increased the salinity (in terms of solute-salt concentration) in the root zone for a simulation period of 1,500 days. This suggests a long term impact on root zone salt, as removal of salt from root zone by moisture fluxes associated with precipitation is very slow. The numerical results presented in this study were not validated with observed data.

Chen et al. (2010) evaluated salinity profile in saline water irrigated soil of a semi-arid region of China by integrated water, salinity, and nitrogen model named ENVIRO-GRO. The simulated and the observed salinity after 3 years of cotton production matched well. The model simulation illustrated that big flood irrigation after harvest can significantly reduce the salt accumulation in the soil profile. Salt transport modelling in context of agricultural field was also studied by some other researchers (Aslam 1995; Ayers and Westcot 1985; Savvas et al. 2007).

Another model named HYDRUS 1D is used to simulate one-dimensional water flow, heat movement, and the transport of solutes involved in sequential first-order decay reactions (Šimůnek et al. 2009). The HYDRUS 1D program numerically solves the Richards' equation for saturated-unsaturated water flow and advection-dispersion type equations for heat and solute transport. The governing advection-dispersion solute transport equations are written in a very general form by including provisions for nonlinear non-equilibrium reactions between the solid and liquid phases, and linear equilibrium reaction between the liquid and gaseous phases. Hence, both adsorbed and volatile solutes can be considered. The HYDRUS 1D code is used to analyse water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The water flow part of the model considers prescribed head and flux boundaries, as well as boundaries controlled by atmospheric conditions, free drainage, or flow to horizontal drains. First and third-type boundary conditions can be implemented in both the solute and heat transport parts of the model. HYDRUS 1D is one of the most widely used codes (Scanlon 2004) for unsaturated flow and solute transport modelling. This model is used by different studies simulating different scenarios of salt transport (Kanzari et al. 2012; Ramos et al. 2011; Sutanto et al. 2012; Sarmah et al. 2005; Li et al. 2015; Tan et al. 2015; Ogden et al. 2015) with a satisfactory outcome.

Table 2.6 Summary of solute transport models

Name of the model	Applied in Country/Purpose	Input variable	Output	Capability
SALTMED (Ragab 2002)	Egypt, Syria/ Agriculture	1. Plant characteristics 2. Soil characteristics 3. Meteorological data 4. Water management data	1. Soil moisture content 2. Salt concentration 3. Leaching requirement 4. Relative and actual crop yield	1. 1D and 2D solute modeling in saturated condition 2. Field water management 3. Crop growth simulation
SALTMOD (Bahceci and Nacar 2007)	Turkey, India/ Agriculture	1. Rainfall 2. Evaporation 3. Irrigation 4. Runoff	1. Root zone salinity 2. Downward percolation 3. Capillary rise 4. Subsurface drainage	1. 1D modeling in saturated condition 2. Water management 3. Drainage
SWAP (Kroes et al. 2000)	China, Iran, the Netherlands/ Agriculture	1. Plant and soil characteristics 2. Meteorological data 3. Soil heat capacity	1. Soil moisture content 2. Salt concentration 3. Pesticide leaching	1. 1D modeling in saturated and unsaturated condition. 2. Heat transport modeling. 3. Crop growth simulation
ALSIS (Xu and Shao 2002)	Australia/ Agriculture	1. Soil characteristics 2. Model parameters 3. Meteorological data	1. Soil moisture content 2. Salt concentration	1. 1D and 3D solute modeling in saturated and unsaturated condition 2. Coupled with ground water flow model (MODFLOW)
Hydrus-1D (Šimůnek et al. 2009)	Australia, China, Tunisia, Turkey, New Zealand, Uzbekistan, the Netherlands/ Diverse field of application	1. Soil characteristics 2. Model parameters 3. Meteorological data	1. Soil moisture content 2. Solute concentration 3. Vapor flow	1. 1D solute and heat modeling in variably saturated media 2. Equilibrium and non-equilibrium phase modeling

2.5 Risk based approach

Risk based approach can be defined as describing the possibilities of occurring an expected and/or unexpected event in a system. A well-organised risk based approach can be helpful for identifying failure of the system in advance, which helps the decision makers to avoid unwanted situation. It also helps to identify different alternatives to solve problems. Most of the time risk based approach is supported by the uncertainty analysis, which provides risk based approach a probabilistic base. Decision makers avail a number of approaches, methodologies and forms to evaluate a risk, which sometimes leads to difficulty for the comparison of risk studies performed by different analysts. Again, a thorough investigation of the uncertainties linked with the result of a risk assessment and the cause of their variability still needs more investigation. Figure 2.2 shows a basic perspective of risk analysis, called analytic-deliberative process. The process is an effective way of synthesising and summarising information about a hazard. The feature of this process is that the judgements are an inherent feature of expert approaches to risk assessment. The scenarios in a risk based approach include application of different methods and theories from scientific background to understand the risk situation, including, 'likelihood' and conditions of a hazard and different options for managing the risks (Amendola 2001).

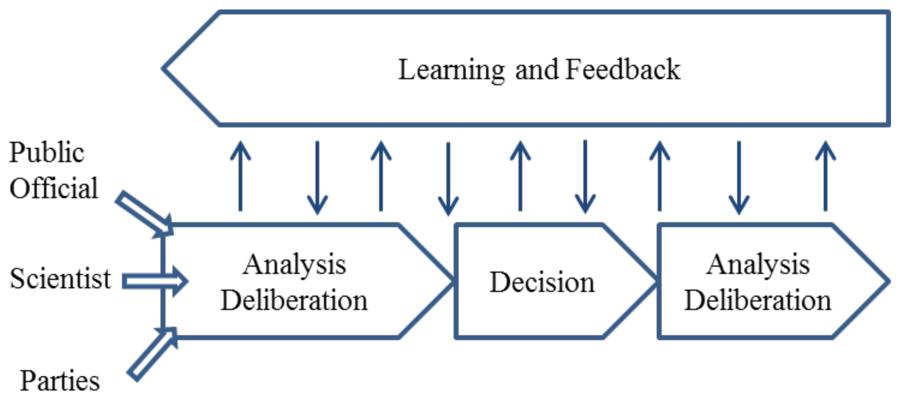


Figure 2.2 Risk Decision Process (Amendola 2001)

The 'likelihood' of a course of action (or lack of a course of action, as the case may be) will result in an event leading towards a potential for harm (hazard).

Risk is measured in terms of the consequences arising from the event and its 'likelihood' (Carroll 2005). In other words, risk is a two dimensional entity involving the possibility of adverse consequences resulting from a hazardous event, and uncertainty. There are three components of risk assessment:

- Hazard identification and characterisation;
- Appraisal of exposure; and
- Risk assessment

Hazard identification means identifying the risks that may impose adverse effect on human or environment, normally the main concern of a risk assessment. Hazard characterisation is a quantitative or qualitative determination of the adverse effect associated with the causal agents or activity. At this stage, the association is sometimes difficult to prove as the causal link has not been established beyond doubt. Appraisal of exposure addresses the evaluation of probability (qualitative or quantitative) of the hazard to the population or environment. Risk assessment is the qualitative/quantitative estimation with the consideration of inherent uncertainties, probability, frequency and the severity of the potential adverse environmental effects, which are liable to occur. It depends on the uncertainties, variations, working hypotheses and conjectures made at each stage of the process. If there is lack of available data to assess risks, a cautious approach is availed to opt for worst-case hypothesis. This worst-case hypothesis gives an exaggeration of the real risk, but provides assurance that the risk is not underestimated (Aven 2008; Carroll 2005).

2.5.1 Bayesian Network

Bayesian network is a widely used tool to predict uncertainty in different field of engineering and business. It is based on Bayes' theorem, which allows one to revise one's belief about certain parameter, given the data that occurred. According to Bayes' law (Bolstad 2004):

$$P(A|B) = P(A)\left[\frac{P(B|A)}{P(B)}\right] \quad (2.6)$$

The above equation can be read as, the probability of A given that B has occurred (the "posterior" probability of A), equals the "prior" probability P(A) multiplied by the ratio of the likelihood of observing B given that A will occur ($P(B|A)$) to the overall or “marginal” probability of B (P(B)) (Hobbs 1997). The basis of this approach is based on the following ideas:

- The parameters are considered as random variables.
- The rules of probability are directly applied to get the inference about parameters.
- Probability statements are interpreted as “degree of belief”. One person can have ones’ own prior, which contains the relative weights that person gives to every possible parameter value. It measures how “plausible” the person considers each parameter value to be, before observing the data.
- After getting the data by Bayes’ theorem, the beliefs about parameters are revised. This gives the “posterior distribution” or the relative weights that is given to each parameter value after analysing the data.

Portraying problem structures by the Bayesian approach includes the discussion of decision flow diagram or decision tree diagram, influence diagrams and belief networks.

2.5.1.1 Decision tree diagram

In the decision tree diagram, analysis of problem is portrayed in chronological order to find the alternative actions that are available to the decision maker as he moves through its various paths. Each set of outcomes from a node, decision alternatives or possible outcomes of uncontrollable events, define a new branch in the tree. Decision tree diagram consists of three major elements (Figure 2.3), i.e. Decision Nodes, chance nodes and outcomes.

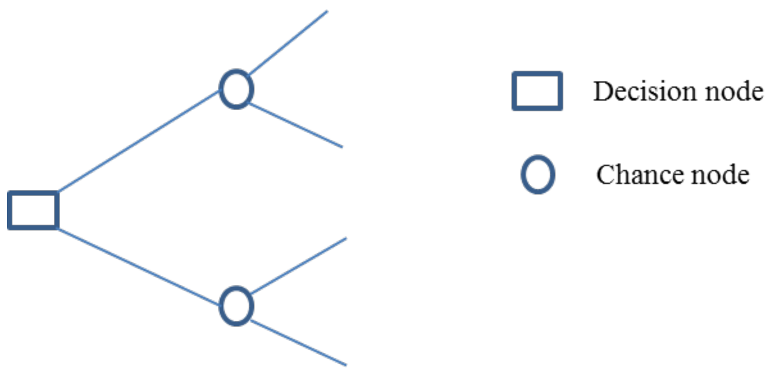


Figure 2.3 Decision tree diagram

“Decision nodes” are represented by squares. In this node the options are to make an irreversible commitment of resources. Examples of such commitment of resources might be decision of carrying out an environmental impact assessment, or implementing new treatment technology to reduce salinity in recycled water. “Chance nodes” are represented by circles. It may consist of different variables. Chance nodes are called uncontrollable events. Probabilities, containing subjective element, are normally associated with each branch on a chance node (Hobbs 1997). “Outcomes” is the final probability of a specific path.

2.5.1.2 Influence diagram

Influence diagram is originally extended from decision tree, which is more compact and computationally more efficient approach to decision analysis. An influence diagram is an acyclic (there is no directed path starting and ending at the same node) Bayesian network of nodes connected with one dimensional links. The nodes represent probabilistic variables (denoted by ovals), deterministic variables (including objective function, rounded rectangles) and decisions (rectangles) (Varis 1997). Figure 2.4 shows a typical example of influence diagram. In the figure, the uncontrollable prior- Environmental impacts (state of nature) is a quantity which is not yet known accurately. The screening node contains a conditional probability distribution, conditioned by the state of nature. The screening results are obtained at the moment of decision on detailed EIA. The satisfaction to the whole process depends on the state of nature and on the decision of EIA.

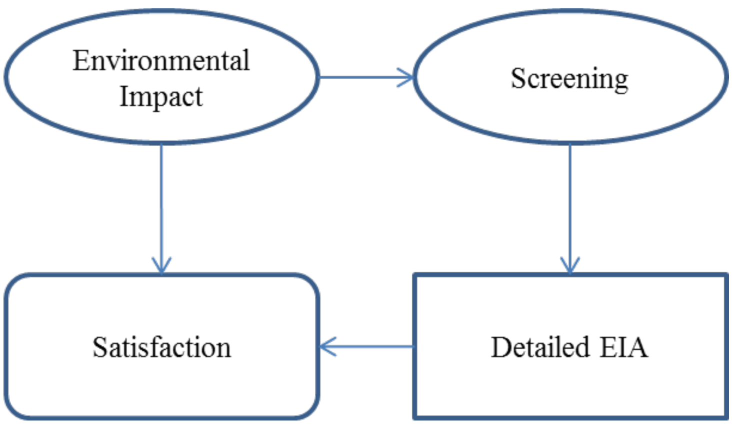


Figure 2.4 A typical influence diagram (Varis 1997)

2.5.1.3 Belief networks

A belief network, also known as causal networks, Bayesian nets, qualitative Markov networks, or constraint networks, is a tool that aids the decision making under uncertainty. Bayesian belief network works effectively in a situation where partial information is known and incoming data is uncertain or partly known. This is a representation of cause and effect of an event via graphical representation by decision tree or influence diagram.

Generally speaking, in a Bayesian network there are three important terms to understand the process. Prior density or probability function, likelihood function and posterior density or probability function. At first, we need to get prior function of an event. This function is based on one's prior knowledge or belief or idea about the probability of the concerned event. Prior density can be selected by three methods, namely, Discrete prior, Beta prior and Histogram prior. Likelihood function is the expression of probability of taking place of the events. For example, say, prior density of an event *p* is denoted by $g(p)$. If we take a random sample with *s* success and *f* failures, then the likelihood function, *L(p)* is given by (Albert 2009):

$$L(p) \propto p^s(1-p)^f, 0 < p < 1 \tag{2.7}$$

Now, the posterior density for *p*, by Bayes' rule, is obtained, up to a proportionality constant, by multiplying the prior density by the likelihood:

$$g(p|data) \propto g(p)L(p) \tag{2.8}$$

In probabilistic terms a BBN represents the joint probability density function of all variables explicitly considered in the problem. A compact joint probability density function is obtained by considering causal relationship among the variables (Bayraktarli 2009). The outcome of the compilation of the BBN is the marginal probability distribution of all variables. The approach to constructing BBN starts with analyzing the concerned problem. The needs of the analysis help to identify different elements of the network. An assessment framework is helpful to perform this step. The next step is to identify the dependencies among the elements. It is advantageous to find the dependencies based on causality. For constructing the BBN, a property called d-separation ("d" for directed graph) is a requirement. It is a property which is used to identify irrelevant information for specific queries in a

BBN or influence diagram. Two nodes of a network are d-separated if they are conditionally independent given a specified set of nodes. For example, if A, B and C are three variables or a set of variables, and if $P(A|B, C) = P(A|C)$ then A nd B are connditionally independent, or d-separated, given C.

The basic steps to construct BBN are described as below:

- Causal interrelationships of events leading to the consequences are formulated, which can be shown by nodes (variables) connected by arrows. Variables with ingoing arrows are referred to as children and variables with outgoing arrows are named as parents.
- Each of the variables are assigned a number of discrete mutually exclusive state
- Children nodes are assigned with conditional probabilities
- Consequences are assigned corresponding to the states represented by the BBN.

Another important aspect in Bayesian network is discretisation. Discretisation, categorisation or the classification of a data set is needed for the approximation of a continuous space of a variable in the network. The continuous space is subdivided into a set of different intervals. In the BBN, generally, a very fine discretisation is preferred but may involve computation inefficiency in terms of time (Bayraktarli 2009). In practice, discretisation steps are decided by taking into account both the desired modelling accuracy and the computational efficacy. Discretisation of a data set can be made according to equidistant split points, equal frequency or supervision (Bayraktarli 2009). In the equidistant split points approach, the length is divided into equal length. The process produces required accuracy when uncertainty of the variable is very large. In a supervised discretisation, the interval number and interval lengths are chosen in a way that the histogram of the data set is represented reasonably.

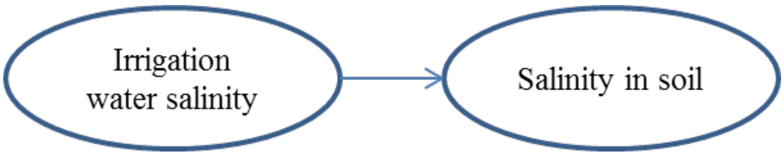


Figure 2.5 A simple BBN network to understand discretisation

In Figure 2.5, a simple BBN network with two nodes “irrigation water salinity” and “salinity in soil” is shown, where irrigation water salinity has influence on salinity in soil. The irrigation water salinity is termed as *parent node* and the other node is called *child node*. For each node a probability table is specified. By definition, parent node contains unconditional probability tables. The irrigation water nodes can be discretised into categorical states, i.e. low salinity, moderate salinity and high salinity or any other number of discrete states. In any case the mutually exclusive states would total to 1. A child variable requires a conditional probability table with the assignment of a probability to each of the mutually exclusive discrete states of the child node given the state of the parent node. In the example shown in Figure 2.5, the salinity in soil node can be discretised into three states like, low risk, moderate risk and high risk. The probabilities of being in each of the risk states need to be assigned for each of the given irrigation water salinity. The similar approach is used when solving network having more parent and child nodes.

There are three main types of connections available for the construction of Bayesian network:

- Serial connection;
- Diverging connection; and
- Converging connection.

In the serial connection of Figure 2.6 (*a*), A has an influence on B, which in turn has an influence on C. Evidence about A will influence certainty of B and C. If the state of B is known then the channel is blocked, and A and C become independent or in other word A and C are d-separated given B. For example, if we observe the rain falling (B), any knowledge that there is a dark cloud (A) is irrelevant to any hypothesis (or belief) about wet lawn (C). On the other hand, if we don't know whether it rains or not, observing a dark cloud will increase our belief about rain, which in turn will increase our belief about wet lawn.

The diverging connection is shown in Figure 2.6 (*b*), where, if the state of A is unknown, then the influence can pass between all the children of A. Here, B and C are d-separated given A. For example, if we observe the rain falling (A) and then that the lawn is wet (B), the added knowledge that the lawn is wet (B) will tell us nothing more about the type of weather report to expect from the radio (C) than the information gained from observing the rain alone. On the other hand, if we don't know whether it rains or not, a rain report in the radio will increase our belief that it is raining, which in turn will increase our belief about wet lawn.

In the converging connection of Figure 2.6 (*c*), the parents B and C are independent if nothing is known about A except the knowledge that may be inferred from the parents. Evidence about one of the parents cannot influence the certainties of the other parent. However, if the consequence is known, then information on one possible cause may reveal something about the other causes. For example, if we know the lawn is wet (A) and that the sprinkler is on (B), then this will affect our belief about whether it has been raining or not (C), as the wet lawn leads us to believe that this was because of the sprinkler rather than the rain. On the other hand, if we have no knowledge about the state of the lawn, then observing that it rains will not affect our belief about whether the sprinkler has been on or not (Jensen and Nielsen 2007; Bayraktarli 2009). Several program packages are available for constructing and evaluating Bayesian belief network among which Hugin Expert™ (Barton et al. 2005; Bromley et al. 2005; Madsen et al. 2005; Johnson and Mengersen 2012), Netica™ (Ghabayen et al. 2004; Aalders 2008; Ticehurst et al. 2011) and WinBUGS™ (Donald et al. 2011; Lunn et al. 2000) are used by several researchers.

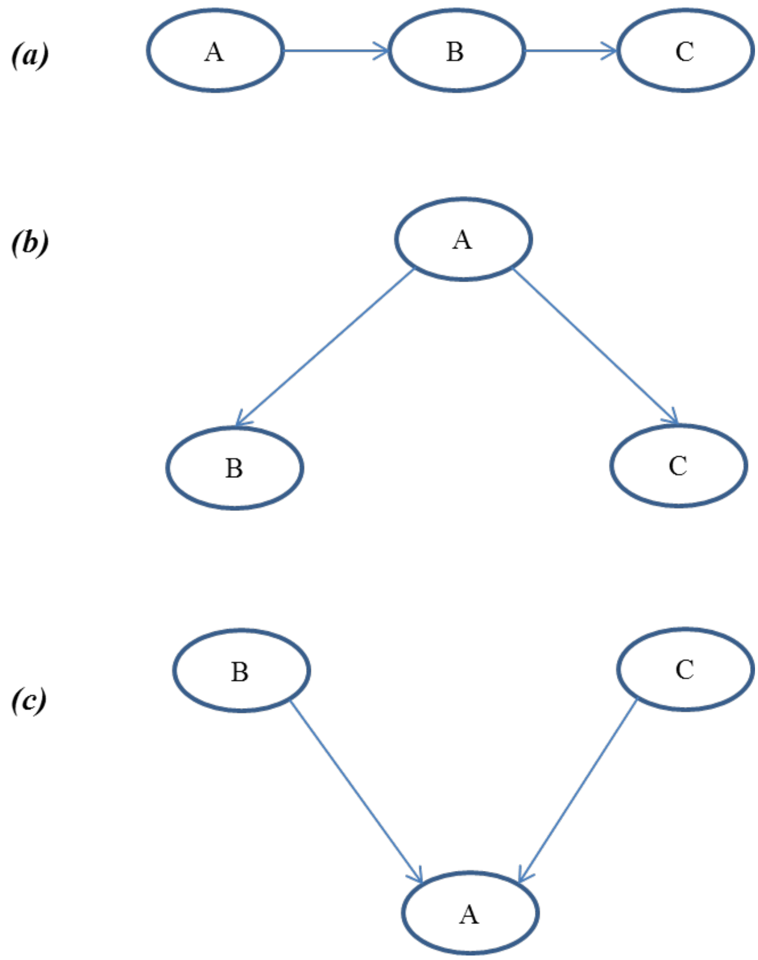


Figure 2.6 Different types of BN connections (*a*) Serial connection, (*b*) Diverging connection, (*c*) Converging connection (Jensen and Nielsen 2007)

2.5.2 Application of Bayesian belief network

Bayesian belief network has been applied for solving different types of environmental problems. Some researchers find this method suitable as this method can address multi criteria problem with diversified data sources. The subjective nature of this method raises some criticism yet its problem solving framework and ease of modelling attracts many researchers to apply this method in their respective field. Hobbs (1997) applied Bayesian belief network for the analysis of climate change by using evidence to make and updating climate change predictions and estimates of model parameters. Three scenarios regarding effect of climate change were summarised. In the first case annual flows of Senegal river of West Africa was examined and the analysis quantified the uncertainty associated with the probability of future drought. In the second case Bayesian Monte Carlo analysis was performed for updating models of sea level rise. A method was developed for using evidence to update probability distributions which were then applied to the problem of projecting sea level rise. In the third case, management of lacustrine wetlands (shallow lake) were investigated under climatic uncertainty. The author developed a “trade off curve’, by which decision makers can decide on when to carry out commercial development in the wetlands after the wetlands get dried out due to climate change.

An unconventional approach like Bayesian belief network needs more time, imagination and ability to see analogies. This was remarked by Varis and Kuikka (1999) after analysing different case studies where influence diagram and belief networks were used to solve environmental problems. To understand the diversified application pattern of belief network, the authors analysed several case studies comprising:

- Restoration of a temperature lake;
- Fisheries management in a tropical reservoir;
- Rehabilitation of fisheries in a temperate river;
- Cod fisheries management;
- Salmon fisheries management; and
- Cost effective water treatment for a river.

The authors highlighted that through the implementation of BBN for each of the mentioned case studies, information from different sources were easily merged into a single framework, and a series of management scenarios were generated, which was helpful for the decision makers.

For the management of groundwater contamination, Bayesian belief network is used by different researchers (Farmani et al. 2009; Marin and Medina 1989). An integrated optimisation tool based on Bayesian belief network was proposed by Farmani et al. (2009) for helping water managers to evaluate cost and benefits of alternative action and to find best decision pathways under uncertainty.

In Australia, Bayesian network has been applied in the risk assessment of salinity, one of the key environmental issues in context of Australia. However, investigations targeted solving mainly land or catchment salinity issues. Grundy et al. (2007) proposed a risk assessment framework for preventing salinity in Fitzroy Basin, Australia with an area of approximately 150,000 km^2. The framework outlined tools to define the timeframe of salinity development, biophysical feature of the landscape with in which salinity develops and the riskiness of current and alternative management systems. More specifically, the framework included four components: (a) Biophysical hazards, (b) Management Influence, (c) Timeframes and (d) Assets (Wearing et al. 2008). The aim of this framework was to improve the understanding of salinity risk in this catchment and subsequently use this knowledge in developing the foundation of salinity program of Fitzroy Basin Association. The same framework was applied in another basin, Condamine catchment, located in southern Queensland (Biggs et al. 2008). Expert knowledge was required for analysing the framework and testing the results. The relevance of expert knowledge was evident in Condamine catchment, where the result was not much different from the expert knowledge available prior to the study. Another study for integrated management of catchment salinity was conducted by Sadoddin et al. (2005). This study was conducted at little river catchment in the upper Macquarie river basin of New South Wales. The catchment covers an area of 2,310 km^2 that is equal to 11.8% of the contributing area to the Dubbo gauging station. A Bayesian decision network approach was applied to consider the influence of management options on environmental, physical, social and economic outcomes. The framework addressed ecological, physical, economic and social aspects of salinity problem and defined the probabilistic relationship among the variables. Other application of Bayesian decision network in Australia includes ecological risk assessment (Fox 2006; Pollino et al. 2007; Chan et al. 2012; Ticehurst et al. 2007) and environmental flows allocation (Shenton et al. 2008).

In the case of recycled water, Bayesian belief network was used mainly for assessing health risks. In addressing the health risk from recycled water, QMRA (Quantitative Microbial Risk Assessment) models are widely used by many researchers (Donald et al. 2009; O'Toole et al. 2009; Hamilton et al. 2007; Hamilton et al. 2006). Hamilton et al. (2006) used QMRA for estimating the annual risk of virus infection associated with the consumption of raw vegetables irrigated with recycled water. Across the various crops, effluent qualities, and viral decay rates considered, the annual risk of infection ranged from 10^{-3} to 10^{-1} when recycled water irrigation ceased 1 day before harvest and from 10^{-9} to 10^{-3} when it ceased 2 weeks before harvest. The model presented a useful starting point for managing risk associated with spray irrigation of certain crops with recycled water. Although QMRA is considered as an essential component of microbial risk assessment of recycled water scheme, the model has some cons; it is tedious and technically demanding. This disadvantage is overcome by including another model RIRA (Recycled water irrigation risk assessment) as part of QMRA assessment process (Hamilton et al. 2007). RIRA is designed to accommodate a wide range of scenarios. The model uses pathogen specific dose-response models to calculate the annual risk of infection, when the pathogen of interest and the exposure scenario is defined. Another study addressing microbial contamination from recycled water was conducted by Donald et al. (2009). The approach provided an additional way of modelling the determinants of recycled water quality and elucidating relative influence of these determinants on a given disease (namely, gastroenteritis) outcomes. The conceptual model was comprised of six elements, i.e. recycled water and distribution pathways, exposure pathways and populations, cumulative end-user dose, identified toxicity and pathogenicity pathways, individual covariates and health endpoints. The Bayesian network was quantified based on expert's opinion. Sensitivity analysis was carried out to find the uncertainties associated to the model predictions. The authors reported that the BBN analyses identified three nodes that contributed most to the occurrence of gastroenteritis. These include, cumulative end user dose to pathogen, age of patients, exposure period to pathogen and quantity of pathogen intake.

2.6 Knowledge gap in the existing literature

Literature review reveals that despite growing concern about the salinity issues related to recycled water irrigation, incorporation of stochastic prediction in the assessment of long-term impact of soil salinisation due to recycled water irrigation has largely been unexplored. Moreover, identification of sources of salinity in the wastewater and their quantification in a probabilistic manner needs more attention. Therefore, a knowledge gap exists in the application of a risk based approach for managing recycled water to tackle soil salinisation in urban open field. Unfortunately, this gap in the literature cannot be filled using a deterministic salt transport model alone (by providing a single predicted value). However, a risk based approach implemented in Bayesian belief network (BBN) can serve the purpose.

The review shows that in the case of recycled water irrigation, most of the studies applied BBN from microbial point of view, which emphasised the human health risk from recycled water. But the application of BBN for managing soil salinity associated with the use of recycled water for urban open field irrigation needs more research. Therefore, in this thesis a methodology is proposed which is capable of identifying sources of salinity in the wastewater along with quantifying the root zone salinity in a probabilistic manner. Additionally, the methodology identifies the level of treatment recycled water needs to keep the soil salinity under a sustainable limit for long-term irrigation with recycled water.

Analyses of soil properties such as texture, existing soil salinity, clay content, and bulk density specific to study area were found to be important factors to implement sensor based irrigation system. An appropriate equation is essential to convert the sensor measured bulk electrical conductivity to soil water electrical conductivity, which is a representative term to denote soil salinisation. A number of equations are proposed in the literature, which is found to be appropriate only for site specific soil. Therefore, it is essential to derive calibration equations specific to study area for a precise measurement of volumetric water content and soil salinity by sensors. Hence, this thesis contributes to the existing literature by examining different soil properties of the study area and by evaluating site specific calibration equations for the implementation of a sensor based irrigation system.

Laboratory based batch column studies were conducted by several researchers to evaluate salt transport parameters using different soil types and irrigation water with varied salinity. In addition, continuous column study was suggested by few studies to understand salt accumulation process in a sensor based irrigation system. Continuous column studies were conducted mostly in a steady state (i.e. flood irrigation) condition; however, column studies in transient condition (i.e. intermittent application of irrigation water) were reported only by some studies to simulate the condition that prevails in the field. From the review of reported column studies, it is not evident the role of soil type on salt accumulation. Few studies highlighted that the salt accumulation increased with the increase of clay content in the soil; however, the salt accumulation pattern for different soil type in a particular sensor based irrigation system needs more research. Hence, continuous column studies in transient condition were conducted in this thesis to examine the impact of soil type, irrigation water type and occurrence of rainfall on the salt accumulation in a sensor based irrigation system.

In regards to salt transport modelling, a number of models have been reported on salt transport modelling under saturated as well as unsaturated conditions as applied to agricultural fields. Among them HYDRUS 1D was found to be widely used by different studies. However, application of HYDRUS 1D to predict long-term salinisation in changed climate condition needs more attention. Hence, this thesis uses HYDRUS 1D to investigate the salt accumulation in vadose zone for recycled water irrigation in field conditions, under drought as well as under future climatic conditions.

The knowledge gaps identified above lead to the objectives of the current research, which are discussed in Chapter 1.

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

This chapter details the methodology used for:

- Soil sampling at field and soil sample preparation for analysis
- Soil analysis methods including: pH, electrical conductivity, mechanical texture classification, field bulk density, saturated hydraulic conductivity, soil water characteristic curve, soluble and exchangeable cations (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+})
- Real-time measurement of water content and salinity in soil
- Continuous column study at laboratory
- Salt transport modelling
- Bayesian belief network modelling

3.2 Study area, soil collection and sample management

3.2.1 Hawkesbury water reuse scheme

The Hawkesbury Water Reuse Scheme is situated within the Hawkesbury Campus of the Western Sydney University in Richmond NSW, approximately 80 km northwest of Sydney (Figure 3.1). The Hawkesbury Water Reuse Scheme has been built upon partnerships between the University and Sydney Water, Richmond TAFE, Hawkesbury City Council, and Clean Up Australia (Booth et al. 2003). The scheme consists of four paddocks namely, Richmond, Blacktown, Londonderry and Claredon paddock (Aiken 2006).

The HWRS receives recycled water from Sydney Water's Richmond STP, which is first collected in a Receiving Pond, and then pumped up into the first University storage, the Effluent Turkey Nest dam (capacity 93 ML) (Booth et al. 2003).

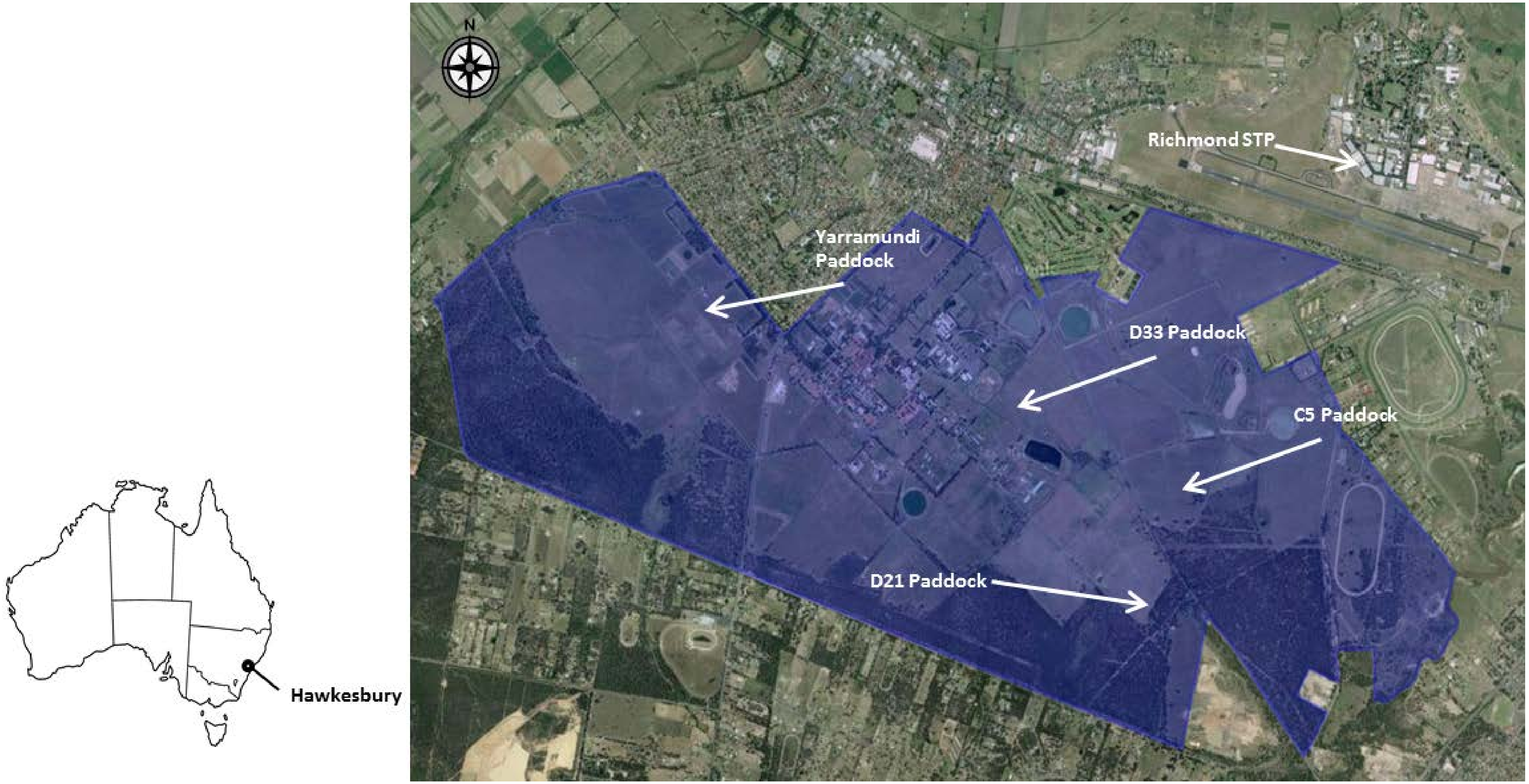


Figure 3.1 Map showing location of study areas within the campus of Western Sydney University, Hawkesbury (the shaded area shows the Western Sydney University campus).

Up to late 2005 the supply from this STP was essentially secondary, involving a trickling filter (TF) process with pond stabilisation. However, in 2005 Sydney water carried out extensive alterations to the STP, replacing the old TF process by intermittently decanted aerated lagoon (IDAL) process with tertiary treatment involving sand filtration and chlorination/dechlorination (Aiken et al. 2010).

Soil samples were collected from following four different paddocks (Figure 3.2):

- D33 paddock (S 33^{0}36.889´ E 150^{0}45.500´)
- D21 paddock (S 33^{0}37.478′ E 150^{0}45.706′)
- C5 paddock (S 33^{0}37.199´ E 150^{0}46.182´) and
- Yarramundi paddock (S 33^{0}36.535´ E 150^{0}44.193´)

Among four paddocks, D33 and D21 are situated under Blacktown paddock and C5 under Claredon paddock. The D33, D21 and C5 paddocks have irrigation history with recycled water since 1967, 1989 and 2000, respectively. However, the irrigation in these paddocks was ceased in 2008. This means that D33, D21 and C5 have irrigation histories of approximately 41, 19 and 8 years, respectively. The Yarramundi paddock was never irrigated with recycled water. Soil samples from these paddocks were collected in the months of July-August of 2012.

D21 Paddock

C5 Paddock

Figure 3.2(a) Photos showing study areas in D21 and C5 paddocks

Yarramundi Paddock

D33 Paddock

Figure 3.2(b) Photos showing study areas in Yarramundi and D33 paddocks

3.2.2 Greygums oval

The Greygums oval (33^0 43.652´S, 150^0 42.406´E) is situated in Cranebrook, New South Wales, Australia (Figure 3.3). The oval is used for athletics during summer season and Australian Rules football during the winter season. This oval is irrigated by sprinkler method using the recycled water from a domestic sewage treatment plant (Penrith Sewage Treatment Plant) since January 2008.

The recycled water used for irrigation is stored in a 25 kL concrete tank. During the study period (January 2008 to June 2011) average TDS of recycled water varied in the range of 480-630 mg/L. Mean hydraulic loading rate and salt loading of applied irrigation water was 160 mm/year and 713 kg/ha/year, respectively. Mean annual rainfall in the study area is 715.9 mm, where wettest months are from October through to March and driest from April to September (BOM 2014).

3.2.3 Soil sampling and management

Soil sample was collected from 0-0.2 m depth by open pit method. The soil sample was transported to lab, and roots and worms were removed. The processing of samples included homogenising the soil by crumbling, thoroughly mixing and by sieving using a 2.36 mm sieve. The soil sample was then air dried at room temperature for three days. The air dried samples were tested for different physical and chemical analysis, and also used in batch study and continuous column study.

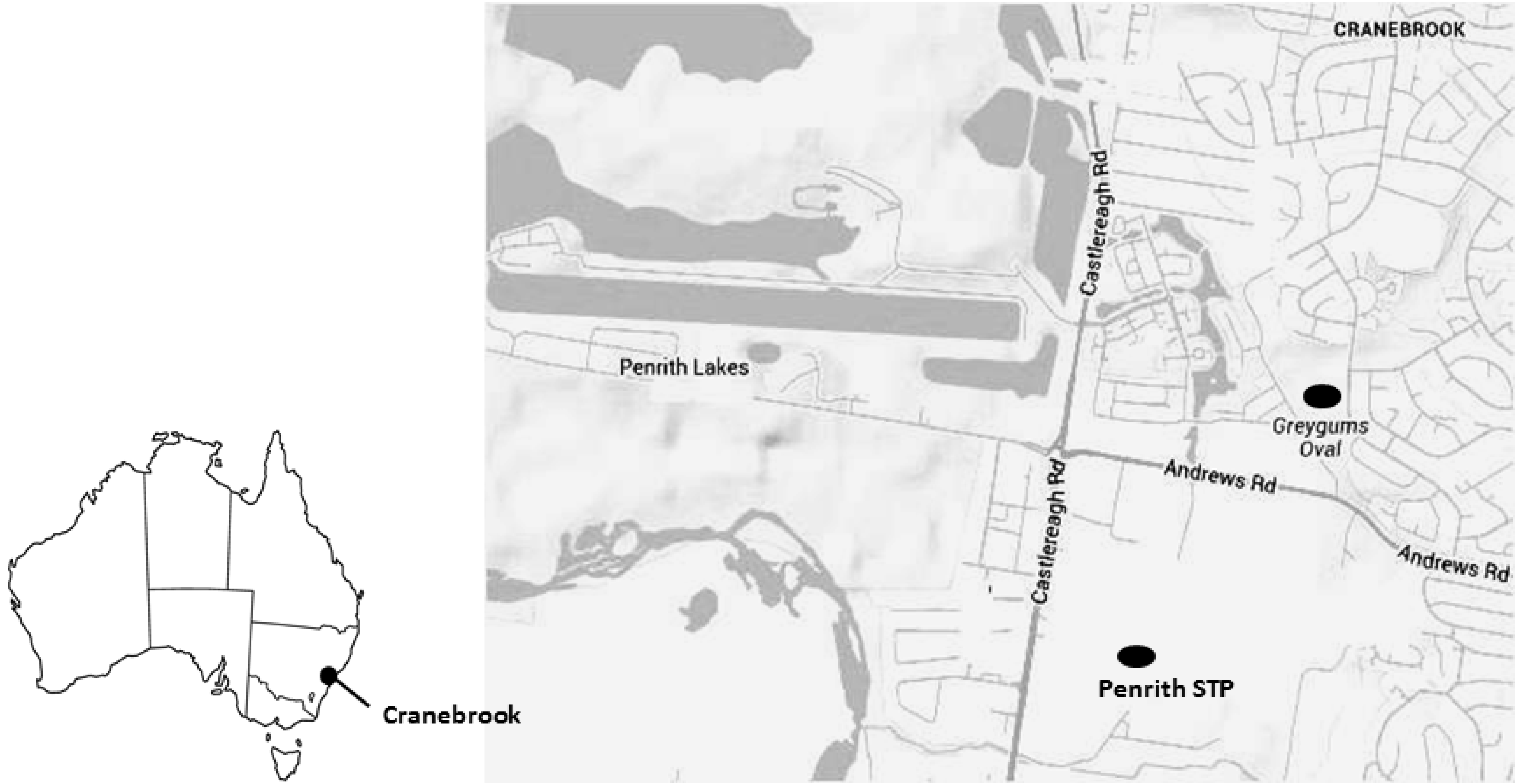


Figure 3.3 Map showing locations of Greygums oval and Penrith Sewage Treatment Plant (STP)

3.3 Soil analysis methods

3.3.1 Mechanical texture determination of clay, silt and sand

Mechanical texture of soil sample was determined according to McDonald and McDonald (1990). Samples of 25 g of air dry soil sieved through 2 mm mesh were combined with 25 mL of 5% Calgon solution (50 g Sodium Hexametaphosphate diluted in 1L deionised water) into a metal beaker and was mixed with an electric spindle mixer for 5 min. A 25 mL Calgon only blank was also prepared. After mixing, the entire content was transferred into a 500 mL measuring cylinder using distilled water. The cylinder was inverted three times to suspend the soil particles and set on a stable surface. All hydrometer readings were recorded using ASTM 152H hydrometer number A 5579 (-5 to 60 grams). Hydrometer readings and solution temperatures (^{0}C) were recorded at 5 and 90 min for each sample against the solution blank. Sedimentation calculation was conducted using blank and sample hydrometer and temperature readings. No meniscus correction was performed. However, hydrometer readings were corrected for sample temperature (T) using the formula (T - 19.5) x 0.3 commonly used in the laboratory (Aiken 2006). Proportions of sand, silt and clay were calculated as percentage values. Clay % was determined by subtraction based on the sand and silt % (measured using the 5 and 90 min readings, respectively). Soil textural classification was based on texture triangle adopted in Australia (McDonald and Isbell 2009).

3.3.2 Determination of soil water characteristic curve

Soil water characteristic curve (SWCC), also known as soil water retention curve, is a graphical representation of the amount of water remaining in the soil at equilibrium as a function of matric suction (Hillel 1980). Using the SWCC, hydraulic properties of unsaturated soil (water flow parameters) are derived (van Genuchten 1980), which are essential for the water and solute transport modelling. In this study, pressure plate extractor was used to construct the SWCC. At equilibrium, in a pressure plate extractor, there is an exact but opposite relationship exists between the air pressure (positive force) in the extractor and the soil suction (negative force). Usually, two methods are adopted in using the pressure plate extractor including the method of weighing soil, which measures the water content by weighing the soil when equilibrium is reached, and the method of weighing outflow, which measures the water content by weighing the outflow from the soil sample after equilibrium is reached. In this study, method of weighing soil was adopted. Typical setup of the ceramic plate extractor (SOILMOISTURE EQUIPMENT CORP., USA) used in this study is shown in Figure 3.4.

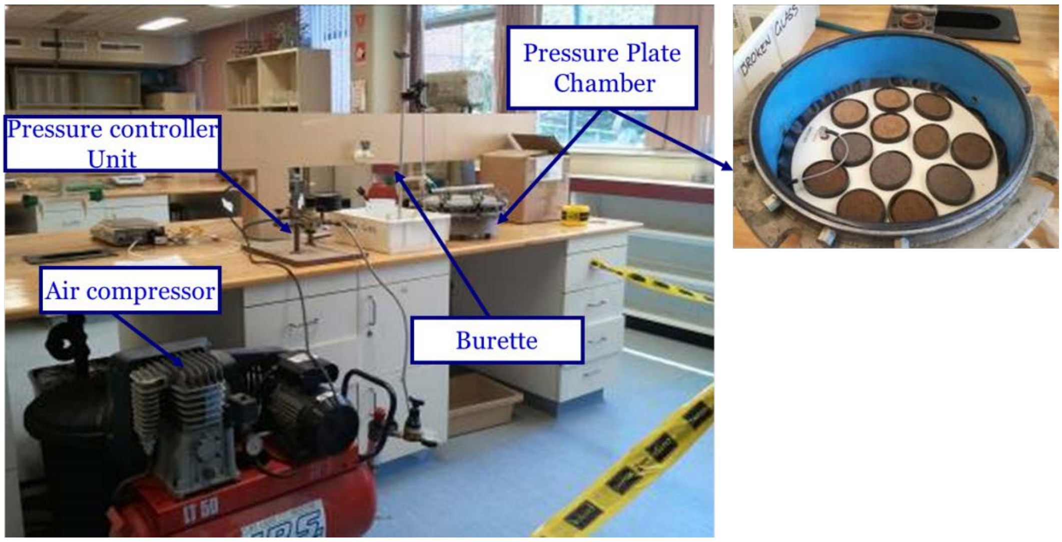


Figure 3.4 Setup of pressure plate extractor

Soil sample of approximately 25 g of air dry soil (each soil type with two replicates) was first loosely placed inside a rubber ring (inside diameter 5.5 cm, height 1 cm) on the designated pressure plate. The soils were lightly tapped on the top after placing inside the rings. On average, the packing density of D21, D33, C5 and Yarramundi soil was calculated as 1.2, 1.1, 1.0 and 1.2 g/cm^3, respectively. Water was poured to half submerge the ring containing soil and kept overnight to saturate the soil samples. Next day any remaining extra water on the plate was removed. The test was conducted individually at suctions of 0.1, 0.33, 1, 3, 5, 10 and 15 bar. At each suction, when equilibrium was reached, soil samples were removed from the pressure plate chamber and analysed for gravimetric moisture content according to method 2A1, Rayment and Higginson (1992). The equilibrium achieved within 24 to 72 hr. Results of the suctions were plotted against moisture content to obtain the SWCC. Data from soil water characteristic curve was used to calculate hydraulic flow parameters using the van Genuchten-Mualem model (van Genuchten 1980); van Genuchten or VG water flow parameters include residual moisture content, saturated moisture content, soil water retention function *a*, and empirical parameter *n*. The van Genuchten-Mualem model (van Genuchten 1980) is as below:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left(1 + \left(a|h|\right)^p\right)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (3.1)$$

$$K(h) = \begin{cases} K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 & h < 0 \\ K_s & h \geq 0 \end{cases} \quad (3.2)$$

Where, m=1-(1/n), n>1

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (3.3)$$

Where, S_e is effective saturation [-], *a* is the soil water retention function [L^{-1}], *m* and *n* are empirical parameters [-], θ_r is residual moisture content [L^3L^{-3}], θ_s is saturated moisture content [L^3L^{-3}], *l* is pore connectivity parameter, using 0.5 as an average for general soils (Šimůnek et al. 2009). For the purpose of determining the VG parameters, RETC code (van Genuchten et al. 1991) was used.

3.3.3 Saturated hydraulic conductivity

Contaminant transport modelling requires the knowledge of soil permeability, which is simply represented as saturated hydraulic conductivity. In determining the saturated hydraulic conductivity of soil samples from study sites, constant head method proposed by (Madsen et al. 2008) was used. The experimental setup is shown in Figure 3.5.

A plexiglass column with 45 mm inside diameter was packed with soil sample to a height of 57 mm. It should be noted that compaction density of soil in the column was maintained close to the bulk density measured in the field. In D21, D33 and Yarramundi soil columns, compaction density was maintained as 1.5 g/cm^3; in C5 soil column compaction density was 1.37 g/cm^3. A stopper with cheesecloth was used at the bottom of the column. Another stopper was used at the top of the column. A space of 5 mm was left between top of the soil surface and the top stopper. Both the stoppers were fitted with tubing to facilitate connection with solution inlet and outlet in a way that the column can be used for upward as well as downward flow. As wetting solution of the soil 0.01M $CaCl_2$ solution was used. The solution was used instead of water to avoid deflocculation of soil aggregate. Before starting the experiment, the soil sample was slowly saturated with 0.01M $CaCl_2$ solution from the bottom up until water began to pond on the surface of the soil. The soil sample was saturated overnight. A constant head of 100 mm was maintained for all the experiments. The fluid began to flow through the column in the downward direction. The volume of fluid was recorded every 3 min until the flow stabilised.

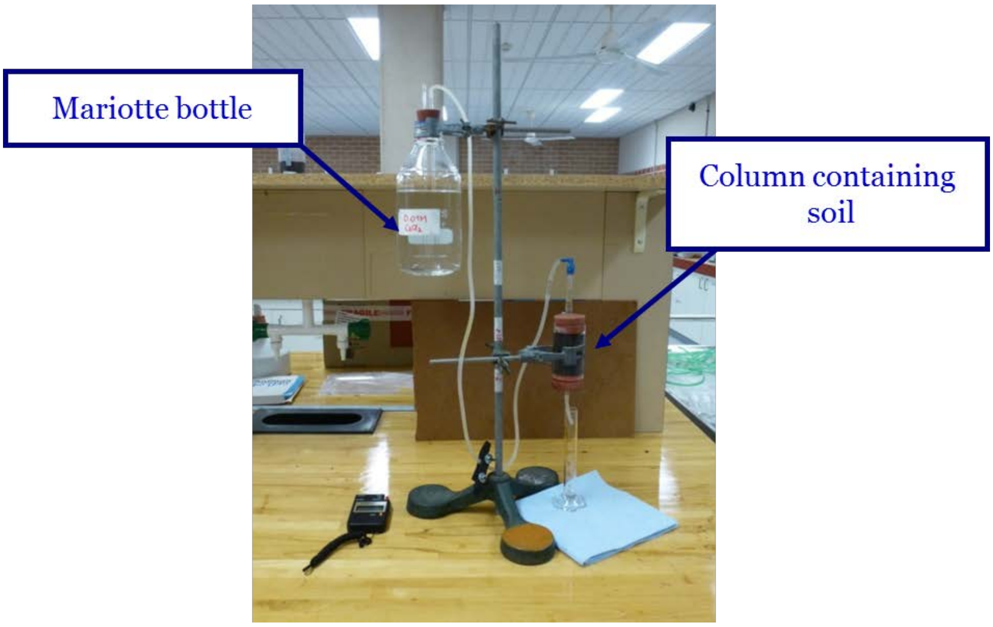


Figure 3.5 Experimental setup for the determination of saturated hydraulic conductivity in soil sample

3.3.4 Determination of electrical conductivity

Electrical conductivity was measured for soil water solutions, soil saturated extracts, and irrigation (recycled) water and leachate from column study. All conductivity values were measured using a HQ 40d portable conductivity meter (HACH Inc.) after calibration with calibration solution (KCl solution) of 1.413 dS/m.

Electrical conductivity of soil water solution was measured as $EC_{1:5}$ (dS/m) according to (Rayment and Higginson 1992) (Method 3A1). Air dry samples passing 2 mm sieve of 20 gm were mixed with 100 ml distilled water to make 1:5 soil: water solutions. The solution was mixed in shaker for 1 hour and allowed to stand for 30 minutes for the soil to settle. Electrical conductivity was measured by the conductivity meter.

Saturated paste extract electrical conductivity, denoted as EC_e (dS/m), was prepared according to Rayment and Higginson (1992) (Method 2D1). Air dry soil samples of 200±0.5 g passing 2 mm sieve was used to make saturated paste. Distilled water was added to the sample while stirring with spatula. The sample container was tapped on the bench time to time to consolidate the soil water mixture. The saturation is assumed to be occurred when the paste glistens as it reflects the light, consolidates easily, slides freely from spatula and flows slightly when container is tipped. The soil water mixture was covered with Parafilm® and allowed to stand overnight to equilibrate. Next day the mixture was checked for the consistency and more water was added (if needed) to obtain appropriate saturated paste. Amount of total added water was determined. The mixture was filtered by 0.45μm filter paper to get the saturated extract. Measured values of electrical conductivity were temperature compensated according to Richards (1954) using following equation:

$$EC_{25\,^0C} = EC_{measured} \times f_T$$

$$f_T = 1.00 + \frac{(25-T)}{49.7} + \frac{(25-T)^2}{3728} \tag{3.4}$$

3.3.5 Determination of field bulk density

In-situ field bulk density was measured in all the study areas. A stainless steel cylinder with both top and bottom open was used to collect soil sample from the surface (Figure 3.6). The cylinder with dimensions 7.3 cm in diameter and 5.04 cm in height (volume of 209.8 cm^3) was driven into the ground by using an outer cylinder, which is closed on the top (Figure 3.6). The top surface of the ground was cleaned to remove the grass before taking the sample. The cylinder was hammered into the ground, trimmed extra soil at the top of the cylinder after collecting soil sample, and soil was stored in a clean bag. Samples were collected in duplicates. Care was taken to avoid loss of moisture from the collected sample. The sample was brought to the laboratory and analysed for moisture content according to Rayment and Higginson (1992) (method 2A1). The bulk density was calculated dividing the dry soil by volume of the ring in g/cm^3.

Figure 3.6 Collection of soil core at the field for determination of field bulk density

3.3.6 Soluble and exchangeable cations

Knowledge of soluble and exchangeable cations present in the soil helps to determine SAR (Equation 2.1) and efficiently manage the irrigated field. Likewise, soil's ability to retain cations is measured by cation exchange capacity (CEC), which is the total of exchangeable cations present in the soil water solution. Exchangeable cations such as Na^+, K^+, Ca^{2+} and Mg^{2+} are considered important in this study and measured for the soils of all study areas. Soluble bases were determined according to Rayment and Higginson (1992) (method 14H1), where soluble Na^+, K^+, Ca^{2+} and Mg^{2+} were measured in saturated paste extract of soil sample using atomic absorption spectrophotometer (AAS). Exchangeable cations in soil samples were measured according to Rayment and Higginson (1992) (method 15D3). In this method, no pretreatment to remove soluble salts or suppress CO_3^{-2} dissolution was considered. Soils were equilibrated with 1M NH_4OAc at pH 7.0 for 30 min using mechanical rotating shaker at a soil solution ratio of 1:10. Suspensions were clarified prior to analysis for exchangeable bases using a 700 series ICP-OES (Agilent Technologies). Some of the soil samples were sent to commercial laboratory (ALS

Environmental, Smithfield, New South Wales) for the determination of soluble cations.

3.3.7 Soil pH

Values of pH were measured according to Rayment and Higginson (1992) (method 4A1) for soil: water solutions, soil saturated extracts, and irrigation and leachate from column study. All pH values were measured using a HQ 40d portable pH meter (HACH Inc.) after calibration with pH standards of 4.0, 7.0 and 10.0.

3.4 Real-time measurement of volumetric water content and salinity in soil

Conventional methods of measuring water content and salinity is described in Section 3.3 of this chapter. Besides these conventional methods, sensor based real-time monitoring were carried out in this study. The real-time monitoring method included measuring water content and salinity in soil using a GS3 sensor (Decagon 2011).

The bulk electrical conductivity in GS3 sensor is derived by multiplying the inverse of the resistance by the cell constant; the cell constant is the ratio of the distance between the electrodes to their area (Decagon 2011). The sensor has three prongs which are 55 mm in length, 3.26 mm in diameter, and 25.4 mm apart from each other. The detailed specifications of a GS3 sensor can be found in Decagon (2011). Each sensor used in the study was tested for accuracy in measuring the electrical conductivity.

As discussed in Section 2.3.2, bulk electrical conductivity in wet soil depends on the volumetric water content of soil. Therefore, reporting electrical conductivity in the soil in terms of soil water electrical conductivity (EC_{SW}) is more preferable than reporting it in terms of EC_{bulk}. In this study, sensor measured EC_{bulk} was converted to EC_{SW} for different volumetric water content and a relationship among these three parameters was proposed.

The relationship was determined with results from a calibration study similar to the one used by (Muñoz-Carpena et al. 2005). In this calibration study, air dried soil was thoroughly mixed by hand with a known volume of synthetic water to achieve a uniform distribution of water and solute. The synthetic water was prepared by mixing four different salts, namely, sodium chloride (0.01 mol), magnesium chloride (0.005 mol), calcium chloride (0.001 mol) and potassium chloride (0.001 mol) in 1 L of distilled water to produce a solution with an electrical conductivity of 2.0 dS/m. The ratio of cations (Na^{+}: Mg^{2+}: K^{+}: Ca^{2+} = 0.6: 0.2: 0.1: 0.1) in the synthetic water was maintained similar to that present in the recycled water. Three different types of synthetic water were prepared with electrical conductivities of 0.5, 1.0 and 2.0 dS/m. Each type of synthetic water was used to prepare duplicate soil samples with three different volumetric water contents. Depending on the soil type (D21, Yarramundi, D33 and C5), volumetric water content varied between 0.2 and 0.4 m^3/m^3. The soil was packed into a steel column of height 52 mm and diameter 98 mm. Mean packing bulk density was kept close to that measured at the field.

Firstly, bulk electrical conductivity (EC_{bulk}) and permittivity (ε) were recorded by GS3 sensors for several minutes. Secondly, a subsample was collected by a volumetric soil sampler (height 38.8 mm and diameter 13.2 mm) to analyse the volumetric water content gravimetrically (method 2A1, Rayment and Higginson 1992). Thirdly, the electrical conductivity of the soil solution was obtained by extracting the solution with a soil water sampler (Slim tube, manufactured by Soil Moisture Equipment Corp.) at suction 60-80 kPa and then reading the value with a laboratory EC meter (HACH Inc.). This procedure was repeated 18 times for all the soil samples which were prepared as explained above.

The calibration equation was developed using multiple linear regression technique, which attempts to model the relationship between two or more independent variables with a dependent variable by fitting a linear equation to the observed data. In this study, the relationship between the dependent variable and the independent variables are assumed to be linear. The following represents a multiple linear regression equation (Montgomery et al. 2012):

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k \qquad (3.5)$$

where, α is the model intercept, $\beta_{1,2,3\ldots k}$ are the slope coefficients, and k is the number of independent variables.

3.5 Continuous column study at laboratory

3.5.1 Construction of columns

Columns were constructed from 2.5 mm thick plexiglass tubes. All columns used in the column study had an external diameter of 160 mm however length of the columns varied depending on the study type. A 200 x 200 mm baseplate was used at the bottom of the column. The base plate was perforated with 2.0 mm diameter holes. Silicon was used at the joint between plexiglass column and the baseplate to avoid any leakage of water. A plastic mesh (mesh size < 800 µm) was used at the bottom of the column along with a sand layer of 30 mm thickness (sand retained on sieve size 800 µm). Appropriate chair made of steel was designed to hold columns in place. Leachate from the column was collected in a plastic container using a 180 mm wide funnel.

3.5.2 Monitoring of meteorological parameters in the laboratory

Meteorological parameters such as minimum and maximum temperature, relative humidity and wind speed were monitored continuously by a weather station (WS-2306, La Crosse Technology). Data was collected every hour. Data from the weather station was downloaded to computer using "heavy weather" software. Solar radiation in the laboratory was monitored by a pyranometer (Model PYR, Decagon Inc.). The pyranometer was connected to a data logger (CR800, Campbell scientific) for continuous data collection one minute intervals.

3.5.3 Irrigation water used in the column studies

Three types of irrigation waters were used to feed columns in the continuous column study:

- Recycled water;
- Tap water; and
- Synthetic saline water.

Recycled water, collected from an on-site dam (Figure 3.7) in HWRS, was used to feed most of the columns. Recycled water was collected in several 20L Jerry Cans and brought to the laboratory. The recycled water was filtered to remove suspended materials and stored in room temperature. The electrical conductivity of the recycled water varied between 0.81 and 0.84 dS/m. The yearly mean values of cations were reported by Sydney Water as 95.9, 20.6, 16.9 and 13.7 mg/L for Na^+, Mg^{2+}, K^+ and Ca^{2+}, respectively (data collected by personal communication). The sodium adsorption ratio was calculated as 3.8.

Tap water was used to feed some columns. The tap water was collected at the laboratory of Western Sydney University, where column studies were conducted. The electrical conductivity of tap water varied between 0.21 and 0.22 dS/m. The values of cations were measured as 19.5, 4.67, 4.65 and 13.52 mg/L for Na^+, Mg^{2+}, K^+ and Ca^{2+}, respectively. The sodium adsorption ratio was calculated as 1.2.

Figure 3.7 Turkey nest dam to store recycled water in HWRS

The synthetic water that was used in the calibration study of GS3 sensor (Section 3.4), the same water was also used to feed some columns in the continuous column study. The electrical conductivity of the synthetic water used in the column study was 2.0 dS/m. The values of cations were measured as 240, 52, 43 and 34 mg/L for Na^+, Mg^{2+}, K^+ and Ca^{2+}, respectively. The sodium adsorption ratio was calculated as 6.0.

3.5.4 Experimental design

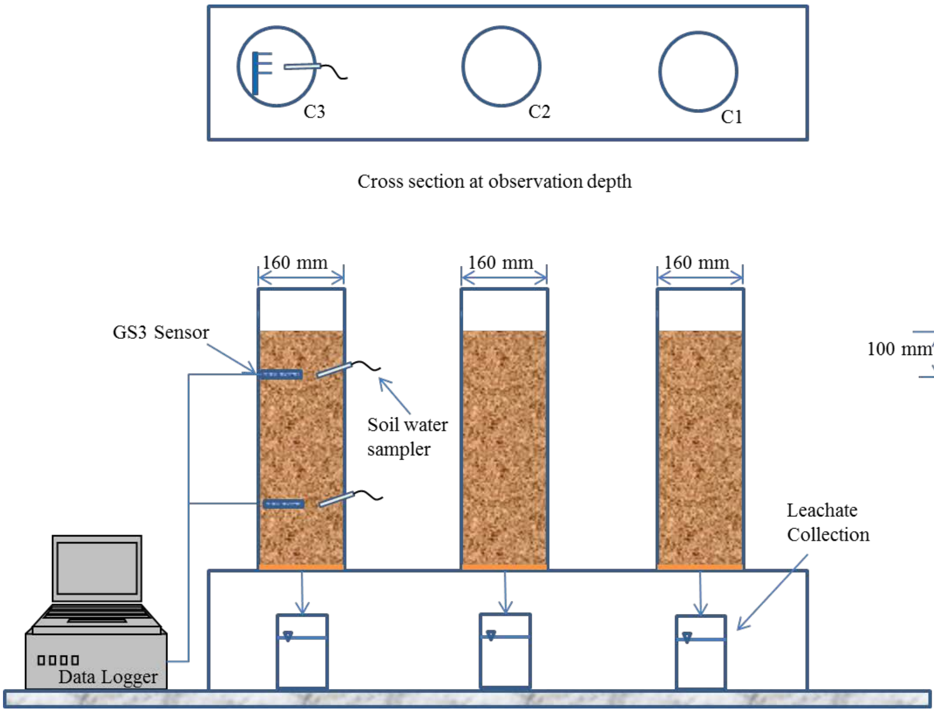
Three sets of continuous column studies were conducted for the purposes of understanding:

i. Salt accumulation at different depths of a soil profile and impact of rainfall on salt accumulation;
ii. Impact of soil type on salt accumulation in a soil profile; and
iii. Impact of irrigation water type on salt accumulation in a soil profile.

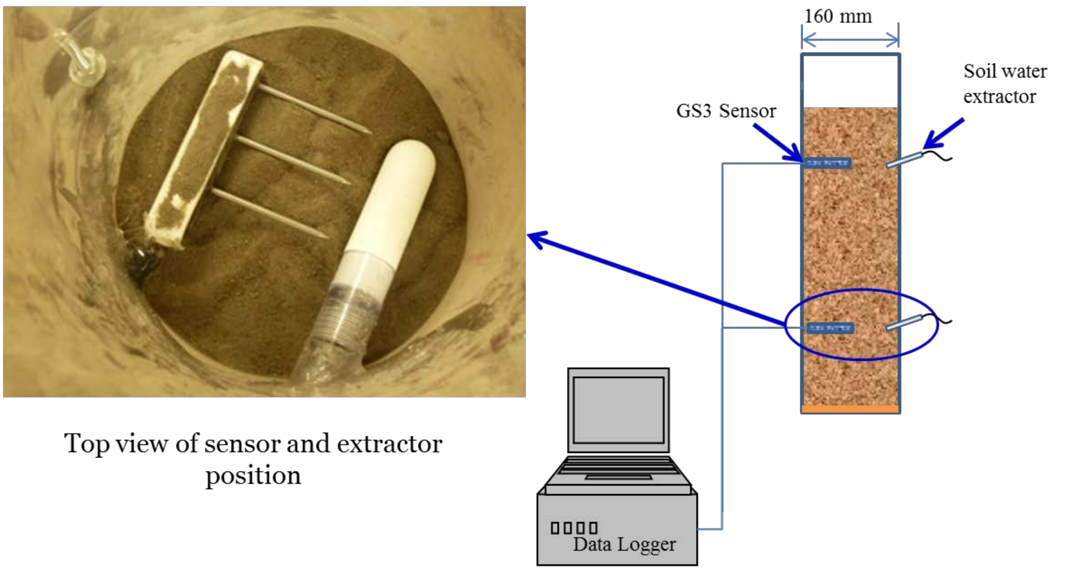
Soil samples collected from the paddocks mentioned in Section 3.2.1 were used for the column studies. Soil samples from D21 paddock was used in the first set of column study. In the second set, impact of soil type of salt accumulation was investigated using soil samples from D21 and C5 paddocks. The third set of column study was conducted using soil samples from D33 and Yarramundi paddocks. In all sets of the study, real-time monitoring system was principally used to get information about the salt accumulation in the soil profile. All the experimental setups were established inside a laboratory at Kingswood campus of the University of Western Sydney.

3.5.4.1 Salt accumulation at different depths of a soil profile

In this continuous column experiment salt accumulation was observed at two depths, namely, 0.1 and 0.35 m from soil surface. Three soil columns (C1, C2 and C3) of identical dimensions were prepared. Soil samples were packed with a height of 470 mm. Figure 3.8 (*a*) shows the schematic of the column setup. One of the three columns (C3) was fitted with two GS3 sensors at depths of 0.1 and 0.35 m from the soil surface. This was done to monitor bulk electrical conductivity at these two specified depths (Figure 3.8*b*). The GS3 sensors were connected to the data logger for continuous data collection at one minute intervals.



(*a*)



(*b*)

Figure 3.8 (*a*) Schematic of column setup to monitor salt accumulation at two depths of D21 paddock soil (*b*) Details of sensor and extractor position

Two soil water samplers were installed at the same depths where the GS3 sensors were installed and were used to collect soil water at the specified depths

(Figure 3.9). The electrical conductivity of collected soil water was measured and recorded as EC_{SW}. The reason behind choosing these two depths was to establish a soil profile similar to the average depth of a root zone of 0.35 m from the soil surface. In practice, length of roots for rye pasture varies between 0.25 to 0.45 m (Allan et al. 1997); the rye pasture was commonly irrigated in this field (Aiken 2006). In the continuous column studies (Sections 3.5.4.1, 3.5.4.2 and 3.5.4.3), actual evapotranspiration was not reported as the soil was bare. This is because the focus of the study was to identify distribution of salt accumulation (in a soil profile similar to the root zone depth) in soil columns rather than plant growth and crop yield in the field. The root water uptake was not considered during the period of continuous column study; hence potential evapotranspiration equals the potential evaporation, which was the existing mechanism to concentrate salt in the leachate. Therefore, continuous column experiment with no vegetation was sufficient to get enough information to monitor the salt accumulation with the help of laboratory measured soil hydraulic and water flow parameters. All three columns were packed in such a way that an identical bulk density of 1511 kg/m^3 was maintained.

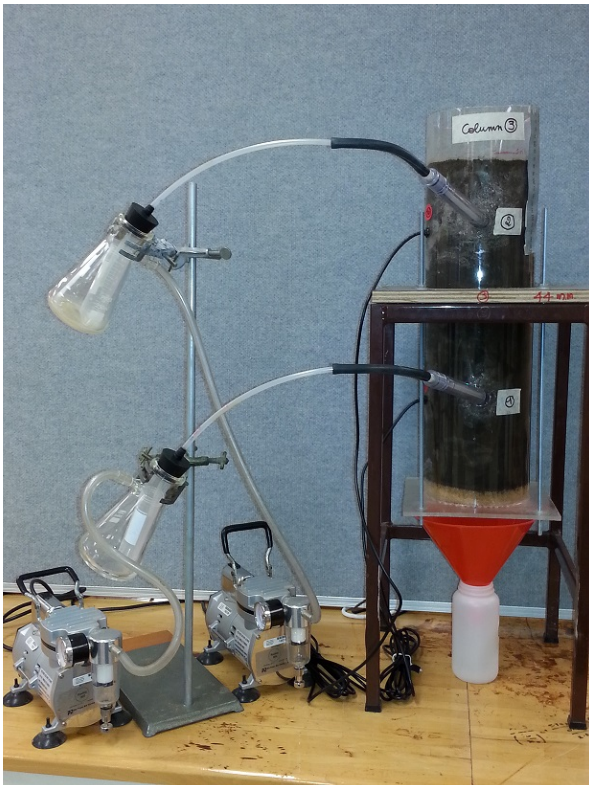


Figure 3.9 Setup for soil water extraction from different depths of D21 column

The column study was conducted for a period of 264 days. The columns were operated under no rain condition for the first 154 days. This period was maintained to allow sufficient time to accumulate salt in the soil profile. Irrigation (recycled) water was applied at a frequency of three times per week as per the current practice; total amount of 730 mm of recycled water was applied as irrigation water during this period. In the next 110 days, simulated rainfall was applied along with the irrigation (recycled) water and the irrigation frequency was reduced to two times per week; rainfall was applied once in a week. In total, about 160 mm of rainfall was applied during this period; total applied amount of recycled water was 215 mm. To simulate the rainfall, distilled water having electrical conductivity of 0.02 dS/m was used. At the end of each week, soil water samples were collected from the column at depths 0.1 and 0.35 m, using the samplers. The volume and electrical conductivity of collected soil water samples were measured. Leached water at the bottom of each column was collected, the volume was measured and it was analysed for electrical conductivity using an EC meter. Results from these experiments are presented and discussed in Chapters 5 and 8.

3.5.4.2 Impact of soil type on salt accumulation using recycled water as irrigation water

In this continuous column experiment two types of soil, namely D21 and C5 were used. Three soil columns of identical dimensions (according to Section 3.5.1) were prepared for each type of soil. Soil samples were packed with a height of 300 mm. Figure 3.10 shows the schematic of the column setup. One of the three columns from each type of soil was fitted with a GS3 sensor and a soil water sampler at the depth of 0.2 m from the soil surface. GS3 sensors were used to monitor bulk electrical conductivity at this specified depth (Figure 3.10). The soil water samplers were used to collect soil water at the specified depth (similar to that shown in Figure 3.9). Electrical conductivity of collected soil water was measured and is denoted as EC_{SW}.

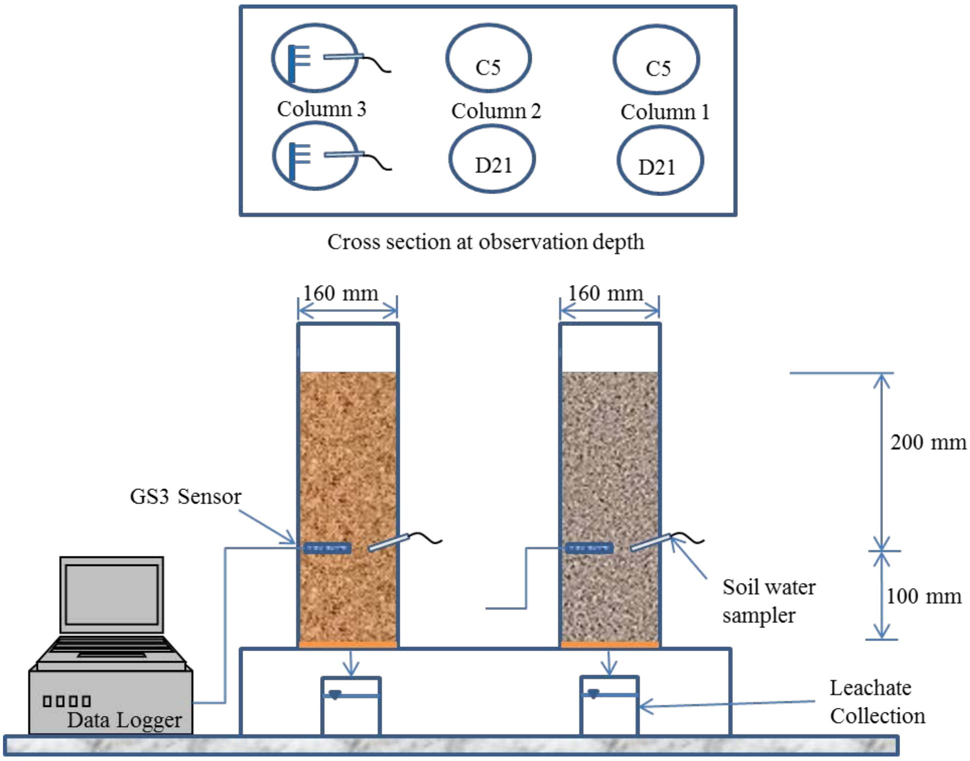


Figure 3.10 Schematic of column setup to monitor impact of soil texture on salt accumulation for D21 and C5 paddock soil.

All three columns of D21 paddock soil were packed in such a way that the same bulk density of 1460 kg/m^3 was maintained. In case of C5 paddock soil columns, packing bulk density of 1370 kg/m^3 were maintained. The soil column experiment was conducted for a period of 400 days. Irrigation (recycled) water was applied three times per week; total amount of 1275 mm of recycled water was applied during the study period. Leached water at the bottom of each column was collected, measured for volume and analysed for electrical conductivity with an EC meter. Soil water samples for measuring EC_{SW} were collected at the end of each week. The volume and electrical conductivity of collected soil water samples were measured. Results from this experiment are shown and discussed in Chapter 6.

3.5.4.3 Impact of irrigation water salinity on salt accumulation

This column study was conducted to compare the impact of irrigation water type (in terms of salinity) on salt accumulation in the soil profile. Three different types of irrigation water namely, recycled water, tap water and synthetic saline water was used in this column study. Details of different types of irrigation water are discussed in Section 3.5.3. Columns were prepared with soils from D33 and Yarramundi paddock. The experiment also highlighted the impact of irrigation water salinity on different types of soil. Nine soil columns of identical dimensions (according to Section 3.5.1) were prepared for each type of soil. Soil samples were packed to a height of 300 mm. Figure 3.11 shows the schematic of the column setup. Each type of irrigation water was used in three of the columns of a soil type. For example, tap water was used in columns 1, 2 and 3; recycled water in columns 4, 5 and 6; and synthetic saline water in columns 7, 8 and 9. Similar application of irrigation water was maintained for both types of soil. One of the three columns from each irrigation water type was fitted with a GS3 sensor at the depth of 0.2 m from the soil surface. No soil water sampler was installed in any of the columns. GS3 sensors were used to monitor bulk electrical conductivity at 0.2 m depth (Figure 3.11).

All 18 columns of both soil types were packed in such a way that the same bulk density of 1500 kg/m^3 was maintained. The soil column experiment was conducted for a period of 330 days. Irrigation (tap, recycled and saline) water was applied three times per week; total amount of 960 mm of each type of irrigation water was applied during the study period. Leached water at the bottom of each column was collected, measured for volume and analysed for electrical conductivity with an EC meter. At the end of the study period, soil samples were collected from every five centimetres of the soil profile. Each soil sample was divided into subsamples to analyse for $EC_{1:5}$, EC_e, and soluble cations (Na^+, K^+, Ca^{2+} and Mg^{2+}). The tests were carried out for all soil samples collected from 18 columns. Results from this experiment are presented and discussed in Chapter 7.

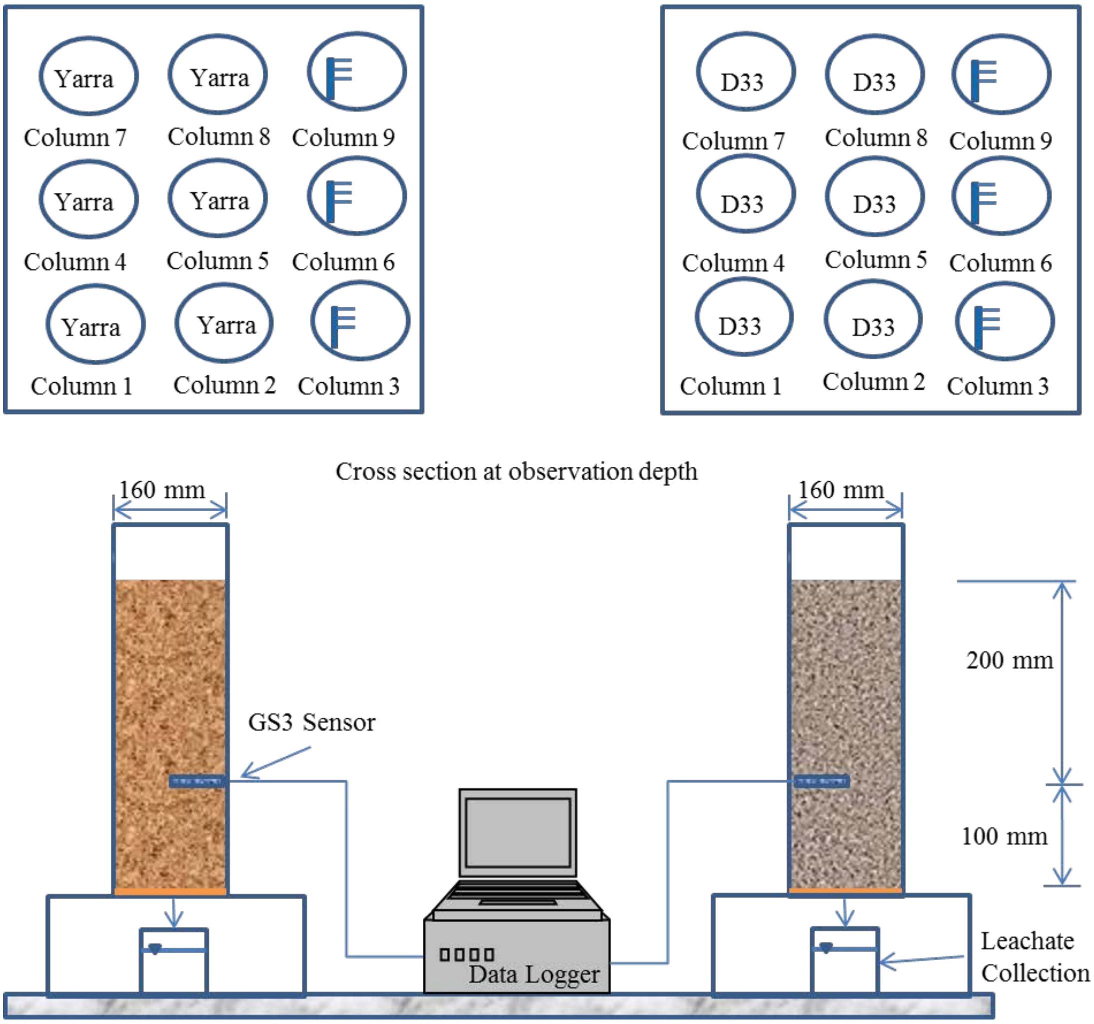


Figure 3.11 Schematic of column setup to monitor impact of irrigation water type on salt accumulation in D33 and Yarramundi soil profile

3.6 Governing equations and software

3.6.1 Water and solute transport modelling

The prediction of accumulation of salt in the root zone is quantified by using an off-the-shelf model, namely, HYDRUS 1D (Šimůnek et al. 2009). This model (HYDRUS 1D) simulates one dimensional water flow and solute transport in incompressible, porous, variably saturated media. The model can be used for different regimes but in this study transient system is used. For water flow modelling HYDRUS 1D uses Richards' equation, which is given by (Celia et al. 1990; Xu and Shao 2002):

$$\frac{\partial \theta}{\partial t} - \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - \frac{\partial K_z}{\partial z} - S = 0 \quad (3.6)$$

Where, K_z saturated hydraulic conductivity [LT^{-1}], θ volumetric moisture content [L^3L^{-3}], *h* pressure head [L], *z* depth in the vertical direction (positive upward) [L], *t* Time [T], and *S* the sink term representing water uptake by plant roots, which is defined as the volume of water removed by plant roots from the soil per unit of time [$L^3L^{-3}T^{-1}$].

For hydraulic properties, van Genuchten-Mualem model (van Genuchten 1980) was used, which provides relationships between the volumetric moisture content, effective saturation, hydraulic conductivity and specific moisture storage (Equations 3.1 to 3.3).

For solute transport, it was assumed that the solutes were non-reactive and there was no solubilization or dissolution of soil minerals. The assumption permitted the salinity in soil to be modelled based on the convection-dispersion equation for nonreactive solution (Dag et al. 2014). The partial differential equation governing one dimensional advective-dispersive transport for transient flow in a variable saturated soil can be written as (Xu and Shao 2002; Šimůnek et al. 2009; Bunsri et al. 2008):

$$\theta R \frac{\partial c}{\partial t} - \frac{\partial}{\partial z}\left(\theta D_z \frac{\partial c}{\partial z}\right) + q_z \frac{\partial c}{\partial z} = 0 \quad (3.7)$$

Where,

$$R = 1 + \frac{\rho_b K_d}{\theta}$$

ρ_b is bulk density [ML^{-3}], K_d is distribution coefficient [L^3M^{-1}], c is concentration of chemical in liquid phase [ML^{-1}], q_z is the volumetric flux density [LT^{-1}], D_z is dispersion coefficient [L^2T^{-1}] that accounts for both diffusion and hydrodynamic dispersion. D_z is calculated using Šimůnek et al. (2009).

$$D_z = \alpha_1 \frac{|q_z|}{\theta} + D_d \tau \qquad (3.8)$$

Where, α_1 is longitudinal dispersivity [L], D_d is the ionic or molecular diffusion coefficient in free water [L^2T^{-1}], τ is a tortuosity factor. The tortuosity factor was evaluated by using Millington and Quirk equation (Chen et al. 2015):

$$\tau = \frac{\theta^{\frac{7}{3}}}{\theta_s^2} \qquad (3.9)$$

The plant solute uptake was assumed to be negligible in the present study. The governing water flow and solute transport equations were solved using upstream weighting finite element method Šimůnek et al. (2009).

3.6.1.1 Initial and boundary conditions

3.6.1.1.1 Initial conditions

For water flow modelling, the initial condition as water content within the flow domain was assumed as (Šimůnek et al. 2009):

$$\theta(z,t) = \theta_i(z) \qquad t = t_0 \qquad (3.10)$$

Where, θ_i is a prescribed function of z, and t_0 is the time when the modelling begins. At the soil surface, $z = L$ and at the bottom of the column, $z = 0$.
For solute transport modelling, the initial condition was assumed as (Xu and Shao 2002):

$$c(z,t_0) = c_0(z) \qquad (3.11)$$

Where, c_0 is the concentration of the incoming water [ML^{-1}].

3.6.1.1.2 Boundary conditions

For water flow modelling, upper boundary condition was represented by *atmospheric boundary condition with surface layer* as follows (Šimůnek et al. 2009):

$$-K_z\left(\frac{\partial h}{\partial z}+\cos\alpha\right)=q_0(t)-\frac{dh}{dt} \qquad at\ z=L \qquad (3.12)$$

Where, α is the angle between the flow direction and vertical axis ($\alpha = 0^0$ for vertical flow and $\alpha = 90^0$ for horizontal flow). The flux q_0 in the equation is the net infiltration rate calculated as the difference between precipitation and evaporation. The above condition allows water to build up on the surface. The height of the surface water layer increases due to precipitation and reduces because of infiltration and evaporation.

Lower boundary condition at the bottom of the column was assumed as *free drainage* or unit hydraulic gradient (Šimůnek et al. 2009):

$$\frac{\partial h}{\partial z}=1 \qquad at\ z=0 \qquad (3.13)$$

For solute transport modelling, a Cauchy third type boundary condition was used as upper boundary as follows (Šimůnek et al. 2009):

$$-\theta D_z\frac{\partial c}{\partial z}+qc=q_0c_0 \qquad at\ z=L \qquad (3.14)$$

At the bottom of the soil column, zero concentration gradient was assumed (Šimůnek et al. 2009):

$$\theta D_z\frac{\partial c}{\partial z}=0 \qquad at\ z=0 \qquad (3.15)$$

The initial and boundary conditions were introduced in the HYDRUS 1D at the time of validating the model with experimental setup, and also at the time of using it for the prediction of future salinisation of root zone soil.

3.6.2 *Bayesian belief network*

The BBN is based on the ideas that the parameters are considered random variables having a number of *states*. As discussed in Section 2.5.1.3, the set of states associated with variables A and B of Bayes' theorem (Equation 2.6) can be denoted by $A = a_1, a_2, \cdots \cdots, a_n$ and $B = b_1, b_2, \cdots \cdots, b_m$. The probability related to variables A and B can be expressed through probability distributions as below (Jensen and Nielsen 2007):

$$P(A) = (x_1, \cdots \cdots, x_n); \qquad x_i \geq 0; \qquad \sum_{i=1}^{n} x_i = x_1 + \cdots + x_n = 1$$

$$P(B) = (y_1, \cdots \cdots, y_m); \qquad y_j \geq 0; \qquad \sum_{j=1}^{m} y_j = y_1 + \cdots + y_m = 1$$

(3.16)

Here x_i is the probability of A being in state a_i and y_j is the probability of B being in state b_j.

Bayes' theorem is fundamentally based on conditional probability of variables. The term $P(A|B)$ in Bayes' theorem (Equation 2.6) contains $n \times m$ conditional probabilities $P(a_i|b_j)$ that specify the probability of obtaining a_i given b_j. It means that the conditional probability for a variable given another variable is a set of probabilities, organized in a $(n \times m)$ table, with one probability for each configuration of the states of the variables involved. The table constructed in this way is called conditional probability table (CPT).

The first step to design the BBN is to find causal interrelationships between variables leading to consequences, which can be shown by nodes connected by arrows. As discussed in Chapter 2, Section 5.1.3, variables with in-going arrows are referred to as *children* and variables with outgoing arrows are named as *parents*; children nodes are assigned with conditional probabilities and consequences are assigned corresponding to the states represented by the BBN. As an example of CPT, if a child node A, has several parent nodes $B_1, \cdots, B_n$ there is an attached CPT to node A as $P(A|B_1, \cdots, B_n)$.

Two frameworks, such as, to identify sources of salinity causing salinisation in the root zone soil, and assessment of treatment needed in recycled water, were developed in BBN. The proposed framework in BBN is essentially a directed acyclic graph (DAG), which is assumed as the most suitable way to represent causal relationship between parent and child nodes. A directed graph is acyclic if no cycle in exposure pathway exists among parent and child nodes in the BBN network. To get a solution to the BBN model, commercial software called Hugin-Expert® (Hugin 2013)was used. The BBN framework to control salinity in recycled water is discussed in Chapter 8 and the framework to assess sources controlling salinity in the root zone is discussed in Chapter 9.

3.7 Goodness of fit indices

Different statistical parameters, namely, mean absolute error (MAE), root mean square error (RMSE), percent relative error (RE) and percent bias (BIAS) were used to evaluate the goodness of fit between experimental and model predicted data.

The mean absolute error (MAE) between observed and predicted values is given by:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|O_i - P_i| \quad (3.17)$$

Where, O_i represents observed values; P_i represents predicted values; and N represents the number of observations. MAE value close to zero indicates good model performance. Similarly, the RMSE can be calculated by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N-1}} \quad (3.18)$$

MAE and RMSE indicate the presence and extent of deviation between the simulated and observed values (Ramos et al. 2011; Kanzari et al. 2012). Units of MAE and RMSE are the units of that particular variable.

RE measures the relative error in the simulated values in terms of percentage with respect to observed values. An ideal value of RE is zero, which indicates good model performance and can be calculated by:

$$RE = \frac{100}{N}\sum_{i=1}^{N}\frac{|O_i - P_i|}{O_i} \quad (3.19)$$

BIAS measures the percentage of the residuals with respect to observed values which indicate whether the model overestimates or underestimates the observed values (Moriasi et al. 2007). The perfect value of BIAS is zero. Low values of BIAS indicate better simulation results by the model where positive and negative values represent underestimation and overestimation bias, respectively in the simulated results. BIAS can be calculated by:

$$BIAS = \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i)} \times 100 \tag{3.20}$$

Statistical analyses were conducted using Minitab® (Minitab 2000).

CHAPTER 4

SOIL CHARACTERISTICS AT THE FIELD SITE

4.1 Introduction

Characterisation of soil collected from Hawkesbury water reuse scheme (HWRS) is reported in this chapter. The first step of soil characterisation includes investigating physico-chemical properties of soil such as pH, electrical conductivity, mechanical texture classification, field bulk density, saturated hydraulic conductivity and soil water characteristic curve. Ionic composition of soil water is essential information to fully understand the soil condition of irrigated field. Specifically, the information is needed to calculate sodium adsorption ratio (SAR) and cation exchange capacity (CEC). Results related to water transport parameters helped in short term and long term modelling of salt accumulation in the root zone. The results from batch studies generated site specific relationships between soil water electrical conductivity and bulk soil electrical conductivity. All the properties mentioned above were analysed at the beginning of the study to constitute the initial condition of different continuous column studies mentioned in the previous chapter (Section 3.5). Thus, properties of soil samples are explored in this chapter.

4.2 Determination of physico-chemical properties of soil samples collected from HWRS

4.2.1 Mechanical texture

Mechanical texture of collected soils was determined according to the method discussed in Section 3.3.1. Detailed calculation and results from the tests for all soil samples are provided in Table A1 (a-d), Appendix A. The amount of sand, silt and clay was reported as percentage (%). Each type of sample was analysed duplicate and the result was averaged. Summary of results is shown in Table 4.1.

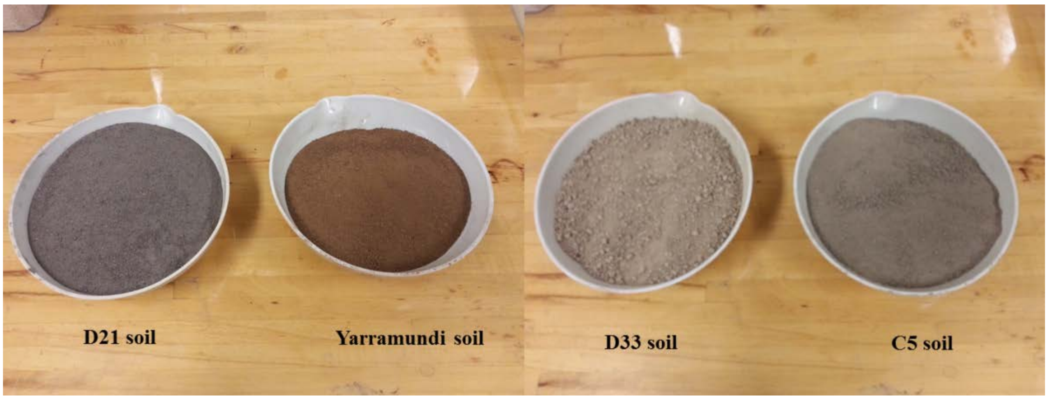


Figure 4.1 Soil samples collected from Hawkesbury Water Reuse Scheme (HWRS)

The results of the mechanical texture of soils highlight that soil of D21 paddock is of coarse grained when compared to C5 and D33 paddocks soil. Soil sample of D33 paddock has highest clay content among all soil types. Soil samples from D21 and Yarramundi paddocks seems similar, however, the colour of the soils are different (Figure 4.1); grey for D21 and reddish for Yarramundi soil (determined by eye estimation).

Table 4.1 Textural classification of soil samples collected from paddocks of HWRS

	Paddocks			
	D21	C5	D33	Yarramundi
Sand (%)	88.1	67.6	45.6	86.6
Silt (%)	6.0	18.0	29.5	9.0
Clay (%)	5.9	14.4	24.9	4.4
Texture class	Loamy sand	Loam	Silty loam	Loamy sand

4.2.2 Bulk density, moisture content, electrical conductivity and pH

Bulk density and moisture content was measured at field condition for all paddocks according to the method discussed in Section 3.3.5. Soil samples from all four paddocks were collected in triplicate and the summary of results of moisture content, bulk density, electrical conductivity and pH is shown in Table 4.2. More detailed results are shown in Table A2-A6, Appendix A. The field bulk density in D21, C5 and D33 paddocks were found to be close or within the usual range of 1100 to 1600 kg/m^3. However, bulk density for Yarramundi paddock showed higher value. This might be because of the reason that this paddock was never been irrigated or cultivated.

The field moisture content in paddocks, which is an indication of soil moisture available in upper part of the soil profile, ranged between 6% and 12%. As expected, coarse grained soil (such as D21 and Yarramundi) showed less moisture content compared to fine grained soil (C5 and D33). It should be noted that field moisture content is dependent on the occurrence of rain before or at the time of collection of the sample. In the case of this study, no rain occurred during the soil sampling.

Electrical conductivity of soil samples were measured in two methods (such as $EC_{1:5}$ and EC_e) as per Section 3.3.4. Electrical conductivity of 1:5 soil water ratio ($EC_{1:5}$) is a quick measure of soil salinity, practiced in the agricultural industry. On the other hand, electrical conductivity of saturated paste extract (EC_e) is a tedious method and requires laboratory facilities to conduct the test properly. Because of its simplicity in the process of determination, sometimes $EC_{1:5}$ are determined in the soil and converted to EC_e by multiplying by a pre-determined conversion factor. The EC_e values are important to understand the salinity tolerance of plants (NRMMC-EPHC-AMC 2006). As shown in Table 4.2 the ratio between EC_e and $EC_{1:5}$ varied from 6.8 to 13.75 for soils collected from the paddocks. This range was similar to the one reported in PIR-SA (2015).

pH was measured in 1:5 soil water solution as well as in saturated paste extract according to Section 3.3.7. As shown in Table 4.2, pH of saturated paste extract (pH_{SE}) was higher for all types of soil than pH of 1:5 soil water solutions.

Table 4.2 Bulk density, moisture content, electrical conductivity and pH of soil samples collected from paddocks of HWRS

D21 paddock

Parameters	Mean	Std. Dev.	CV (%)	Maximum	Minimum
Field moisture content (g/g)	0.06	0.01	18	0.07	0.05
Field Bulk Density (g/cm^3)	1.50	0.01	1	1.51	1.49
$EC_{1:5}$ (dS/m)	0.04	0.00	1	0.04	0.04
EC_e (dS/m)	0.55	0.01	2	0.56	0.54
$pH_{1:5}$	5.59	0.07	1	5.65	5.52
pH_{SE}	5.92	0.39	7	6.27	5.52

C5 paddock

Parameters	Mean	Std. Dev.	CV (%)	Maximum	Minimum
Field moisture content (g/g)	0.12	0.00	1	0.12	0.12
Field Bulk Density (g/cm^3)	1.47	0.03	2	1.50	1.43
$EC_{1:5}$ (dS/m)	0.05	0.00	0.4	0.05	0.05
EC_e (dS/m)	0.34	0.01	2	0.35	0.34
$pH_{1:5}$	5.49	0.14	3	5.58	5.33
pH_{SE}	7.01	0.04	1	7.04	6.97

D33 paddock

Parameters	Mean	Std. Dev.	CV (%)	Maximum	Minimum
Field moisture content (g/g)	0.09	0.00	4	0.10	0.09
Field Bulk Density (g/cm^3)	1.62	0.02	1	1.65	1.61
$EC_{1:5}$ (dS/m)	0.06	0.00	0	0.06	0.06
EC_e (dS/m)	0.82	0.08	10	0.90	0.71
$pH_{1:5}$	6.01	0.06	1	6.07	5.95
pH_{SE}	7.16	0.20	3	7.40	6.99

Yarramundi paddock

Parameters	Mean	Std. Dev.	CV (%)	Maximum	Minimum
Field moisture content (g/g)	0.06	0.00	2	0.06	0.06
Field Bulk Density (g/cm^3)	1.68	0.01	1	1.69	1.67
$EC_{1:5}$ (dS/m)	0.03	0.00	5	0.03	0.03
EC_e (dS/m)	0.28	0.01	4	0.29	0.27
$pH_{1:5}$	5.35	0.05	1	5.40	5.31
pH_{SE}	6.95	0.11	2	7.06	6.85

Note: All the results were averaged over three replicates of soil samples

4.2.3 Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_s) in soil samples was measured according to the method discussed in Section 3.3.3. Saturated hydraulic conductivity is an important measure of soil permeability used in water and solute transport modelling. The saturated hydraulic conductivity measured in the soil samples from paddocks are shown in Table 4.3; K_s values reported by different literature are also shown. The measured saturated hydraulic conductivity was compared with the output generated by a neural network code named Rosetta®, developed by US Salinity laboratory and implemented in HYDRUS 1D (Šimůnek et al. 2009). Rosetta implements pedotransfer functions (PTFs) which predict van Genuchten (1980) water retention parameters and the saturated hydraulic conductivity in a hierarchical manner from soil textural class information, such as sand, silt and clay percentage, and bulk density. Results from the Rosetta® are also shown in Table 4.3. As shown in Table 4.3, the measured values of K_s for soils from paddocks are close to the values reported in literature. Saturated hydraulic conductivities predicted by Rosetta® are close to the values determined experimentally, except for D33 paddock soil, which may be because of experimental error.

4.2.4 Soil water characteristic curve

Soil water characteristic curve for soil sample collected from HWRS was determined according to method described in Section 3.3.2. Soil samples in triplicate was analysed for each of the paddock soil. While detailed calculation is shown in Table A7 (a-d) of Appendix A, Figure 4.2 shows the average value of soil water characteristic curve of soil of each paddock.

From Figure 4.2 it is obvious that the soil water characteristic curve is strongly affected by soil texture. In general, the water retention at any particular suction is more with increasing clay content in soil sample (Hillel 1980). Similar observation can be made from Figure 4.2, where at suction 1, 3, 5, 10 and 15 bars the values of volumetric water content are in the order of D33 > C5 > Yarramundi > D21. The observation also conforms to the clay content of soils reported in Table 4.1. It should be noted that D21 and Yarramundi soils are almost similar in composition and texture. Therefore, same soil water characteristic curve was expected for these two soil samples. However, a slight anomaly in volumetric water content at suctions 3 and 5 bars might be because of the experimental error which includes determination of the volumetric water content. At low suctions, such as 0.1 and 0.33 bars, volumetric water contents are close for D21 and Yarramundi soils; the higher value of volumetric water content for C5 soil as compared to D33 at these suctions may be due to the error associated with the determination of volumetric water content. In practice, volumetric water content at suction 0.33 and 15 bars are significant as the values represent the field capacity and the permanent wilting point of soil, respectively. The difference in volumetric water contents corresponding to field capacity and permanent wilting point represents soil available water, which is an important parameter for irrigation scheduling.

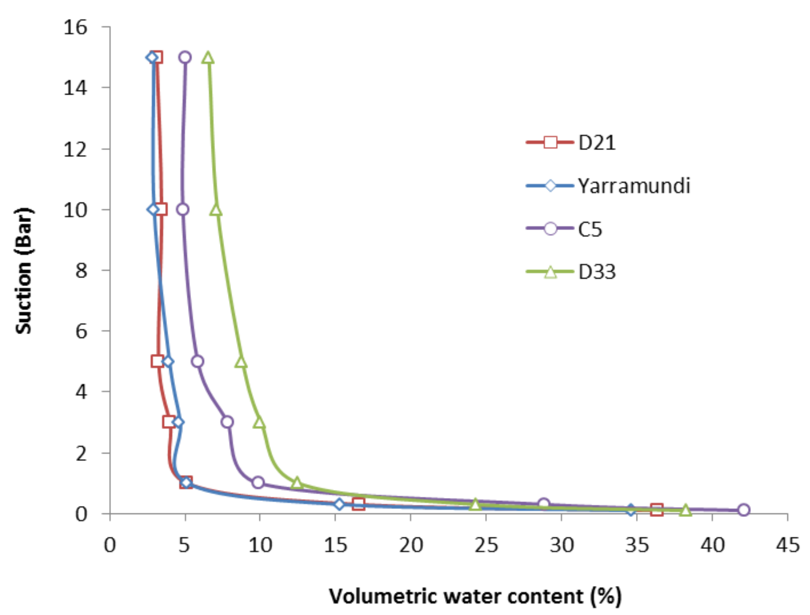


Figure 4.2 Soil water characteristic curve for soils collected from HWRS

Data obtained from soil water characteristic curve were used in RETC code (van Genuchten et al. 1991) to get the VG parameters. The VG parameters were estimated by Non-linear regression analysis using the RETC program. Results of three replicate analyses are shown in Table A8 (a-d) of Appendix A. Table 4.3 shows the summary of the results along with values of VG parameters reported in different literature. As shown in Table 4.3, the determined values of θ_r, θ_s, α, and n for soils from the paddocks are generally very close to the literature reported values; however, the difference may be because of the varied composition of the sand, silt and clay percentage in the individual soil (Gonçalves et al. 2001).

Table 4.3 van Genuchten (1980) hydraulic function parameters for different types of soil

Soil type	VG parameters				K_s (cmd^{-1})	Reference
	θ_r (cm^3cm^{-3})	θ_s (cm^3cm^{-3})	α (cm^{-1})	n (-)		
Sandy	0.021-0.065	0.39-0.48	0.015-0.028	1.52-4.33	39-1218	Vanderborght et al. (2001)
Sandy loam	0.049-0.063	0.37-0.42	0.003-0.007	1.04-2.57	39.1-74.4	
Silty loam	0.075-0.123	0.398-0.417	0.001-0.002	0.55-0.80	1.2-7.9	
Loam	0.001	0.4	0.011	1.29	38.0	
Sandy loam	0.000-0.108	0.372-0.380	0.027-0.245	1.146-1.205	16.6-84.4	Barão et al. (2010)
Silty loam	0.000	0.378	0.141	1.135	42.0	
Loam	0.000	0.332-0.375	0.045-0.079	1.169-1.188	42.0-101.6	
Silty loam	0.050-0.108	0.427-0.428	0.029-0.108	1.16-1.21	18.2-99.3	Gonçalves et al. (2006)
Loam	0.000	0.373	0.040	1.15	21.4	
Loamy sand (D21)	0.031-0.034	0.383-0.429	0.005-0.007	2.589-3.000	*229.7±71.6 (272.2)	This study
Loamy sand (Yarramundi)	0.033-0.035	0.410-0.418	0.006-0.007	2.302-2.608	290.3±72.8 (245.0)	
Loam (C5)	0.048-0.056	0.426-0.468	0.003-0.005	2.213-2.516	72.5±9.4 (62.36)	
Silty loam (D33)	0.039-0.075	0.451-0.504	0.005-0.013	1.547-2.365	38.6±4.8 (9.48)	

Note:
*mean ± standard deviation
The bracketed K_s shows values predicted by Rosetta®

4.2.5 Soluble and exchangeable cations

Soluble and exchangeable cations were measured in soil samples before using the soils in the column studies. Soluble cations (Table 4.5) including Na^+, K^+, Ca^{2+} and Mg^{2+} were measured in the pore water (saturated paste extract) of soil according to the method described in Section 3.3.6. Subsequently, sodium adsorption ratio (SAR) was calculated using Equation 2.1. For the determination of exchangeable cations (Table 4.6), procedure described in Section 3.3.6, were used. The values reported in Tables 4.4 and 4.5 are important to establish the initial condition of the column study. Especially, for a particular paddock soil, the initial values of dissolved cations present in the soil will be compared with soil sample collected from different depths of the soil profile at the end of the column study; subsequently a salinity profile will be depicted. The salinity profile in soil column helps to understand salt accumulation process, especially, in the root zone soil and helps to devise sustainable measure to control salinisation. Moreover, initial values of soluble cations reported in Table 4.5 were used to compare with samples collected at the end of the column study and focused on the amount of cations retained in the soil due to recycled water irrigation.

Table 4.4 Major soluble cations and SAR in soil samples collected from paddocks of HWRS before using in column studies

Paddock	Na^+ [1]mmol(c)/L	Ca^{2+} mmol(c)/L	Mg^{2+} mmol(c)/L	K^+ mmol(c)/L	SAR
Yarramundi	0.497	0.258	0.158	0.502	1.09
D21	1.170	0.288	1.509	0.563	1.23
D33	1.319	0.135	1.406	0.976	1.50
C5	0.718	0.050	0.666	0.629	1.20

[1]mmol (c)/L is similar to milliequivalent/L

Table 4.5 Exchangeable cations and CEC in soil samples collected from paddocks of HWRS before using in column studies

Paddock	Na^+ cmol(c)/kg	Ca^{2+} cmol(c)/kg	Mg^{2+} cmol(c)/kg	K^+ cmol(c)/kg	CEC
Yarramundi	0.001	0.277	0.030	0.047	0.355
D21	0.005	0.042	0.095	0.030	0.172
D33	0.055	1.089	0.188	0.046	1.378
C5	0.003	0.412	0.076	0.042	0.533

4.3 Determination of soil solution electrical conductivity from bulk electrical conductivity in soil samples collected from HWRS

Soil solution electrical conductivity (EC_{SW}) was determined from bulk electrical conductivity (EC_{bulk}) and permittivity (ε) (measured by GS3 sensor) for different volumetric water content (θ). The procedure of this method is described in Section 3.4. Relationship among soil water electrical conductivity, bulk electrical conductivity and volumetric water content was reported by different researchers (Rhoades et al. 1976; Rhoades et al. 1989; Amente et al. 2000; Noborio 2001; Vogeler et al. 1996). However, relationship among EC_{SW}, EC_{bulk}, θ and ε in soil, specific to the study area, ascertain more reliability in a *real-time monitoring system*. The relationships among the above mentioned four parameters were calculated in two steps:

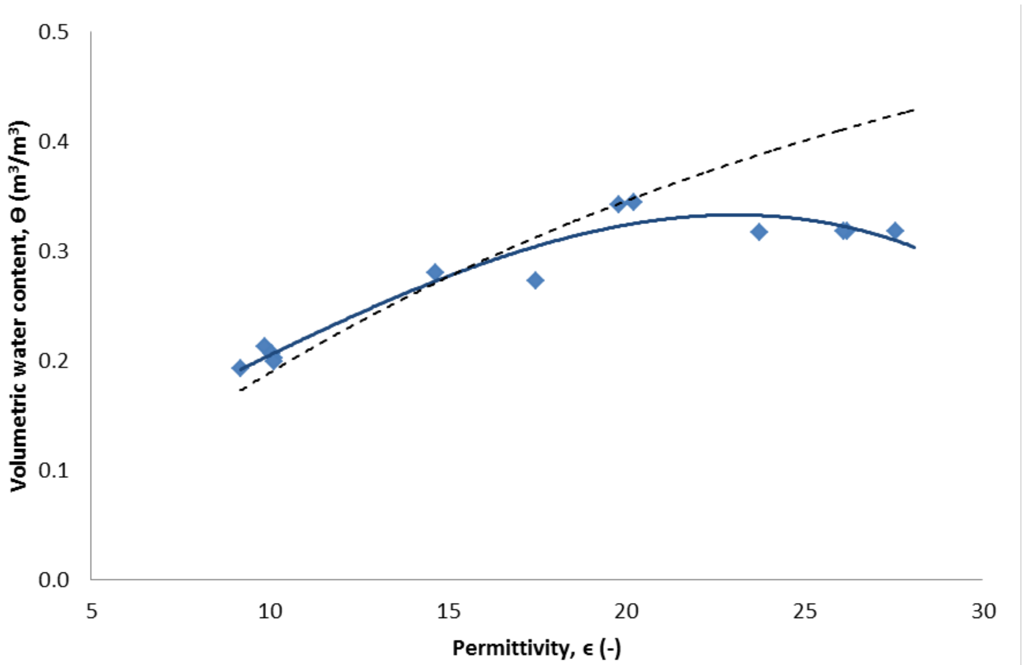
- Determination of an empirical calibration equation to calculate volumetric water content from sensor measured permittivity;
- Determination of a regressed equation to calculate soil water electrical conductivity from volumetric water content and bulk electrical conductivity.

Detailed results from the calibration study for four soil samples are shown in Table A9 (a-d), Appendix A, however, summarised in this section.

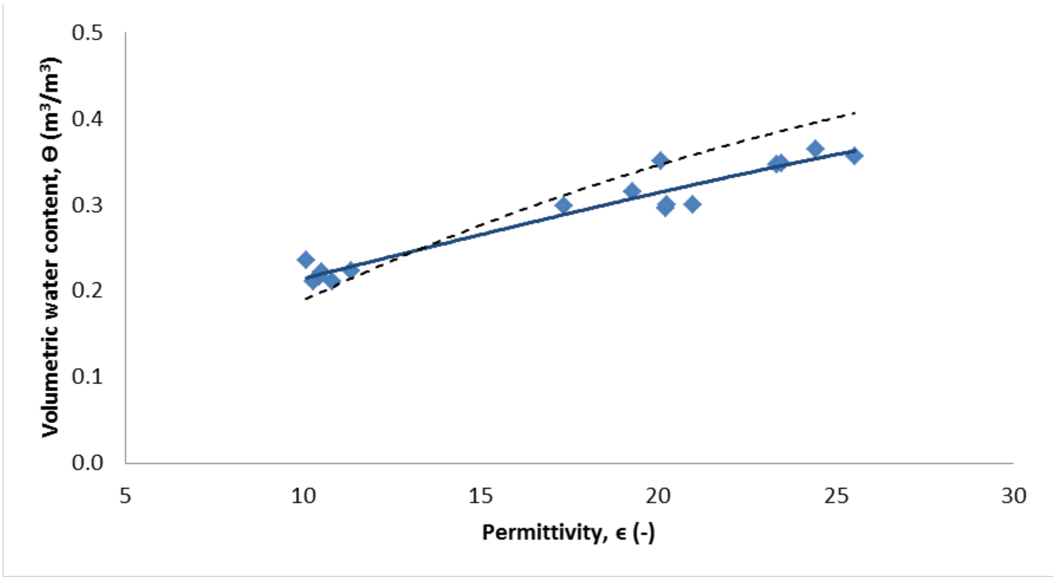
4.3.1 Determination of calibration equation to calculate θ from ϵ

Results of the calibration of volumetric water content for D21 and Yarramundi paddock soils are shown in Figure 4.3, where GS3 sensor measured permittivity (ε) is plotted against gravimetrically determined volumetric water content (θ). As shown in Figure 4.3, the calibration curve for D21 and Yarramundi soil are almost similar to each other (both were constructed within the close range of average VWC, which is 0.22-0.33 m^3/m^3 for D21 soil and 0.22-0.35 m^3/m^3 for Yarramundi soil). This is expected because in terms of mechanical texture, these two types of soil are similar (Table 4.1) and should show similar value of VWC for a given permittivity; however, at higher permittivity values, the behavior appears to be different. Calibration results for soil from D33 and C5 paddocks are shown in Figure 4.4.

It can be observed from Figure 4.4 that calibration curve for D33 soil was constructed for the average VWC of 0.36 to 0.43 m^3/m^3. Similarly, for C5 soil, the average VWC ranged between 0.25 and 0.36 m^3/m^3. It was intended to maintain same VWC for all soil types in developing the calibration curves shown in Figures 4.3 and 4.4. However, it was not possible for D33 soil. At low VWC water content (i.e. 0.2-0.3 m^3/m^3), no water could be extracted even when the suction was applied over a longer time. This is supported by the results obtained from soil water characteristic curve of soil samples (Figure 4.2), which shows at a given suction, D33 soil retains more water than the other three soil samples. Therefore, during the calibration studies described in this section, higher VWCs were maintained to calibrate D33 soil as compared to D21, Yarramundi and C5 soil samples

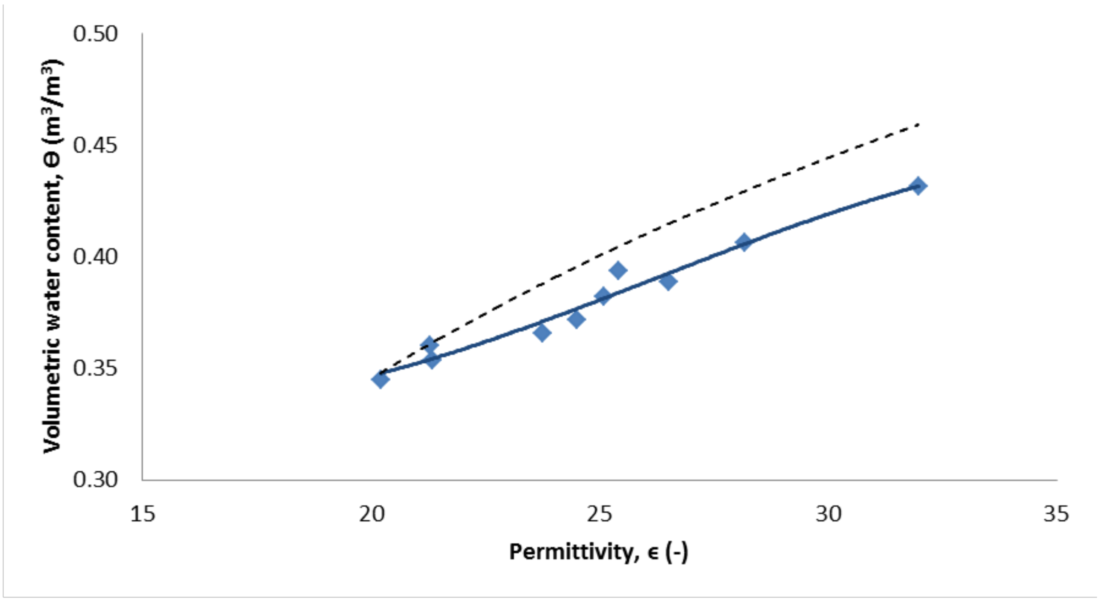


(a)

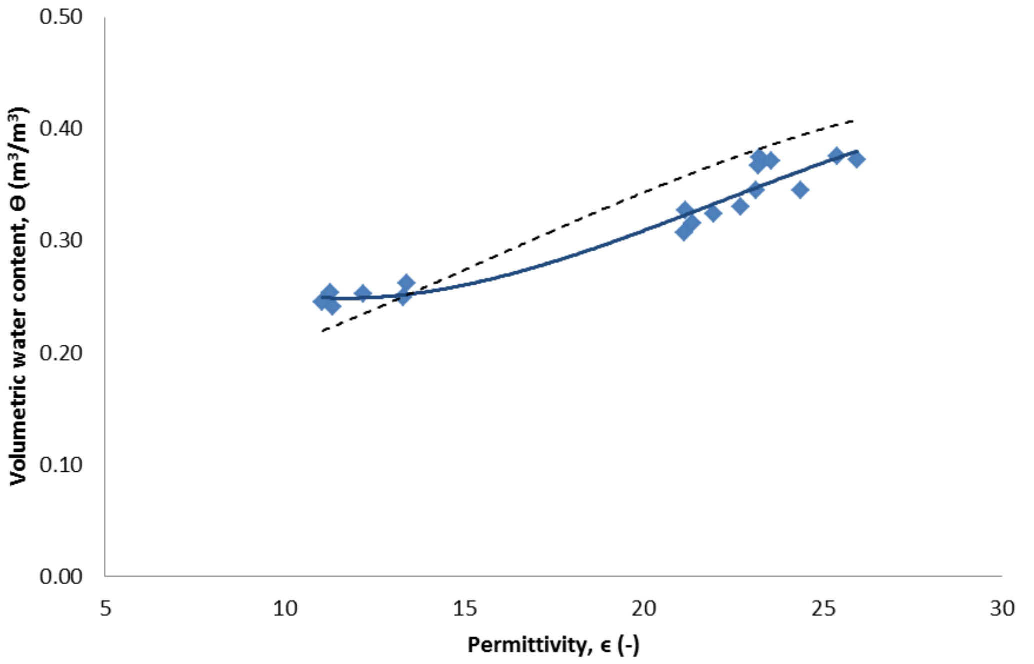


(b)

Figure 4.3 Relationship between gravimetrically determined water content and GS3 recorded permittivity for *(a)* D21 paddock and *(b)* Yarramundi paddock soil. The solid line shows the fitted quadratic function and the broken line shows the empirical relationship suggested by Topp et al. (1980).



(a)



(b)

Figure 4.4 Relationship between gravimetrically determined water content and GS3 recorded permittivity for *(a)* D33 paddock and *(b)* C5 paddock soil. The solid line shows the fitted quadratic function and the broken line shows the empirical relationship suggested by Topp et al. (1980).

Empirical calibration curves were obtained, to determine θ from ε, by fitting quadratic functions to the data of four soil samples (Figures 4.3 and 4.4), which are:

For D21 soil:

$$\theta = -2.0 \times 10^{-5}\varepsilon^3 + 5.0 \times 10^{-4}\varepsilon^2 + 1.23 \times 10^{-2}\varepsilon + 5.26 \times 10^{-2}$$

$$R^2 = 0.95 \quad (4.1)$$

For Yarramundi soil:

$$\theta = -3.0 \times 10^{-6}\varepsilon^3 + 9.0 \times 10^{-5}\varepsilon^2 + 9.4 \times 10^{-3}\varepsilon + 11.43 \times 10^{-2}$$

$$R^2 = 0.93 \quad (4.2)$$

For D33 soil:

$$\theta = -2.0 \times 10^{-5}\varepsilon^3 + 1.9 \times 10^{-3}\varepsilon^2 - 4.27 \times 10^{-2}\varepsilon + 6.24 \times 10^{-1}$$

$$R^2 = 0.97 \quad (4.3)$$

For C5 soil:

$$\theta = -4.0 \times 10^{-5}\varepsilon^3 + 2.5 \times 10^{-3}\varepsilon^2 - 4.32 \times 10^{-2}\varepsilon + 4.706 \times 10^{-1}$$

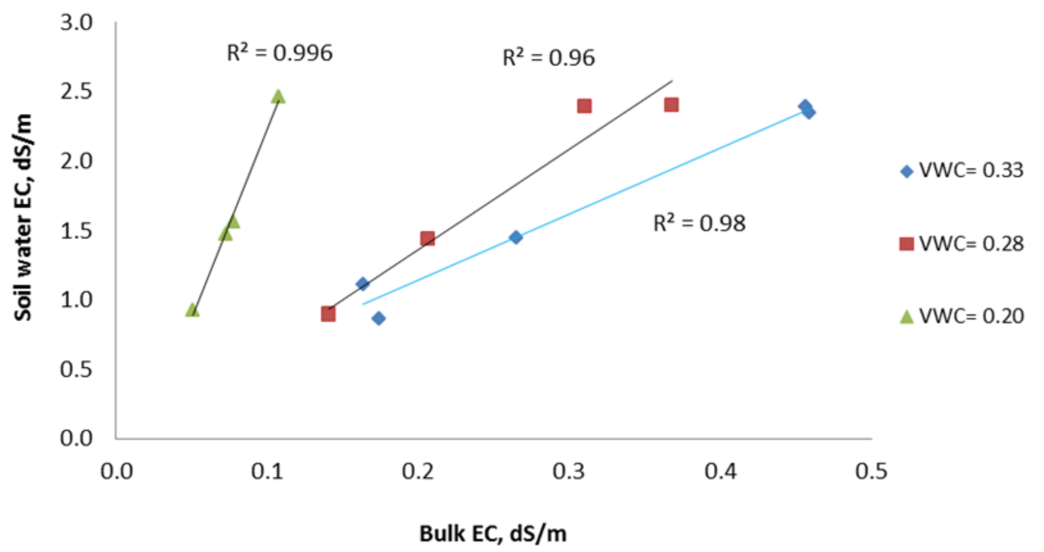
$$R^2 = 0.94 \quad (4.4)$$

These evaluated empirical relationships deviate from the relationship suggested by Topp et al. (1980) (Equation 2.3) by a maximum value of 0.1 m^3m^{-3} for all soil samples. The Topp et al. (1980) equation is also shown in Figures 4.3 and 4.4 (broken line). The deviations by similar magnitudes were also observed by Vogeler et al. (1996), which might be due to the difference in soil texture including bulk density, clay content and organic matter present in the soil. Equations 4.1-4.4 will be used in the *real-time monitoring system* to quantify volumetric water content from sensor measured permittivity for soils from D21, Yarramundi, D33 and C5 paddock, respectively (Chapters 5, 6 and 7). The Equations were developed because of its more accurate estimation, as was constructed with site specific soil.

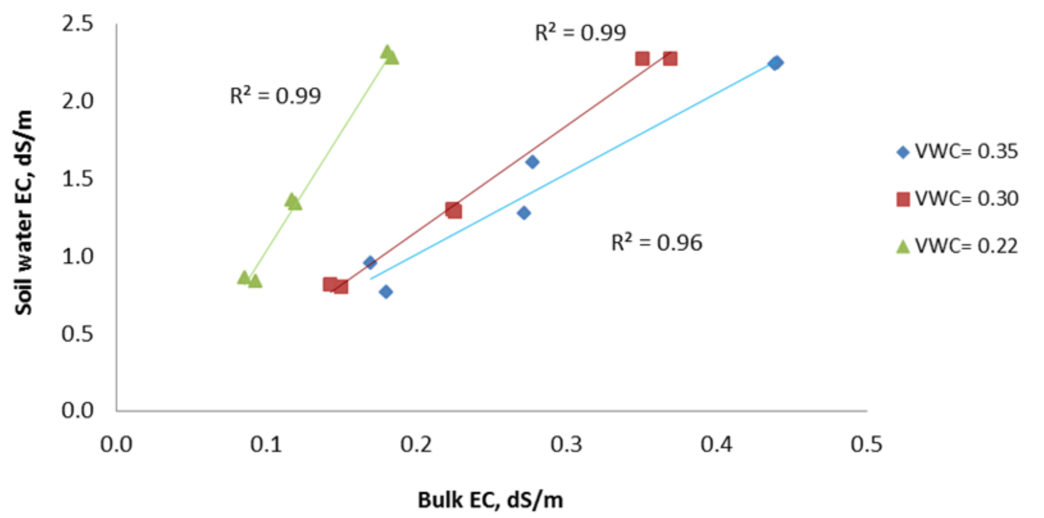
4.3.1 Determination of EC_{SW} from EC_{bulk}

Results of the soil water calibration for the D21 and Yarramundi soil are shown in Figure 4.5, where the electrical conductivity of soil water is plotted against GS3 sensor measured bulk electrical conductivity for different volumetric water contents. Soil water calibration results for D33 and C5 soil are presented in Figure 4.6. The solute concentration calibration is needed because the electrical conductivity of the soil water changes from that of added water when mixed with soil (Vogeler et al. 1996).

Generally, for all analysed soil samples (Figures 4.5 and 4.6), soil water electrical conductivity changed linearly with bulk electrical conductivity for given volumetric water content. From the results of calibration study, a regressed equation (Table 4.6) was developed for predicting EC_{SW} from sensor measured EC_{bulk} and gravimetrically determined VWC data for each soil sample. There are reported relationship among EC_{SW}, EC_{bulk} and VWC (Vogeler et al. 1996; Nadler 1997; Muñoz-Carpena et al. 2005); however site specific relationship among these parameters provided further accurate estimation of EC_{SW}.

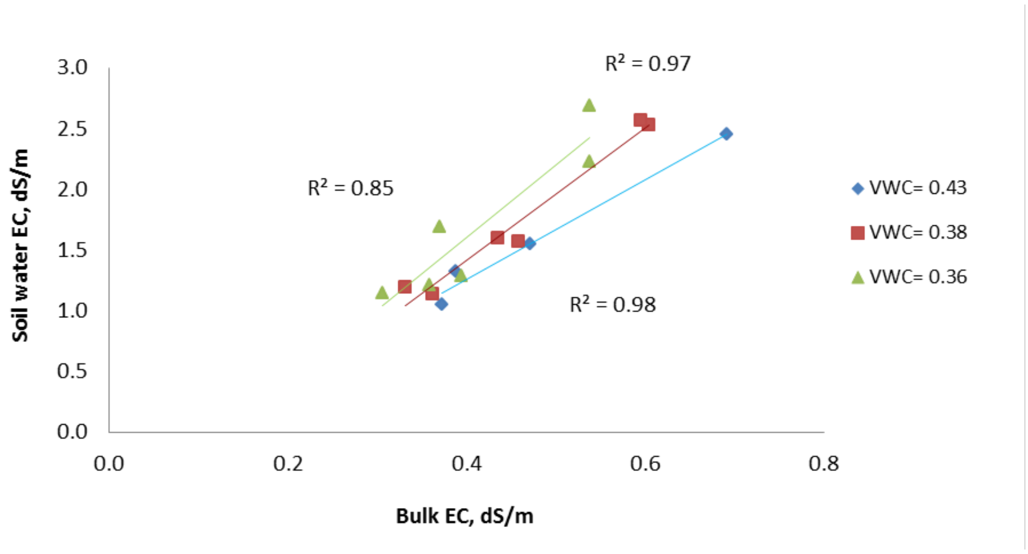


(a)

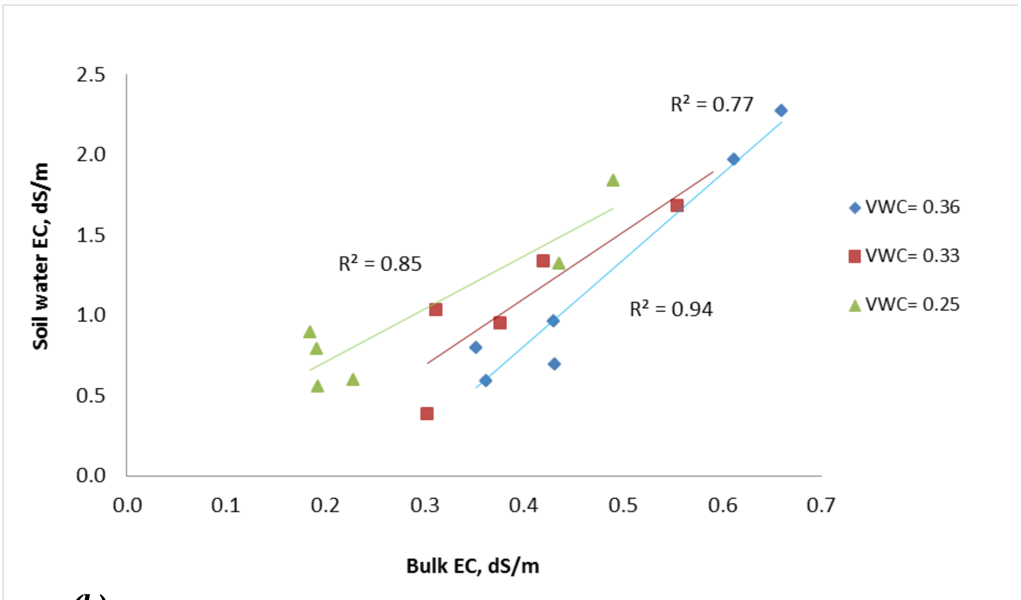


(b)

Figure 4.5 Relationship between soil water electrical conductivity and the GS3 sensor measured bulk electrical conductivity for different volumetric water content for *(a)* D21 paddock and *(b)* Yarramundi paddock soil. Fitted relationships are shown in solid line.



(a)



(b)

Figure 4.6 Relationship between soil water electrical conductivity and the GS3 sensor measured bulk electrical conductivity for different volumetric water content for *(a)* D33 paddock and *(b)* C5 paddock soil. Fitted relationships are shown in solid line.

Table 4.6 Regressed equation to determine EC_{SW} from EC_{bulk} *in s*oil samples collected from paddocks of HWRS

Soil sample	Equation regressed from calibration data	p-value	R^2	MAE	RMSE	BIAS
D21	$EC_{SW} = -4.40 + 6.56 \times EC_{bulk} - 3.59 \times Log_e(\theta)$	<0.0001 <0.0001	90.2	0.16	0.19	2.10
Yarramundi	$EC_{SW} = -2.78 + 6.51 \times EC_{bulk} - 2.24 \times Log_e(\theta)$	<0.0001 <0.0001	84.0	0.17	0.19	2.80
D33	$EC_{SW} = -2.18 + 4.65 \times EC_{bulk} - 1.83 \times Log_e(\theta)$	<0.0001 0.034	91.1	0.13	0.16	1.47
C5	$EC_{SW} = -1.82 + 3.59 \times EC_{bulk} - 1.31 \times Log_e(\theta)$	<0.0001 0.003	82.4	0.16	0.18	2.98

Results of goodness of fit indices as mentioned in Section 3.7 are determined for regressed equation of each paddock soil and shown in Table 4.6. The p-value of both predictor variables i.e. EC_{bulk} and θ of the regressed equation is close to zero. The low p-value suggests the predictors as a meaningful entity in the regression equations (Table 4.6). The regressed EC_{SW} were found to be highly correlated with experimental EC_{SW}, which is shown by correlation coefficient, R^2. Other indices including MAE and RMSE show satisfactory agreement between experimental and regressed values. However, the regressed EC_{SW} determined for soil samples underestimate the experimental EC_{SW} by 2-3%, which is indicated by BIAS as shown in Table 4.6.

Equations presented in Table 4.6 were used in the *real-time monitoring system* to quantify soil water electrical conductivity from the sensor measured bulk electrical conductivity for the soils taken from D21, Yarramundi, D33 and C5 paddock, respectively (Chapters 5, 6 and 7).

CHAPTER 5

SALT ACCUMULATION IN SOIL UNDER DROUGHT CONDITION

This chapter is partial reproduction of the following two journal papers:

Paper 1

[1]Rahman, M.M., Hagare, D., [2]Maheshwari, B. and [3]Dillon, P. (2014). Continuous real-time monitoring of salt accumulation in the soil due to recycled water irrigation. Water 41 (1), 63-68 (ERA 2010 ranked paper)

[1] School of Computing, Engineering and Mathematics, Western Sydney University, Australia
[2] School of Science and Health, Western Sydney University, Australia
[3] CSIRO Land and Water, Australia

Paper 2

[1]Rahman, M.M., Hagare, D., [2]Maheshwari, B. and [3]Dillon, P. (2015). Impacts of prolonged drought on salt accumulation in the root zone due to recycled water irrigation. Water, air & soil pollution, 226:90, (Impact factor 1.685)

[1] School of Computing, Engineering and Mathematics, Western Sydney University, Australia
[2] School of Science and Health, Western Sydney University, Australia
[3] CSIRO Land and Water, Australia

5.1 Introduction

Abiotic stresses such as drought and salinity affect the plant growth and crop production (Wang et al. 2003). The probable reason for this growth reduction is water deficiency or osmotic effects imposed by drought and salinity by reducing the soil water potential (Hu and Schmidhalter 2005). Under the drought conditions, the expected rainfall fails to occur at the right time, which causes loss of soil moisture, surface runoff and groundwater recharge. Drought in Australia is a recurring phenomenon, with the most recent occurrence between 2000 and 2006 (also called 'millennium drought') (Bond et al. 2008). While different research focused on the impact of this drought period on groundwater-surface water interaction (Tweed et al. 2009), freshwater ecosystems (Bond et al. 2008) and fluctuations of water table in irrigation areas (Khan et al. 2008), there have been limited studies looking at the impact of prolonged droughts on salt accumulation in root zone due to recycled water irrigation. In this chapter, impact of prolonged drought period on salt accumulation in the D21 paddock soil of HWRS was investigated. This chapter is based on two journal papers, which are listed above.

5.2 Methodology

The chapter starts with understanding the salt accumulation and spatial distribution of salinity in the D21 column soil profile, which includes:

- The conventional method comprising water and salt mass balance, and the relationship of leaching fraction with salt build-up in the soil profile; and
- The real-time monitoring method showing spatial distribution of salinity at two different depths (0.1m and 0.35m) of the soil profile.

The detailed procedure of the operation of the column study is described in Section 3.5.4.1. As discussed in Section 3.5.4.1, the first part of the column experiment was conducted under no rain condition and the second part under simulated rain condition. Results from the first 103 days of column operation under no rain condition are presented in this chapter (daily observation of the column study is shown in Table B1 (a-c) of Appendix B). The same results are used to validate the HYDRUS 1D model. The validated HYDRUS 1D model was then used to predict salt accumulation in the root zone soil of the D21 paddock in the field condition when recycled water irrigation is practiced over a long period of time, say 5 years, under drought condition.

5.2.1 Mass balance of water and salt

The amount of irrigation water applied (L) and leachate (L) collected at the bottom of the soil column after each application of irrigation water, were recorded as per Section 3.5.4.1. Subsequently, cumulative amount of applied and leached water (L) was calculated over the study period of 103 days. Amount of applied irrigation water as well as irrigation scheduling was same for all three columns.

The cumulative mass of leached salt (g/m^2) was calculated by multiplying total dissolved solids (TDS) in the leached water (g/m^3) by the amount of leached water (m). Salt concentration in the leached water was measured in terms of electrical conductivity (dS/m) and converted to TDS by using a multiplication factor of 640 (Stevens et al. 2008; Tchobanoglous and Burton 1991).

The leaching fraction was determined by dividing the depth of water leached from the soil column (mm) by the depth of water applied at the surface (mm) (Richards 1954).

5.2.2 In-situ extracted and in-situ sensor measured soil water electrical conductivity

In this chapter, the terms ‘in-situ extracted’ and ‘in-situ sensor measured’ soil water electrical conductivity are used in many occasions, such as in Section 5.5.4. A brief narration of these two terms is helpful to understand the content of this chapter. The soil water that was extracted by soil water sampler at depths 0.1 and 0.35 m are denoted here as ‘in-situ extracted soil water’ and the electrical conductivity of the soil water as in-situ extracted electrical conductivity ($EC_{SW\ (in\ situ)}$). The process of extracting the $EC_{SW\ (in\ situ)}$ is discussed in Section 3.5.4.1. On the other hand, electrical conductivity of soil water converted from sensor measured EC_{bulk} is denoted as in-situ sensor measured electrical conductivity ($EC_{SW\ (sensor)}$). The development of equation used to convert EC_{bulk} to $EC_{SW\ (sensor)}$ for D21 paddock soil is discussed in Section 4.3; the equation for D21 paddock soil is presented in Table 4.6. The equation in Table 4.6 for D21 paddock soil was used to convert EC_{bulk}, to $EC_{SW\ (sensor)}$ in this chapter.

5.3 Salt mass balance as an indicator of salt accumulation

Mass balance calculation of solute in a soil profile provides general information regarding accumulated salt in the profile. The results presented in this section aid an understanding of the general trend of salt accumulation in the soil profile without considering the specific depth.

For a proper understanding of salt build-up in the soil profile knowledge of water balance including amount of incoming and outgoing water from the soil profile is important. Figure 5.1 shows volume of applied irrigation water and water leached during the first 103 days of study period. At the end of 103 days, 20% of applied water leached through the soil profile. Amount of water leached from individual columns is shown in Figure 5.6. It should be noted that the water stored in the soil profile was not calculated because of the lack of information on water evaporated from the columns.

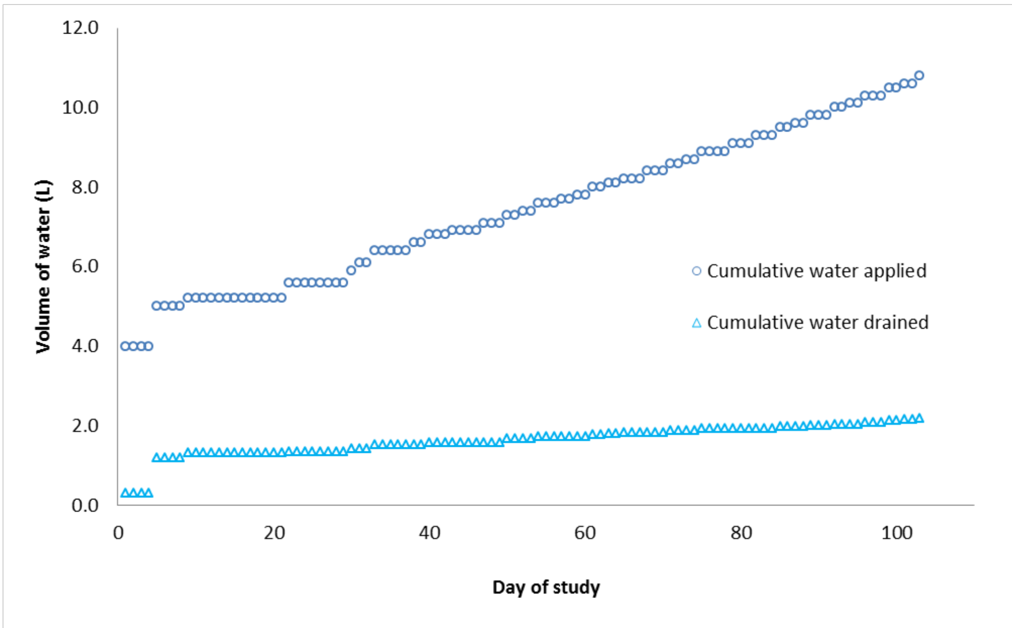


Figure 5.1 Cumulative water applied and water leached from the column profile (averaged over the results from three columns).

Figure 5.2 shows applied, stored and leached salt loads during the study period. Leached salt load was calculated according to Section 5.2.1. Leached salt load from all three columns varied with a standard deviation of 0.4 to 2.7 g/m^2, except for the first day, which was 6.9 g/m^2 (results not shown). This variation in the leaching of salt can be attributed to variations in the packing of the columns. Throughout the study period, the total cumulative leached salt mass (averaged for three columns) was significantly less than the total cumulative applied salt mass (Figure 5.2). Thus, the total cumulative salt mass stored in the soil profile showed an increasing pattern. Variation of leached salt load from individual columns is shown in Figure 5.7.

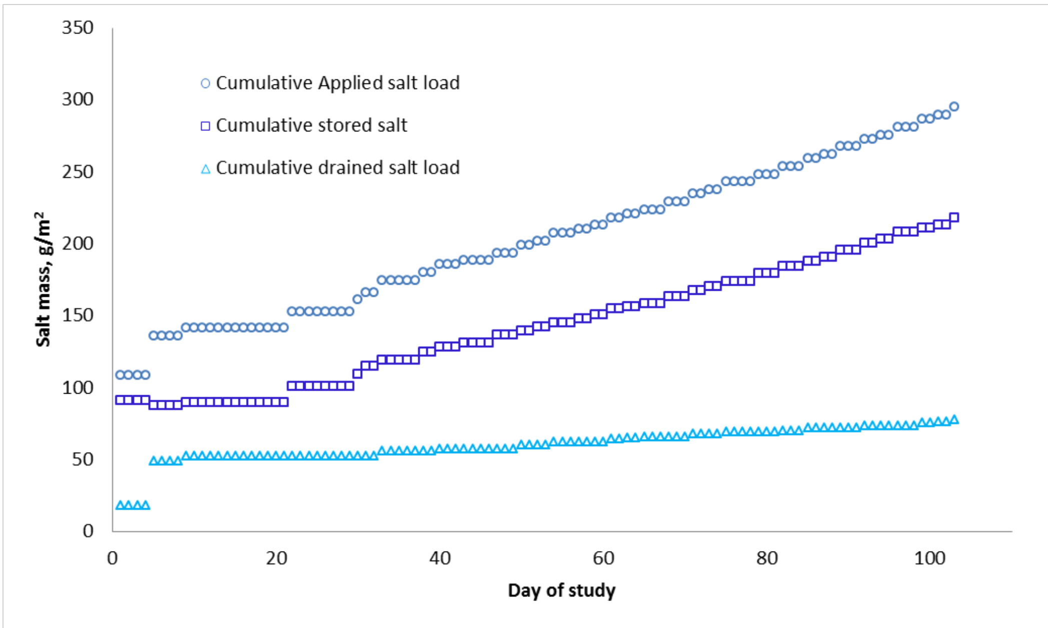


Figure 5.2 Cumulative salt mass applied, salt mass leached and salt mass stored in the column profile (averaged over the results from three columns).

Leaching of salt is considered one of the irrigation management options by field managers (Corwin et al. 2007). Conventionally, in the field, leaching fraction (LF) is used to calculate the salt buildup in the soil (Duan et al. 2011). Figure 5.3 is constructed with results from the first 103 days of column operation. The salt mass stored in the soil profile (g/m^2) and LF was calculated according to Section 5.2.1 on daily basis. Results from the column study shows a strong correlation (R^2 = 0.95) between salt accumulation in the soil profile and leaching fraction, which is shown in Figure 5.3. Results from Figure 5.3 show that the salt build-up in the soil profile decreased with increasing LF. A similar observation was reported by Corwin et al. (2007) and Duan et al. (2011). However, no correlation equation between these two variables (i.e. salt build-up and LF) was proposed because LF is not the only parameter associated with salt build-up in a soil profile; other factors such as evapotranspiration and rainfall are important and may impact the calculation of salt accumulation in a soil profile.

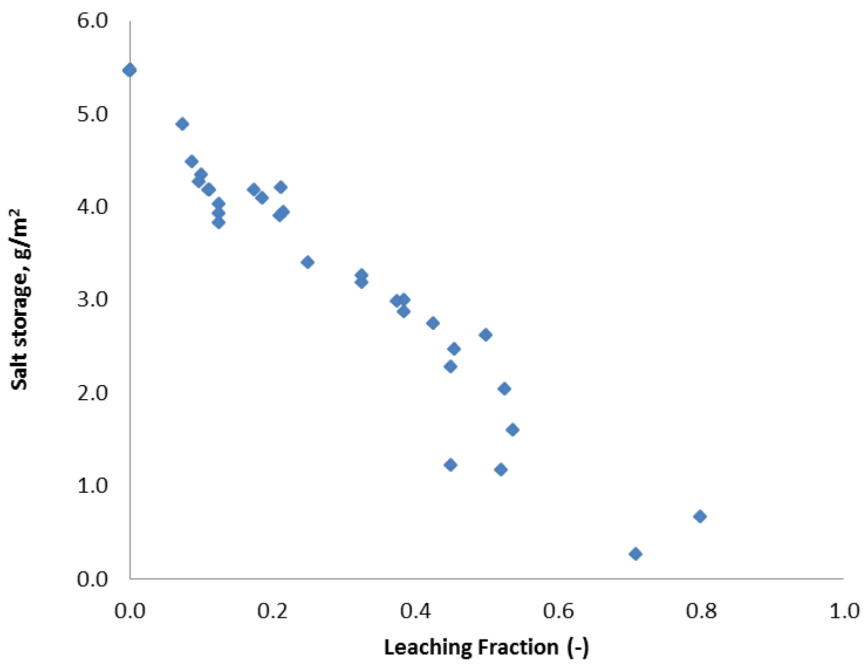


Figure 5.3 Controlling salt build-up in soil profile by leaching fraction

5.4 Continuous real-time monitoring of salt accumulation

In the previous section, the salt mass balance provided a picture of salt accumulation in the soil profile. Data recorded from the sensors are more useful in monitoring salt accumulation at different depths, which is presented in this section (daily observation is shown in Table B2 of Appendix B).

Results of bulk electrical conductivity measured by GS3 sensors at the depths of 0.1 and 0.35 m are presented in Figure 5.4. The fluctuation of EC_{bulk} was strongly influenced by applied irrigation water and thus by volumetric water content (VWC). As shown in Figure 5.4, initially (up to day 9), relatively higher amount of recycled water were applied. These higher applications were required to soak the soil in the column, after which the columns were kept dry for 13 days. This period helped to understand more clearly the impact of drying and wetting of columns and its subsequent effect on spatial and temporal variation of bulk electrical conductivity (Figure 5.4).

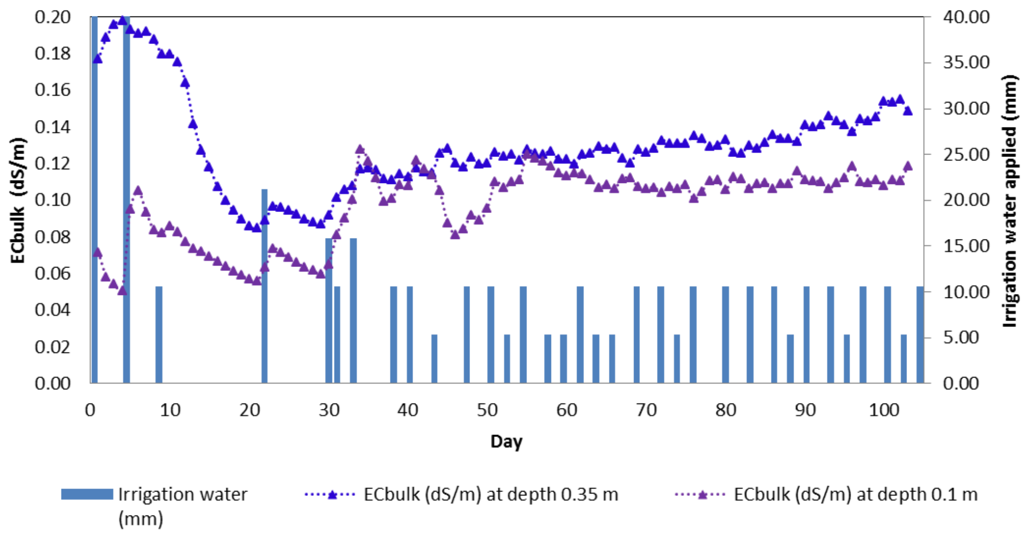


Figure 5.4 **Dependency of EC_{bulk} on volumetric water content**

The measured EC_{bulk} was dependent on VWC (also discussed in Section 3.4). The EC_{bulk} increased when the VWC increased and vice-versa. This can be observed in Figure 5.4. As shown in the figure, during the initial stages when the irrigation water was not applied, there is significant decrease in the EC_{bulk}. As such, EC_{bulk} is not a proper representative of salt accumulation in the soil. Therefore, EC_{bulk} was converted to soil water electrical conductivity for different VWC (in a manner discussed in Section 5.2.2), which is a more acceptable measure of soil salinity (Malicki and Walczak 1999).

5.5 Validation of HYDRUS 1D model with continuous column study result

In this section, the capability of HYDRUS 1D for the prediction of water flow and salt accumulation in the soil profile is explained. The model was used to predict leachate amount and leached salt load from the soil column. In addition, spatial variation of VWC and soil water electrical conductivity were predicted using HYDRUS 1D and validated using observed data. HYDRUS 1D has been validated by several past researchers (Kanzari et al. 2012; Ramos et al. 2011; Sutanto et al. 2012; Sarmah et al. 2005) with generally satisfactory outcome. In some studies

HYDRUS 1D was calibrated by inverse modelling (Kanzari et al. 2012; Sutanto et al. 2012) with observed data from part of the study period. Through inverse modelling soil hydraulic modelling parameters were obtained which were used for validating the model in combination with the observed data of the rest of the study period. However, in this study, soil hydraulic or water flow parameters were determined in the laboratory (Section 4.2.4, Table 4.3) and used in the HYDRUS 1D model.

5.5.1 Model parameters of HYDRUS 1D

The input parameters required by the HYDRUS 1D model were collected from different sources. The model requires input parameters such as physical, hydrological and solute transport characteristics of soil profile, daily standard meteorological data as well as water stress parameters for root water uptake. The input parameters are summarised in Table 5.1. Physical characteristics of the soil such as textural analysis (McDonald and Isbell 2009) and saturated electrical conductivity (EC_e) were determined in the laboratory. Bulk density was measured at the time of packing the columns. Water flow parameters were evaluated by fitting laboratory measured soil water characteristics data using the RETC software package (van Genuchten et al. 1991). The soil water characteristics curve was evaluated by pressure plate method (ASTM 2002). Detailed results of above mentioned physico-chemical and water flow parameters of D21 paddock soil are discussed in Chapter 4. Solute transport parameters were collated from literature and are given in Table 5.1. Initial and boundary conditions are discussed in detail in Section 3.6.1.1.

Some of the important input parameters for HYDRUS 1D for transient modelling of salt transport are time dependent boundary conditions (Upper BC for water flow modelling in Table 5.1) including, precipitation, evaporation and transpiration. For the column study, time variable boundary conditions (Section 3.6.1.1.2) were determined from meteorological parameters measured in the laboratory. Daily values of potential evaporation (ET_0) were calculated using Penman-Monteith method by HYDRUS 1D (Šimůnek et al. 2009). Daily values of ET_0 were in the range of 0.7-1.0 mm/day (Figure 5.5). Generally, there was not much variations in the minimum (18 to 23^{0}C) and maximum (19.6 to 24.9 ^{0}C) temperatures. A significant variation in the relative humidity was observed, which ranged from 30 to 60%. The wind speed in the laboratory depends on the flow from the air conditioner, working between 6 am and 6 pm over the 5 working days (Monday – Friday). During the weekend, the air-conditioner was not running. Irrigation scheduling included applying recycled water three times per week (Figure 5.4). In the first nine days, 270 mm of recycled water was applied. On an average, 97.2 mm of irrigation water was applied per month.

Table 5.1 Input parameters of HYDRUS 1D model for modelling salt accumulation in columns with soil from D21 paddock.

Description	Value
Depth of soil in the column	47 cm (length unit in 'cm')
Modelling period	103 days (time unit in 'days')
Modelling type	Water flow modelling Solute transport modelling
Iteration criteria	Maximum number of iterations = 20 Water content tolerance = 0.0001
Hydraulic Model	VG-Mualem
Soil type	Loamy sand: Sand = 88.1%, Silt = 6.0%, Clay = 5.9%
Bulk Density	1511 kg/m^3
Water flow Parameters	θ_r = 0.03 m^3/m^3, θ_s = 0.41 m^3/m^3, α = 0.006, n = 2.771, K_s = 264.85 cm/day
Longitudinal Dispersivity	1.3 cm^{-1} (Vanderborght and Vereecken 2007)
Profile discretisation	Number of nodes 101
Initial condition	θ = 0.09 m^{3}m^{-3}, EC_{SW} = 2*EC_e (Ayers and Westcot 1985; Stevens et al. 2008), EC_e=0.375 dS/m
Water flow boundary condition (BC)	Upper BC: Atmospheric with surface layer Lower BC: Free drainage
Solute transport boundary condition (BC)	Upper BC: Concentration flux Lower BC: Zero gradient concentration
Type of transport model	Equilibrium model
Molecular diffusion coefficient in free water	1.75 cm^2/day (James and Rubin 1986)
Irrigation water EC	0.83 dS/m
Meteorological parameter	Recorded in Laboratory
Root water uptake	Not considered

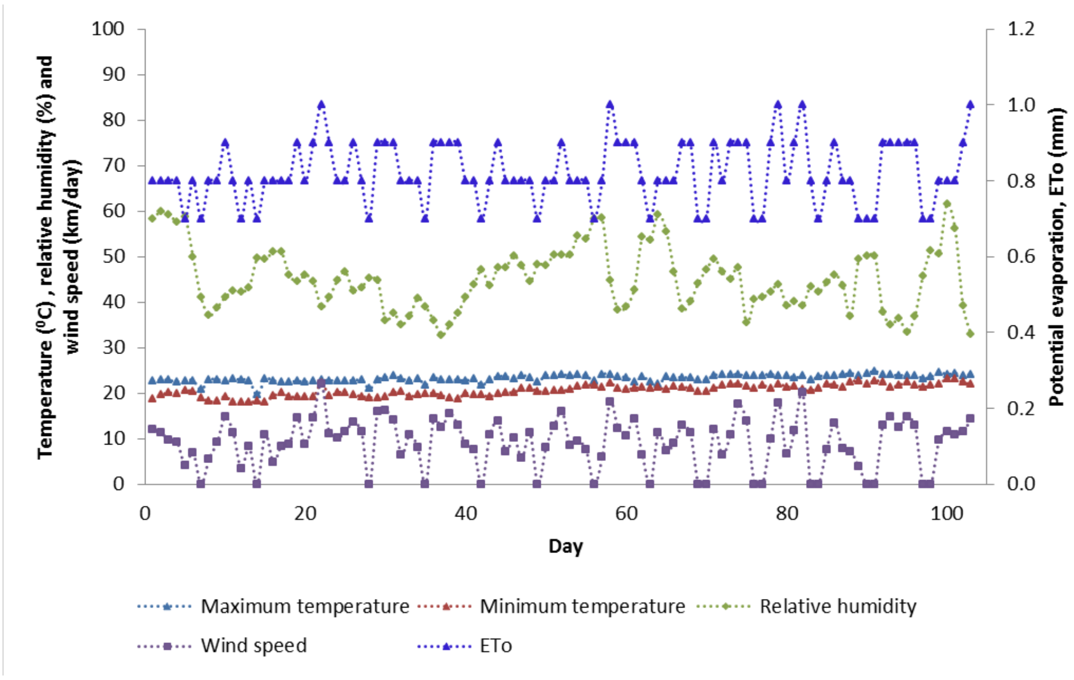


Figure 5.5 Variation of temperature, humidity and wind speed measured in the laboratory during the first 103 days of the study period. ET_0 was calculated using Penman-Monteith method by HYDRUS 1D.

5.5.2 Modelling of water and salt leached from column

Figure 5.6 shows the cumulative quantity of leached water for all the three columns considered in this study. The figure also shows the average cumulative leached water for all three columns and the one predicted by HYDRUS 1D. Compared to columns 1 and 2, water drained less in column 3; this may be because of extracting soil water from the column for measuring $EC_{SW\ (in\ situ)}$ during the study period. Average leaching fraction ranged between 0.16 and 0.2. HYDRUS 1D predicted the cumulative water drained with MAE 0.38 L and RMSE 0.41 L. These values were calculated against the average leached water. Initially the predicted volume of leached water was more but after about 60 days, the predicted values were within the range of water leached from columns. The predicted values were closer to that observed in the column 1. HYDRUS 1D predicted the water leached from column 1 with MAE 0.22 L and RMSE 0.31 L; RE and BIAS were estimated as 10.4% and 1.3%, respectively.

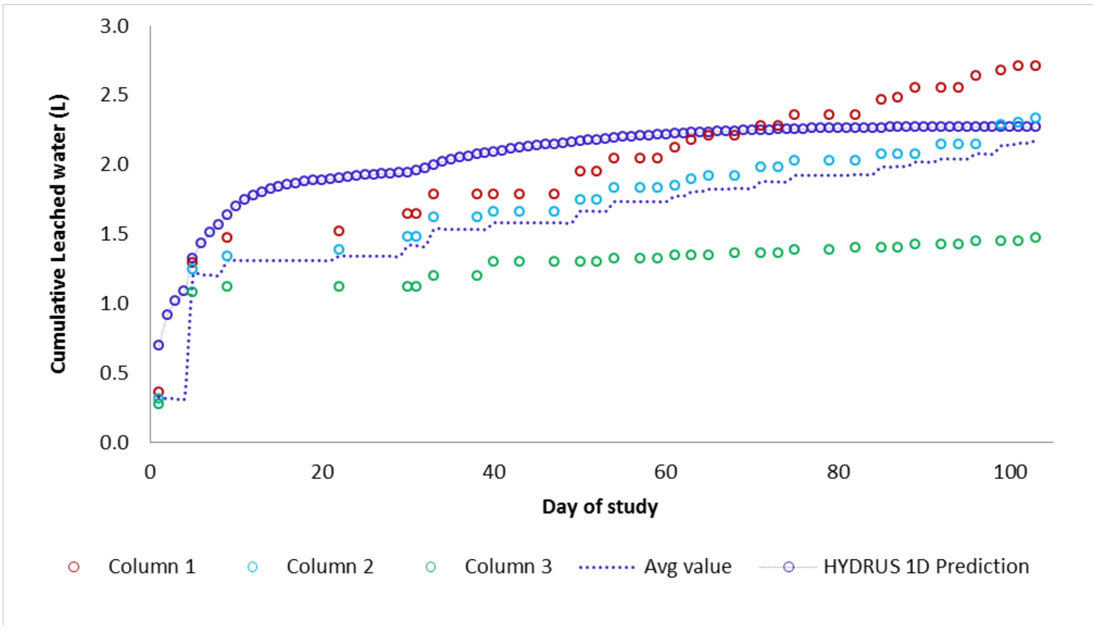


Figure 5.6 **Measured and simulated cumulative water leached from columns**

The cumulative salt leached from columns, and those predicted by HYDRUS 1D, over the first 103 days of experiment are presented in Figure 5.7. As can be seen from the figure, the HYDRUS 1D predicted salt load was within the range of that was leached from columns throughout the study period. However, the predicted salt in the leachate was closer to the one observed in Column 3. MAE and RMSE values were calculated against the average leached salt load which was 3 and 3.85 g/m^2 respectively; RE and BIAS were calculated as 6.7% and 6.5%, respectively.

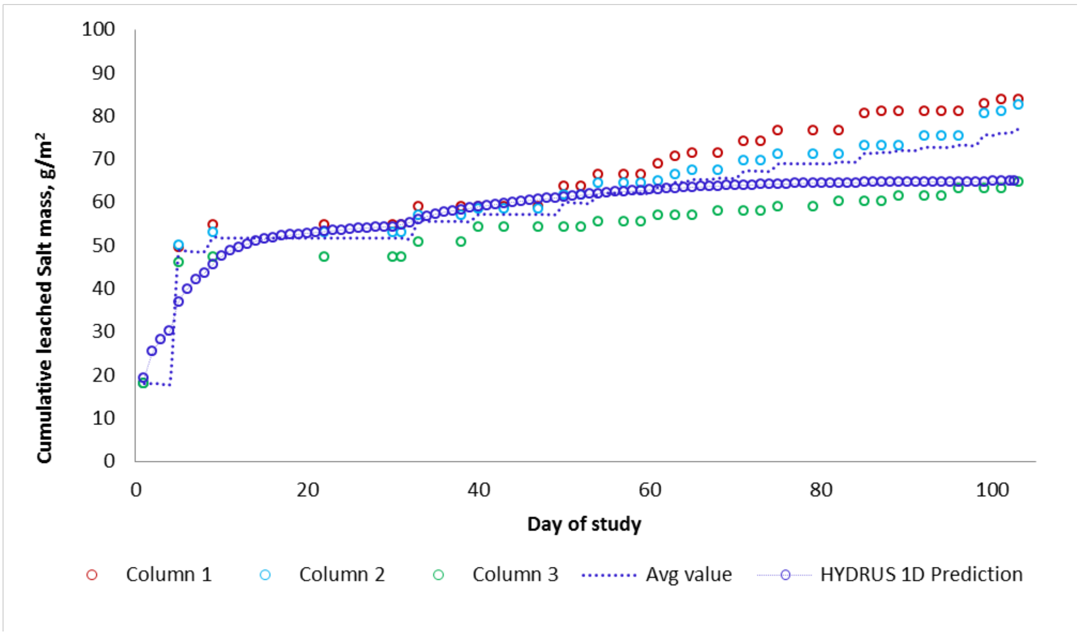
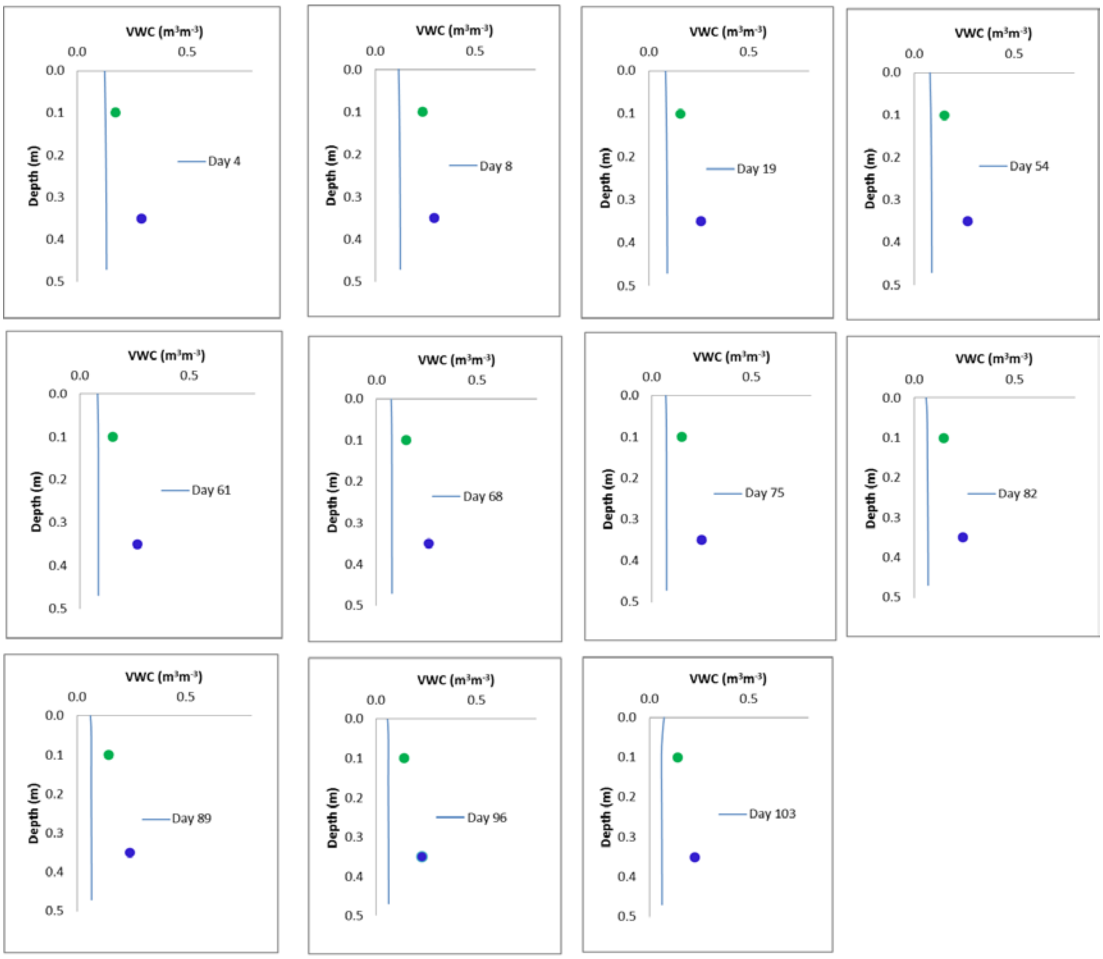


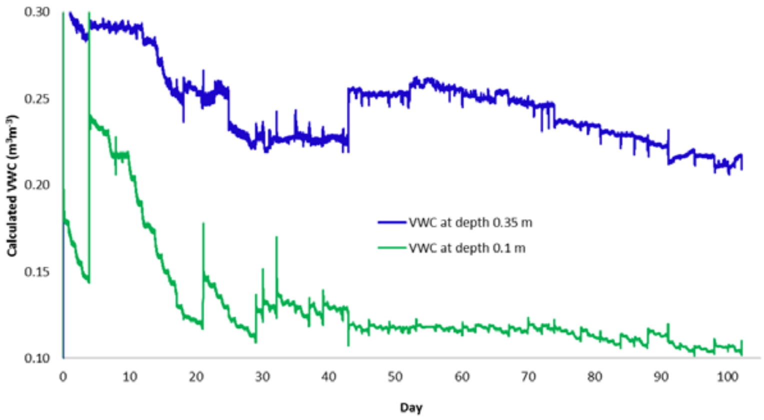
Figure 5.7 **Measured and simulated cumulative salt leached from columns**

5.5.3 Modelling spatial variation of volumetric water content

The calculated VWC using Equation 4.1 and that predicted by HYDRUS 1D is shown in Figure 5.8 (*a*) for the depths of 0.1 m and 0.35 m during different sampling periods. HYDRUS 1D predicted the VWC at 0.1 m depth with MAE 0.07 and RMSE 0.08 and at depth 0.35 m with MAE 0.17 and RMSE 0.18. The values of MAE and RMSE are within the range found by other studies who used HYDRUS 1D (Sarmah et al. 2005; Czarnomski et al. 2005). Knowledge of spatial distribution of VWC aids in the understanding of when to apply irrigation water. During the study period, reported in this chapter, VWC at depth 0.1 m reduced by 33% (from 0.21 to 0.14) and at the depth of 0.35 m by 28% (from 0.32 to 0.23). This result is expected because the top portion of the column is subjected to more evaporation than the bottom portion. The variation of VWC with time at the observed depths is shown in Figure 5.8 (*b*). The peaks in the graphs of Figure 5.8 (*b*) represent the changes in VWC due to the application of irrigation water; between two successive irrigation events, the VWC curve continued to fall due to evaporation. As shown in the figure, up to day 32 of the study period, the peaks at the depth of 0.1 m were higher than the later stage of the experiment, which occurred because of higher application of irrigation water during this period (Figure 5.4 and Section 5.4). Also, the decline of VWC during the period between day 4 and day 21 was due to the delayed application of irrigation water to bring down the VWC close to the field capacity (Figure 4.2).



(a)



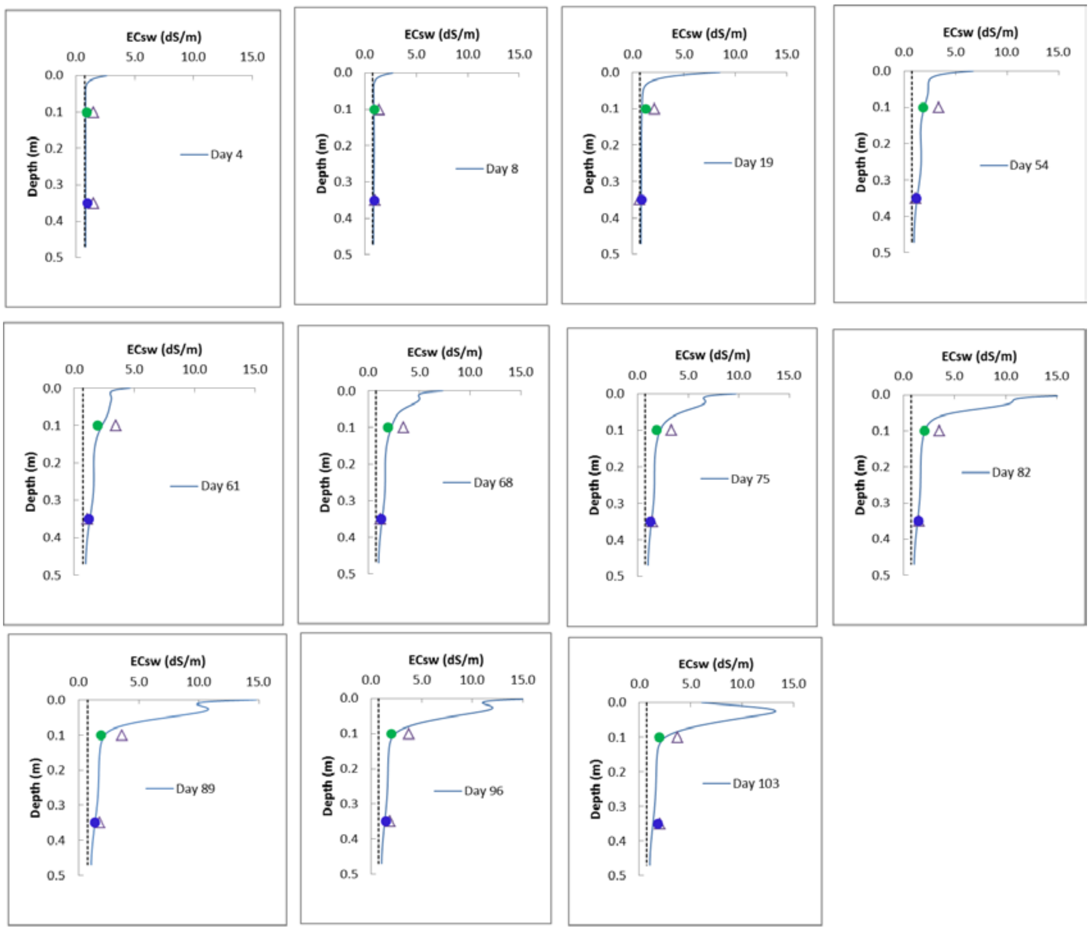
(b)

Figure 5.8 ***(a)*** **Measured and simulated soil VWC profile during different sampling time. The line represents HYDRUS 1D prediction, circle represents calculated VWC by Equation 4.1** ***(b)*** **Variation of calculated VWC using Equation 4.1 with time at depths 0.1 m and 0.35 m; data recorded at every minute interval.**

5.5.4 Modelling spatial variation of soil water electrical conductivity

The in-situ measured electrical conductivity, $EC_{SW(in\ situ)}$ and the HYDRUS 1D predicted EC_{SW} are shown in Figure 5.9 (*a*) for the depths 0.1 m and 0.35 m on all sampling occasions. At both the depths, an increasing pattern of $EC_{SW(in\ situ)}$ over time was observed (Figure 5.9*b*). The $EC_{SW(in\ situ)}$ was relatively higher at the depth of 0.1 m compared to the value at depth 0.35 m. The $EC_{SW(in\ situ)}$ increased by about 1.9 times above its initial value (from 1.0 to 1.9 dS/m) at the depth of 0.35 m and about 2 times (from 1.0 to 2.0 dS/m) at the depth of 0.1 m. $EC_{SW(in\ situ)}$ increased substantially at 0.1 m depth between five and 60 days then stabilised. $EC_{SW(in\ situ)}$ at 0.35 m depth was stable until about 70 days, and then increased gradually to 100 days. This shows that salt accumulation shifts from shallower to deeper depths as the irrigation continues. Initially, $EC_{SW(in\ situ)}$ is higher at the shallower depths due to lower volumetric water content owing to evaporation. However, as the irrigation continues, the salt is transported to lower levels, thereby gradually increasing the $EC_{SW(in\ situ)}$ at deeper depths. The calculated MAE, RMSE, RE and BIAS between in-situ measured and simulated $EC_{SW(in\ situ)}$ are shown in Table 5.2. The MAE and RMSE decreased with depth, indicating better prediction of $EC_{SW(in\ situ)}$ by HYDRUS 1D at depth 0.35 m, compared to predictions at depth 0.1 m. However, RMSE values for prediction of $EC_{SW(in\ situ)}$ for both the depths agreed with the range reported by other researchers (0.21 to 3.73 dS/m) who used HYDRUS 1D for salt transport modelling (Ramos et al. 2011; Kanzari et al. 2012; Yurtseven et al. 2013; Forkutsa et al. 2009).

The sensor measured electrical conductivity, $EC_{SW(sensor)}$ (as discussed in Section 5.2.2) for both the depths are also shown in Figure 5.9 (*a*). As shown in Table 5.2, the correlation between $EC_{SW(in\ situ)}$ and simulated EC_{SW} appears to be superior compared to the correlation between $EC_{SW(sensor)}$ and simulated EC_{SW}. As such, in all the forthcoming analysis in-situ measured EC_{SW} values were used.



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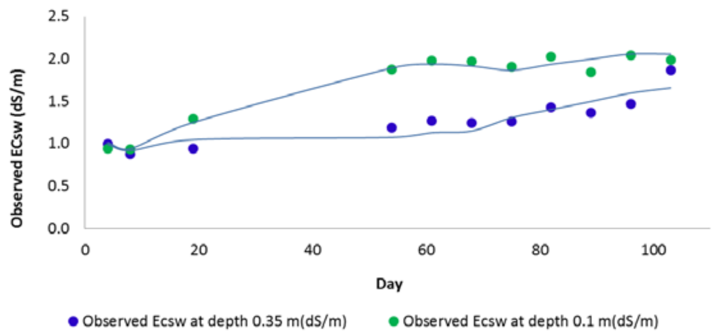


(b)

Figure 5.9 ***(a)*** **Measured and simulated soil water concentration (EC_{SW}) profile during different sampling time. Dotted line represents the initial value, solid line represents HYDRUS 1D prediction, circle represents *in situ* extracted EC_{SW}, and triangle represents calculated EC_{SW} *(b)* Variation of *in-situ* measured and HYDRUS 1D predicted EC_{SW} with time at depths 0.1 m and 0.35 m**

Table 5.2 Results of the goodness of fit indices between observed and predicted EC_{SW} at different depths

Goodness of fit indices	0.1 m		0.35 m	
	$EC_{SW(in\ situ)}$ vs. Simulated EC_{SW}	$EC_{SW(sensor)}$ vs. Simulated EC_{SW}	$EC_{SW(in\ situ)}$ vs. Simulated EC_{SW}	$EC_{SW(sensor)}$ vs. Simulated EC_{SW}
RMSE (dS/m)	0.22	1.18	0.22	0.32
MAE (dS/m)	0.18	1.09	0.14	0.25
RE (%)	11.21	38.40	9.62	17.56
BIAS (%)	-1.83	34.33	5.00	9.79

$EC_{SW(sensor)}$ at 0.1m depth shows high percentage of bias (BIAS 34.33%). The relative error is also very high (RE 38.40%). This could be due to the limited VWC points which were considered for developing calibration curve. The regressed equation for D21 paddock soil (Table 4.6) was developed with average VWC of 0.2, 0.28 and 0.33 m^3/m^3. Values of VWC less than 0.2 m^3/m^3 was not considered because of the difficulty in extracting sufficient water to measure EC_{SW} (discussed in Section 4.3.1).

Agreement between simulated and measured results on amount of leachate and leached salt, and spatial variation of VWC and EC_{SW} strongly suggests that the HYDRUS 1D model can be used with confidence in predicting salt accumulation in paddocks for which it is validated. However, the discrepancy observed between the observed and predicted values (in terms of different goodness of fit indices) might be due to the edge effect, preferential flow and locally entrapped air (Peck 1969), which are not considered in this application of the model. Effort was made to minimise these phenomena by using loamy sand soil and relatively wide columns, not fully drying columns during experimental cycles, and by positioning sensors and samplers at the central part of the column. However, the existence of cracks, roots, and sometimes gaps between soil and column material may cause preferential flow, which is the reason for uneven and rapid water and solute movement in the soil (Phillips 2006). Edge effect and preferential flow may cause applied irrigation water to bypass soil matrix without accomplishing adsorption of salt causing its accumulation in the soil. The existence of preferential flow in column studies is reported by different researchers (Camobreco et al. 1996; Duan et al. 2011).

5.6 Application of HYDRUS 1D for modelling salinity levels in D21 paddock under drought condition

5.6.1 Model parameters in field condition

The validated HYDRUS 1D model, by column study, was used to predict long-term salt accumulation in the D21 paddock. For this purpose, the soil type, soil hydraulic model and parameters, boundary conditions for water and solute transport, type of transport modelling, molecular diffusion coefficient, partitioning coefficient, initial conditions for water content and soil water concentration, and irrigation water salinity were kept identical to those used in the laboratory column study modelling. For the field prediction, a soil profile up to 1 m below the ground level is considered. Bulk density and longitudinal dispersivity was 1,500 kg/m^3 (measured in the field) and 20 cm^{-1} (Vanderborght and Vereecken 2007), respectively. An irrigation schedule was calculated based on Allan et al. (1997) for rye pasture in loamy sand soil. For loamy sand, water holding capacity was 55 mm/m (SARDI 2014) and the average root depth of rye pasture was assumed as 0.35 m (Allan et al. 1997). The maximum amount of irrigation water to be applied (19.25 mm in Figure 5.10) per irrigation was calculated based on the product of the average water holding capacity of the soil and root depth of rye pasture. The irrigation interval in a month was then calculated dividing the maximum irrigation by actual average monthly evapotranspiration. For this, a crop factor of pasture was used for different months varying between 0.4 and 0.7 (Allan et al. 1997). Using Allan et al. (1997) method, a total of 47 irrigation events per year were calculated and distributed from January to December as 7, 5, 5, 3, 2, 1, 1, 2, 3, 5, 6 and 7, respectively, for each month.

The long-term prediction over 5 years was carried out. As stated earlier, the purpose of this simulation was to observe the accumulation of salt during the drought period. It is expected that the drought period yields the worst case scenario as under normal rainfall conditions the salt may be flushed from the root zone. Thereby, reduce the potential for salt accumulation under normal rainfall conditions. Meteorological data was collected from the weather station (Station number 067021) at Hawkesbury campus, University of Western Sydney. To identify the minimum rainfall year of the drought period (2000 to 2006) within the preceding decade, rainfall data from 2001 to 2013 was statistically analysed and found out that the year 2006 had the least amount of rainfall compared to other years. The total amount of rainfall in the year 2006 was 525.20 mm. This amount of rainfall was about 15% less than in the year 2005 and 49% less than in the year 2007. The rainfall of other years of this decade varied within the above mentioned range. Mean annual rainfall for this weather station for the period of 1881 to 2013 is 801mm (BOM 2014), which is 53% higher than the rainfall in 2006. Therefore, for the purpose of calculating maximum amount of salt accumulation (due to minimum rainfall), it was assumed that the climatic condition of the year 2006 would continue for a period of 5 years under drought condition.

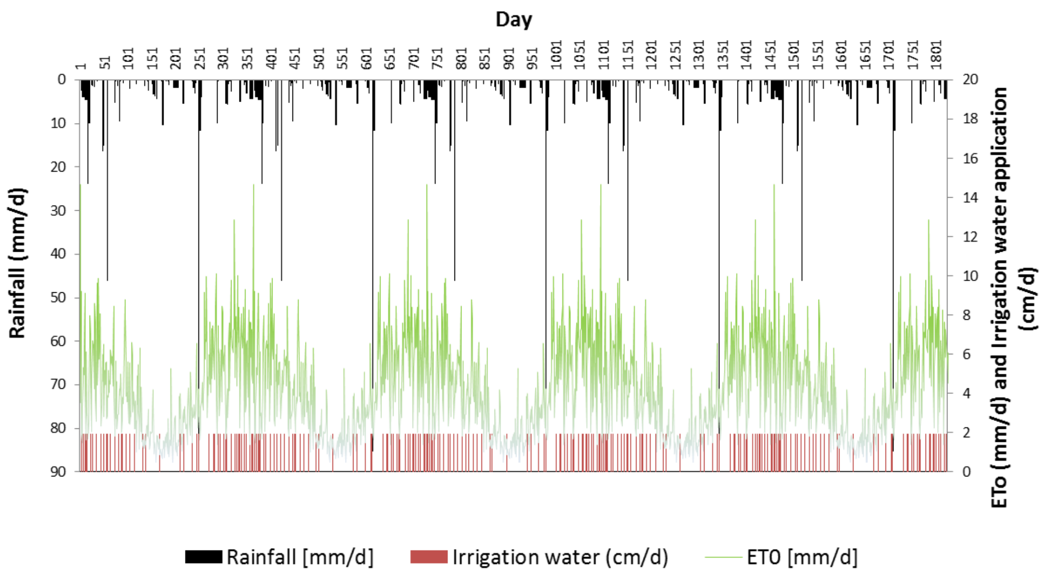


Figure 5.10 Variation of ET_0 (mm/d), rainfall (mm/d) and irrigation water applied (cm/d) under drought condition

The climatic condition of the year 2006 was used to calculate potential evapotranspiration (ET_0), which is shown in Figure 5.10. In HYDRUS 1D, daily potential evaporation (E_p) and transpiration (T_p) are required as input data. The model then converts them into actual evaporation (E_a) and transpiration (T_a) based on the available soil moisture content. Potential evapotranspiration was calculated by the Penman-Monteith method by HYDRUS 1D (Šimůnek et al. 2009) with the data collected from the weather station. ET_0 was then divided into potential transpiration (T_p) and evaporation (E_p) using Beer's Law (Wang et al. 2009):

$$E_p = ET_0 \times e^{-k \times LAI} \tag{5.1}$$

$$T_p = ET_0 - E_p \tag{5.2}$$

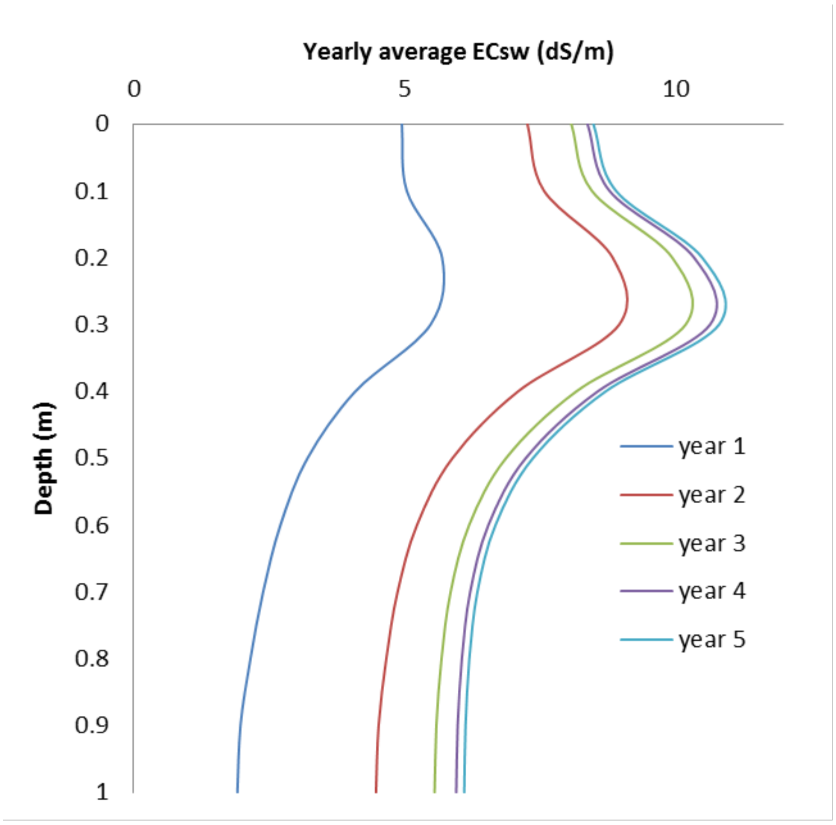
$$LAI = 5.5 + 1.5\ln(h_c) \tag{5.3}$$

k is an extinction coefficient set to be 0.463[-] and LAI is leaf area index [LL^{-1}]. LAI was calculated from a crop height (h_c) of 0.3 m (Allen et al. 1998). The potential transpiration and evaporation varied in the range of 0.4 to 12 mm/d and 0.1 to 2.7 mm/d, respectively. Crop type, root water uptake model and water stress parameters for root water uptake were taken from the HYDRUS 1D built-in library. For root water uptake (shown in Equation 3.9), Feddes et al. (1978) model implemented in HYDRUS 1D was used. Water stress parameters of Feddes et al. (1978) model, suggested by Wessiling (1991) for pasture were used during the modelling. Solute stress by plant was assumed to be negligible in the present study.

5.6.2 Long-term prediction and risk of salt accumulation

As explained earlier, the HYDRUS 1D model was applied for studying the possible impacts of recycled water irrigation on salt movement and accumulation in the paddock over the period of 5 years of continuous irrigation during drought condition. The results obtained from the simulation of 5 years of irrigation are presented in Figure 5.11.

The reported salt accumulation profile (Figure 5.11*a*) represents the salt accumulation averaged over a particular year. For example, the year 1 profile shows an average variation of salt accumulation throughout the profile depth considering all days in the year. As expected, the soil salinity profile shows a cyclical pattern (alternatively increasing and decreasing with time) in the same year (Figure 5.11*b*). The cyclical pattern of the salt accumulation in the soil profile is linked to the variation of rainfall and evapotranspiration (Devitt et al. 2007). Similar patterns of salt accumulation were also reported by other researchers (Kanzari et al. 2012; Kato et al. 2008; Thayalakumaran et al. 2007).



(a)

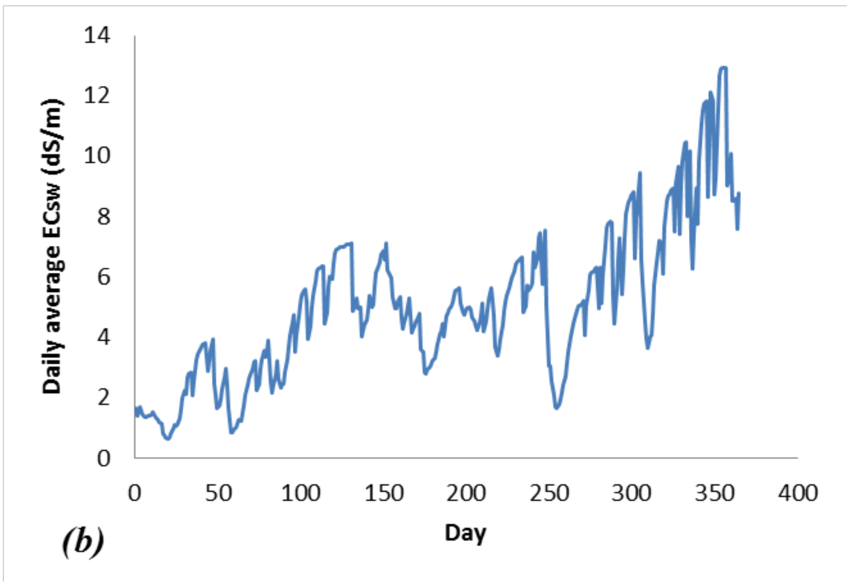


Figure 5.11 (*a*) Long-term simulated soil water salinity profile for irrigation with recycled water under drought condition (*b*) Cyclical pattern of daily average root zone salt accumulation in the Year 1.

An increasing pattern of soil water concentration in the root zone (0 to 0.4 m) with years of irrigation was observed (Figure 5.11*a*). With the increase of time, the rate of increase of root zone EC_{SW} decreased. From the year 1 to the year 2, root zone EC_{SW} (averaged over 0 to 0.4 m) increased by 57%. Similarly, between two subsequent years, i.e. years 2 to 3, 3 to 4 and 4 to 5, EC_{SW} increased by 13, 4 and 1%, respectively. This trend of decrease of salt accumulation rate indicates that the system is trying to reach equilibrium by increasing the vertical transport (Allen et al. 1998). The yearly averages of root zone EC_{SW} for the years 1 to 5 were found to be higher than the tolerance thresholds for pastures (in terms of EC_{SW}) including clovers and rye. According to NRMMC-EPHC-AMC (2006) the threshold varies from 3.0 to 5.0 dS/m. The yearly averages of root zone EC_{SW} for the years 1 to 5 exceeded the tolerance threshold by 1, 59, 79, 87 and 90%, respectively.

Another aspect of the long-term simulation is to identify the risk of accumulation of salt at deeper levels of the soil profile, which is transported vertically. This is important because washed out salt from the root zone may end up contaminating groundwater aquifers. It is interesting to see from Figure 5.11*a* that the use of recycled water for irrigation resulted in the increase of EC_{SW} with time at the depth of 1.0 m. From the year 1 to the year 5 of continuous irrigation, the yearly average EC_{SW} at the depth of 1.0 m was increased almost three times (from 1.9 to 6.1 dS/m). On average, in the lower portion of the soil profile (0.5 to 1.0 m), salt accumulation was less than that of root zone salinity. From year 1 to year 5, EC_{SW} in the lower portion of the soil profile was 53, 38, 34, 32, and 32% less than that of root zone EC_{SW}, respectively. The results indicate more evapotranspiration in the root zone occurred than the lower portion of the soil profile and, over the period, migration of salt downwards.

5.6.3 Seasonal variation of salt accumulation in the root zone

The D21 paddock is situated in the temperate climatic zone of Australia, where there are four seasons, namely, summer (December to February), autumn (March to May), winter (June to August) and spring (September to November) (Wells 2013). The seasonal variation of salt accumulation is important in the sense that this provides more succinct picture of salt accumulation than the yearly average of root zone EC_{SW}

for a certain crop. The seasonal variation of root zone EC_{SW} is highlighted in Figure 5.12.

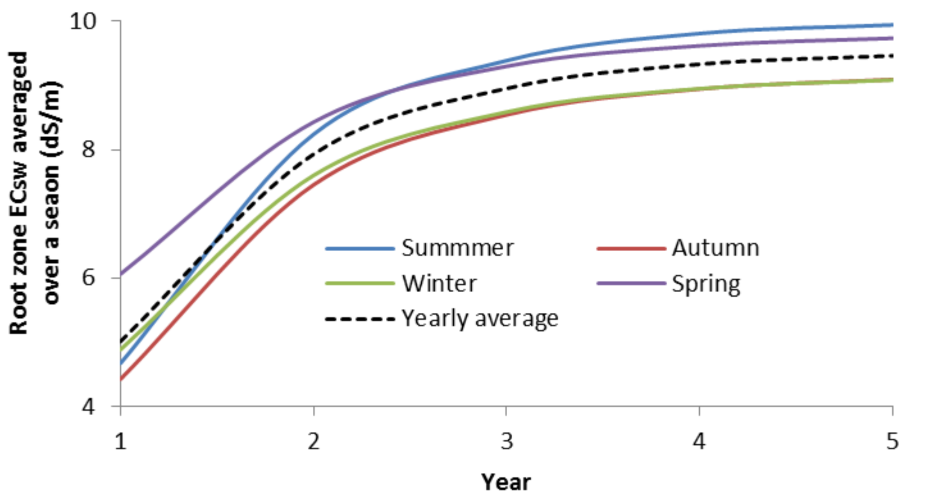


Figure 5.12 Seasonal variation of simulated root zone salinity under drought condition.

The seasonal variation of root zone EC_{SW} follows similar pattern of yearly salt accumulation, where salt accumulation is trying to reach equilibrium condition over 5 years period. Spring and summer seasons showed more salt accumulation than winter and autumn seasons throughout the simulation period. Initially, up to second year, spring season showed more salt accumulation than summer season; however at fifth year the summer season showed 2% more salt accumulation compared to spring season, and about 9% more salt accumulation than autumn and winter seasons. This can be explained based on the application of recycled water for irrigation and occurrence of rainfall. During spring and summer, as explained earlier, the field receives higher quantity of recycled water. This, coupled with relatively higher evapotranspiration during these two seasons explains the higher levels of EC_{SW} in the root zone. The gradual change in the higher EC_{SW} from spring (up to 3rd year) to summer (from 3rd to 5th year) can be attributed to the rainfall, which incidentally higher both in spring and summer. This is a result of progressive accumulation and leaching of salt within the root zone to reach a state of equilibrium. The average root zone EC_{SW} of all the seasons were found higher than the maximum threshold of salinity tolerance (i.e. 5 dS/m). However, root zone EC_{SW} of summer, autumn and winter of the year 1 were found below the threshold limit.

From the above discussion it can be said that continuous irrigation with recycled water during the drought condition progressively increased the salt accumulation in the root zone. An appropriate management option including treatment alternatives of recycled water is needed for an efficient control strategy of root zone salt accumulation. Management options to control root zone salinity due to recycled water irrigation is discussed in Chapter 8.

5.7 Summary

A column study was conducted under no rain condition to investigate the salt accumulation in the soil of D21 paddock using recycled water. Based on the observed experimental result at the end of 103 days, it can be concluded that:

1. Mass balance showed increasing pattern of salt accumulation in the soil profile; salt mass load increased 2.4 times from 91 to 218 g/m^2.
2. Salt accumulation was found highly correlated to leaching fraction; salt build-up in the soil profile decreased with increasing leaching fraction.
3. The sensor measured EC_{bulk} was found to be dependent on moisture content; the EC_{bulk} increased when the moisture content increased and vice-versa.

An off-the-shelf salt transport model HYDRUS 1D was validated under no rain condition. During the validation, the relative error and the bias between observed and simulated soil water electrical conductivity were found to be low and varied in a range of 9 – 11% and 2 - 5%, respectively. The in-situ measured soil water electrical conductivity was strongly correlated to HYDRUS 1D prediction in comparison to sensor measured soil water electrical conductivity.

The validated model was then used to predict long-term (5 years) salt accumulation under drought condition. The yearly averages of root zone EC_{SW} for the years 1 to 5 exceeded the maximum salinity tolerance threshold (5.0 dS/m) by 1, 59, 79, 87 and 90%, respectively. Irrespective of seasons, in 5 years' time, root zone EC_{SW} exceeded the maximum salinity threshold by around 2 times, which may lead to the detrimental effects on the pasture.

Overall, the experimental results and modelling of drought condition indicate the possibility of salt accumulation in the root zone and highlights the importance of a suitable management option to control the root zone salinity due to recycled water irrigation.

CHAPTER 6

IMPACT OF SOIL TYPE IN PREDICTING SALT ACCUMULATION

This chapter is partial reproduction of the following journal paper

[1]Rahman, M.M., Hagare, D., [2]Maheshwari, B., [3]Dillon, P. and [4]Kibria, G. (2015) Modelling of the impact of future climate changes on salt accumulation in paddocks of different soil types due to recycled water irrigation. Water Science and Technology: Water Supply, Accepted (Impact factor 0.394).

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[2] School of Science and Health, Western Sydney University, Australia
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6.1 Introduction

Salt accumulation pattern varies with different types of soil. Effect of texture on salt accumulation in soil is not direct. Texture of various types of soils affects the water flow and evaporation, which then affect solute transport and salt accumulation. In this chapter impact of soil type on salt accumulation in two different paddocks of HWRS due to recycled water irrigation is discussed; the D21 and C5 paddocks soil, which are of loamy sand and loamy soil, respectively, used for the purpose. The main objective of this chapter is to apply a salt transport model for predicting the impact of soil type on salt accumulation in the vadose zone soil, when recycled water irrigation is practiced over 20 years. For this purpose, Global Climate Model data was used in the modelling.

6.2 Methodology

Firstly, salt accumulation due to variation in soil type was recognised based on experiment conducted under laboratory environment. Results from the continuous column experiment described in Section 3.5.4.2 were discussed in this chapter. Impact of soil type on salt accumulation was analysed using:

- salt mass balance in the soil profile, according to Section 5.2.1, for both D21 and C5 paddock soil columns; and
- real-time monitoring of salinity at 0.2 m depth from the surface of the soil column;

Afterwards, salinity at 0.2 m depth was reported in terms of in-situ measured EC_{SW} and the values were compared with EC_{SW} calculated with regression equations developed in Chapter 4 for D21 and C5 soil. Later, HYDRUS 1D model was used to predict the salt accumulation in D21 and C5 paddock in field condition. It should be noted that the HYDRUS 1D model was validated in Chapter 5, hence it was not validated in this chapter with the observed column experimental data.

6.3 Impact of soil type on the salt mass balance

Figure 6.1*a* shows applied and average stored salt loads during the study period for D21 and C5 paddock soil columns. Leached salt load from all three columns of D21 paddock soil varied with a standard deviation of 0.1 to 7.5 g/m^2 and for C5 soil columns this value was between 0.1 and 3.9 g/m^2. This variation in the leaching of salt can be attributed to variations in the packing of the columns. Clearer picture of variation in leachate salt concentration (in terms of EC) is evident in Figure 6.1 (*b*) over the study period. The variation in EC of leachate was more for D21 soil than the C5 soil (Figure 6.1*b*). Throughout the study period, the total cumulative leached salt mass (averaged for three columns) was less than the total cumulative applied salt mass. Thus, the total cumulative salt mass stored in the soil profile showed an increasing pattern for both types of soils. However, the rate of increase of accumulated salt was not same throughout the study period. For D21 soil columns, in the first 120 days salt accumulation increased by 129 g/m^2 (from 55 to 185 g/m^2), which was 107 g/m^2 (from 185 to 292 g/m^2) from day 120 to day 330, and increased by 84 g/m^2 (from 292 to 380 g/m^2) from the day 330 to day 400. Similar result was observed for C5 columns where, in the first 120 days salt accumulation increased by 127 g/m^2 (from 55 to 182 g/m^2), which was 105 g/m^2 (from 185 to 290 g/m^2) from day 120 to day 330, and increased by 117 g/m^2 (from 290 to 407 g/m^2) from the day 330 to day 400. It is interesting to see that in terms of salt mass loading (Figure 6.1*a*), both D21 and C5 paddock soil showed similar pattern with insignificant variation of salt accumulation between them during most of the study period.

The reason of the uneven increase of salt accumulation in Figure 6.1 (*a*) can be explained with the variation of leachate collected from both types of soil columns (Figure 6.1*c*). As shown in Figure 6.1 (*c*), the rate of increase of cumulative leachate amount increased after 120 days and this is more prominent for D21 soil compared to C5 soil. After 120 days, cumulative leachate from D21 columns was 27% more than the leachate from C5, which was 23% between days 120 and 330. The reasons for increased leachate in the case of D21 soil are given in Section 6.5.5. From the day 330 to the end of the study period, both D21 and C5 columns showed insignificant amount of leachate. The observations made from the results corroborate that salt accumulation in soil depends on its capability to leach salt from the soil profile. Daily observation of column study with D21 and C5 soil is shown in Table C1 (a-c) and Table C2 (a-c) of Appendix C.

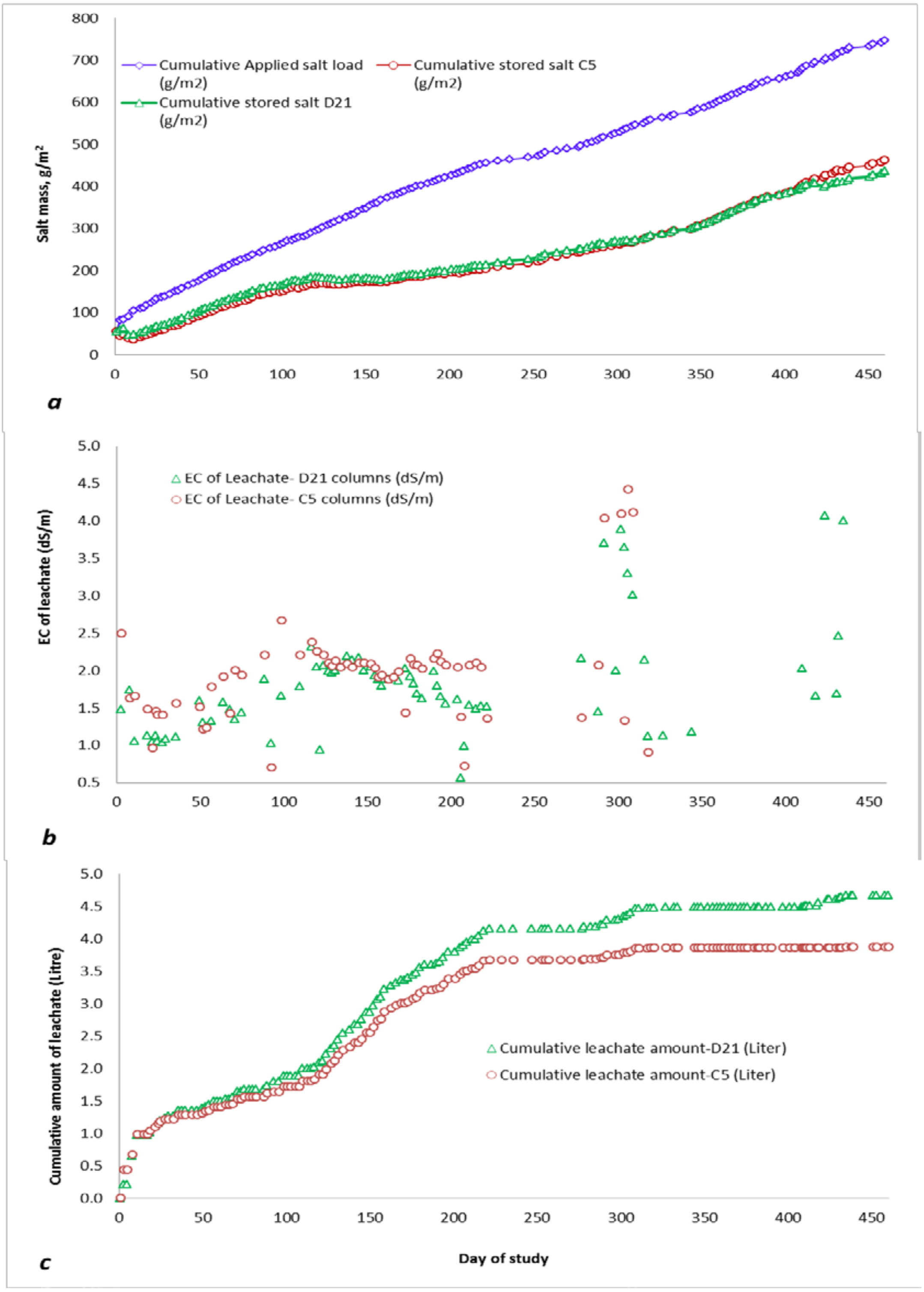


Figure 6.1 (*a*) Cumulative salt mass applied and salt mass stored in the column (averaged over the results from three columns) for D21 and C5 paddock soil (*b*) Variation of electrical conductivity (EC) of leachate (*c*) Variation of cumulative leachate amount during the study period.

As discussed in Section 5.3, leaching of salt (leaching fraction, LF) is generally considered as one of the irrigation management options by field managers for managing the salt accumulation in the root zone. In this study (reported in this chapter), a considerable correlation between salt accumulation in the soil profile and leaching fraction was observed for both types of soil (Figure 6.2). Figure 6.2 is constructed with monthly average results from the whole study period. More clearly, the salt mass stored in the soil profile (g/m^2) and LF was calculated by averaging the daily values over a month during the continuous column study of all three columns. Results from Figure 6.2 show that salt build-up in the soil profile decreased with increasing LF for both types of soil. For average monthly salt build-up of 2.85 g/m^2, average monthly LF in D21 soil was 0.15 (maximum LF of 0.4); on the other hand, for C5 soil, the leaching fraction was found to be 0.12 (maximum LF of 0.32) for almost same quantity (2.83 g/m^2) of salt build-up. A similar observation regarding salt accumulation and LF was reported by other researchers, which is discussed in Chapter 5.

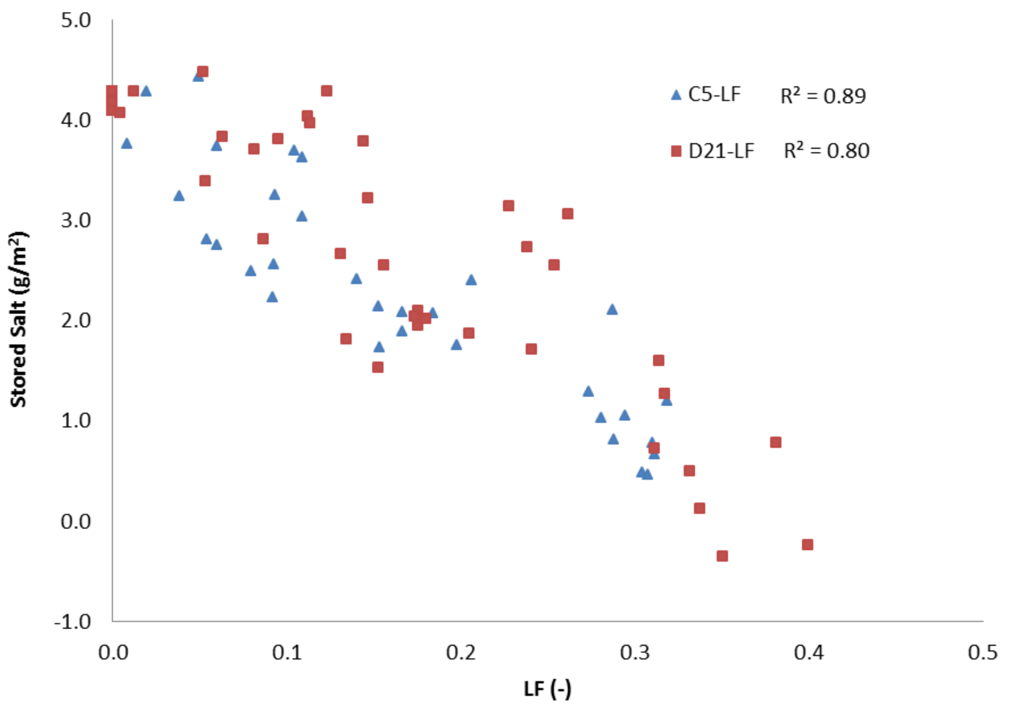


Figure 6.2 Controlling salt build-up in soil profile by leaching fraction. For C5 soil R^2=0.89 and for D21 soil R^2=0.80 (data represents monthly values from all columns).

6.4 Impact of soil type on continuous real-time monitoring of salt accumulation

As discussed in Section 5.4, sensor based real-time monitoring of salt accumulation at certain depth was helpful to get instantaneous status of salt accumulation in the soil profile. In this section, impact of soil type on the continuous real-time monitoring of salt accumulation is investigated. The daily monitored data is reported in Table C3 of Appendix C.

6.4.1 Volumetric water content and bulk electrical conductivity

Results of volumetric water content and bulk electrical conductivity measured by GS3 sensor are presented in Figure 6.3 for D21 and C5 soil columns. As shown in Figure 6.3 (*a*), initially the VWC is higher than the rest of the study period. This is because of applying relatively higher amount of recycled water at the beginning of the study. These higher applications were required to soak the soil in the column. In the first eleven days, in both types of soil columns, 201 mm of recycled water was applied. The amount of applied water during rest of the study period varied between 30 and 120 mm per month (Figure 6.3*a*) to keep the water content in the soil close to the field capacity (Figure 4.2). However, as the purpose of the experiment was to compare the impact of soil texture on the salt accumulation, same amount of irrigation water was used in both types of soil column. Therefore, VWC was close to the field capacity in C5 soil columns, but, was higher for D21 soil columns. The fluctuation of VWC (Figure 6.3*a*) was strongly influenced by applied irrigation water, which is also evident from this figure. During the study period, moisture content in D21 column (at depth 0.2 m) was reduced by 42% (from 0.31 to 0.18) and in C5 column by 32% (from 0.31 to 0.21). This result is expected because water holding capacity of loamy soil (C5) is more than that of loamy sand soil (D21).

The measured EC_{bulk} was dependent on VWC for both types of soil. As expected, the EC_{bulk} increased when the VWC increased and vice-versa. In most of the time of the study period, EC_{bulk} of C5 was higher than the EC_{bulk} of D21; however, in some occasions such as between day 340 and day 370, the values were closer to each other. Therefore it is not possible to conclude the dependence of EC_{bulk} on soil type.

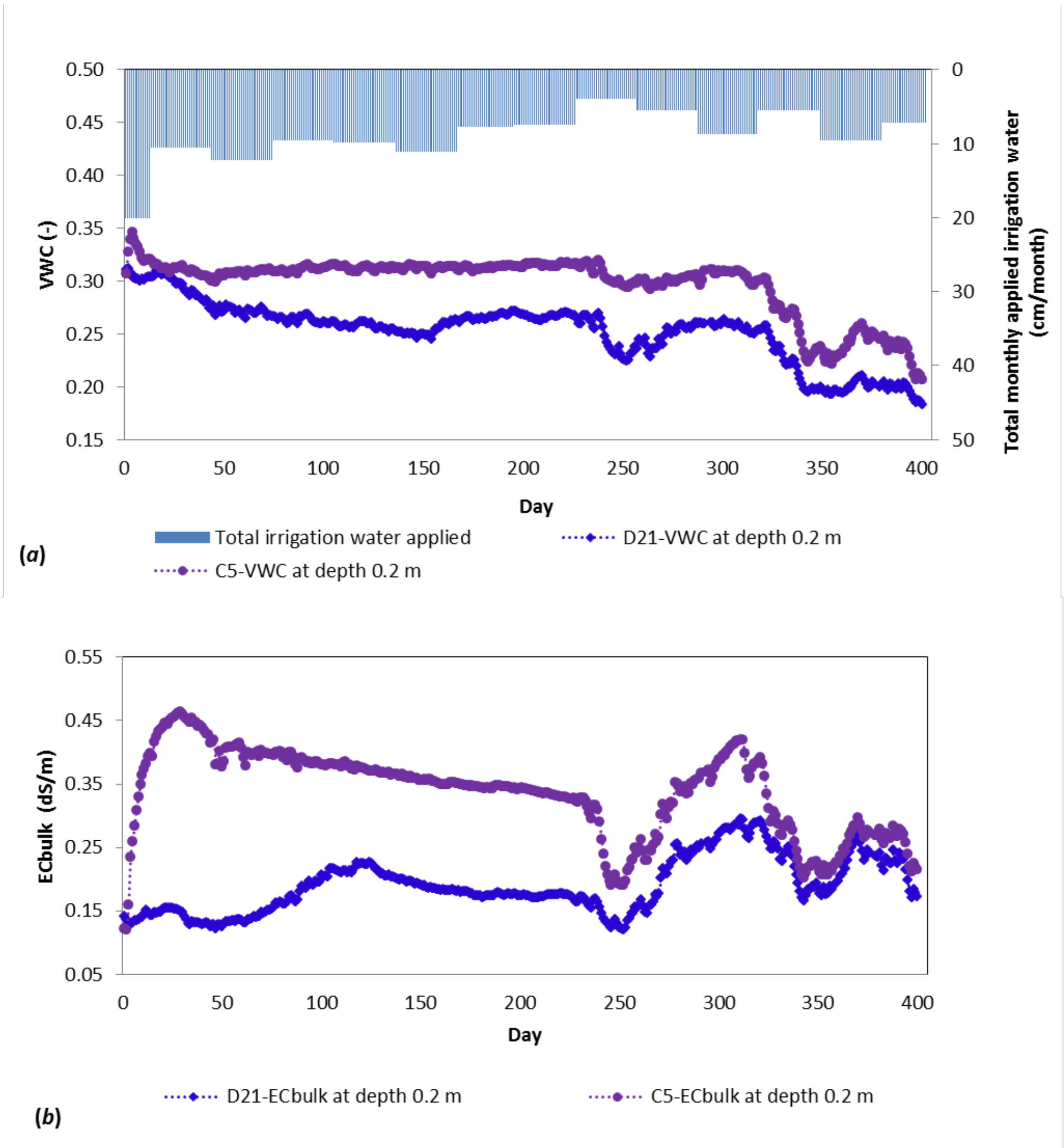


Figure 6.3 (*a*) Variation of volumetric water content and (*b*) bulk electrical conductivity at 0.2 m depth measured by GS3 sensor for D21 and C5 paddock soil columns (VWC and ECbulk averaged over a day)

6.4.2 In-situ measured EC_{SW} and predicted EC_{SW} for different soil types

As seen from Section 6.4.1, EC_{bulk} is not a proper representation of salinity when real-time monitoring is implemented. However, sensor measured EC_{bulk} can be converted to calculated EC_{SW} ($EC_{SW\ (sensor)}$) with the help of calibration equation (such as equations mentioned in Chapter 4, Table 4.6). The EC_{SW} was found more appropriate to represent salinity in soil, which is discussed in Section 5.5.4.

Figure 6.4 shows the variation of $EC_{SW\ (in\text{-}situ)}$ with time for both D21 and C5 soil columns. The purpose of monitoring the $EC_{SW\ (in\text{-}situ)}$ in this column study is two folded. Firstly, the variation of EC shows the difference in behavior of salt accumulation in *loamy* and *loamy sand* soil; secondly, the observed $EC_{SW\ (in\text{-}situ)}$ is used to verify results of the calibration equations for converting EC_{bulk} to $EC_{SW\ (sensor)}$.

It is evident from Figure 6.4 that the behavior of salt accumulation at 0.2 m depth for D21 and C5 soils are quite different. For D21 soil, salt accumulated in a stepwise manner. For example, EC_{SW} increased until day 68, stabilised for 14 days, increased again until day 117 and then gradually decreased until day 173 and stabilised again for 56 days. This is because of the transportation of the salt from upper portion of soil column to this depth (0.2 m). It should be noted that in Figure 6.4 the $EC_{SW\ (in\text{-}situ)}$ was not reported between days 229 and 290, which is because the soil water was not extracted during these days. It is evident from Figure 6.4 that the trend of salt accumulation at 0.2 m depth in D21 soil column from day 290 to the end of the study period followed similar pattern (salt accumulation in stepwise manner) as discussed above, however, an increased rate of salt accumulation was observed. The salt transport was dependent on the soil texture of D21 paddock including hydraulic conductivity of soil and other solute transport parameters mentioned in Chapter 4. The pattern of salt accumulation discussed above is indicative to the drought condition. Impact of rainfall on the same soil (D21) is reported in Chapter 8. Overall, from day 19 to day 397 (over 378 days) the stored salt increased by about 4.5 times (from EC_{SW} value of 0.98 to 4.38 dS/m) at 0.2 m depth.

For C5 soil, the $EC_{SW\ (in\text{-}situ)}$ decreased until day 61 and showed a slight increase until day 229. The EC_{SW} increased by about 7% (from EC value of 1.64 to

1.75 dS/m) over the period of 167 days (from day 62 to day 229). The initial decrease in $EC_{SW\ (in\text{-}situ)}$ in C5 soil may be attributed to the lower hydraulic conductivity (around 5 times less as shown in Table 4.3) compared to D21 soil; decrease in hydraulic conductivity results in higher water retention and hence dilution in salt in the soil. As stated earlier, at the beginning of the experiment (up to day 11 in Figure 6.3 (*a*) a considerable amount of irrigation water was applied to soak the columns, which flushed salt from the soil profile more quickly in D21 soil column than that of C5 soil. This indicates relatively slow transport of salt in C5 soil, which has comparatively higher percentage of clay content (Table 4.1). The slow movement of salt in C5 soil also explains the increasing trend of $EC_{SW\ (in\text{-}situ)}$ at 0.2 m depth from day 290 to the end of the study period. Overall, from day 61 to day 397 (over 336 days) the stored salt increased by about 2.2 times (from EC_{SW} value of 1.64 to 3.65 dS/m) at 0.2 m depth.

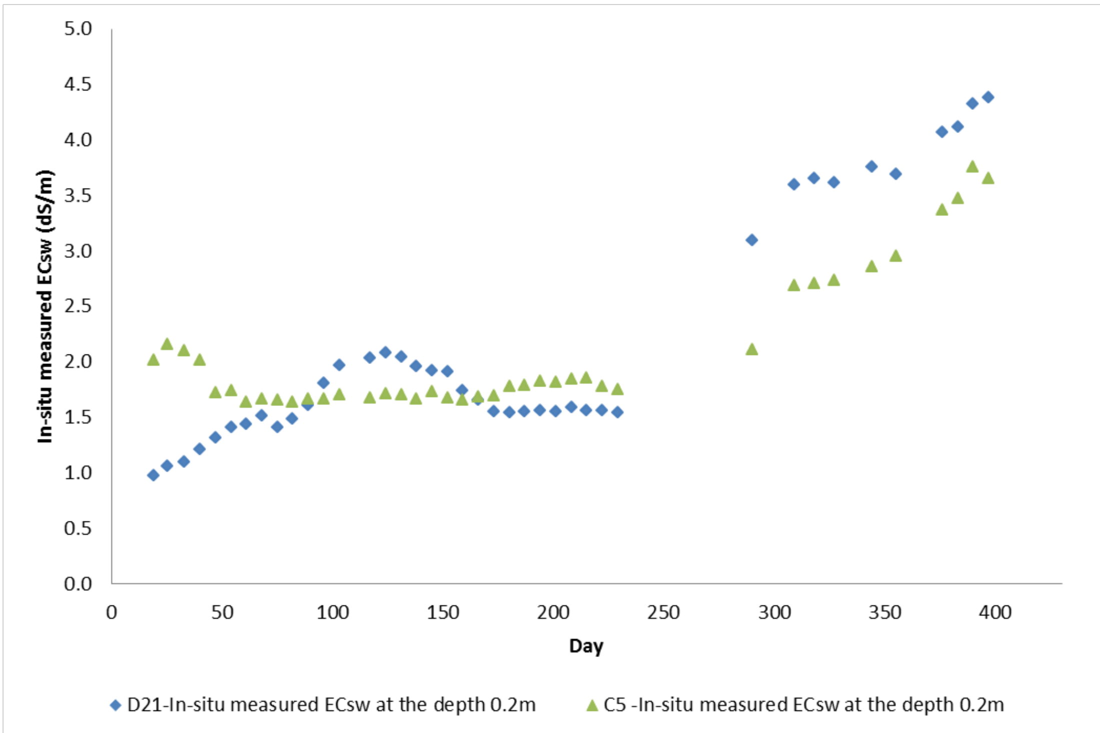


Figure 6.4 Variation of in-situ measured EC_{SW} ($EC_{SW\ (in\text{-}situ)}$) collected at 0.2 m depth of D21 and C5 columns

Results of validation of the regressed equation for converting EC_{bulk} into the $EC_{SW\ (sensor)}$ values for D21 soil column are shown in Figure 6.5. The 1:1 line in the figure represents the perfect correlation of observed and calculated values. As shown in Figure 6.5 (*a*), the observed and calculated $EC_{SW\ (sensor)}$ are highly correlated (R^2 = 0.93) with each other, however, shows relative error of 14% and underestimation of 19%. This may be because of the reason that the regressed equation for D21 (Table 4.6) to convert EC_{bulk} to $EC_{SW\ (sensor)}$ was constructed with EC_{SW} values ranged between 0.9 and 2.5 dS/m (Figure 4.5*a)*, and is not suitable for values outside this range. Consequently, $EC_{SW\ (in\text{-}situ)}$ values less than 2.5 dS/m were plotted separately and shown in Figure 6.5*b*. The correlation between the observed and calculated values in this graph increased (R^2 = 0.94), and values of all statistical indices improved (Figure 6.5*b*). Therefore, the regressed equation for D21 paddock soil works better with EC_{SW} in the range of 0.9 to 2.5 dS/m.

For C5 soil columns, results of validation of the regressed equation for converting EC_{bulk} to $EC_{SW\ (sensor)}$ are shown in Figure 6.6. As shown in Figure 6.6 (*a*), the calculated values of $EC_{SW\ (sensor)}$ are weakly correlated (R^2 = 0.3) to the observed values, and the statistical indices were found very high. The result may be attributed to the reason described above of constructing the regression equation with EC_{SW} values ranged between 0.4 and 2.3 dS/m (Figure 4.5*b*). Effort was made to see if segregating and plotting observed $EC_{SW\ (in\text{-}situ)}$ values less than 2.3 dS/m improve the predictability of the regression equation, which is shown in Figure 6.6 (*b*). As shown in the figure, the correlation between the observed and calculated values did not improve; MAE, RMSE, RE and BIAS improved compared to the values outside the maximum range of 2.3 dS/m, however the values are still high and cannot be concluded that the measured values of $EC_{SW\ (in\text{-}situ)}$ are correlated with $EC_{SW\ (sensor)}$ values. The above discussion suggests that GS3 sensor is not suitable for the soil from C5 paddock.

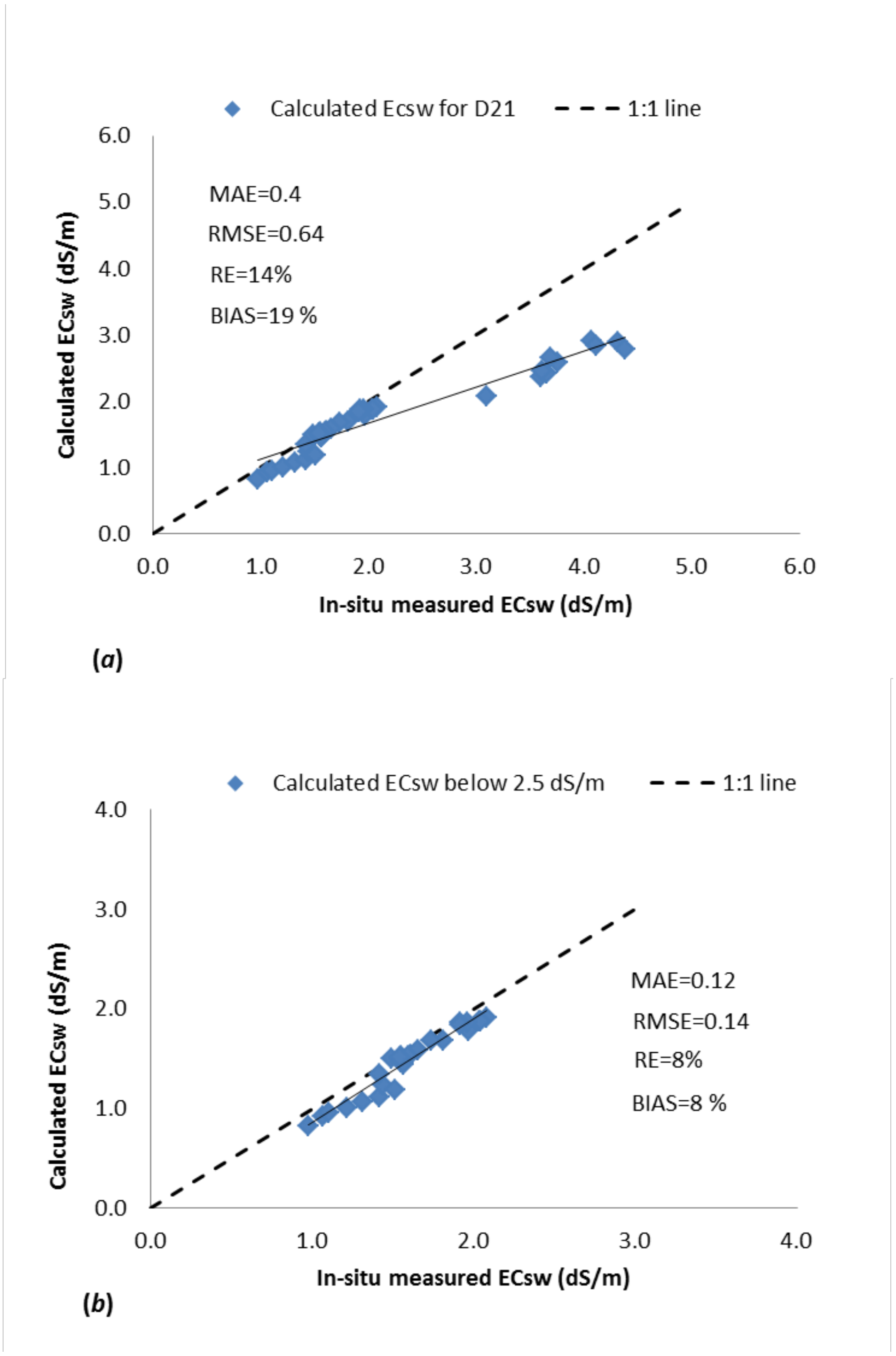
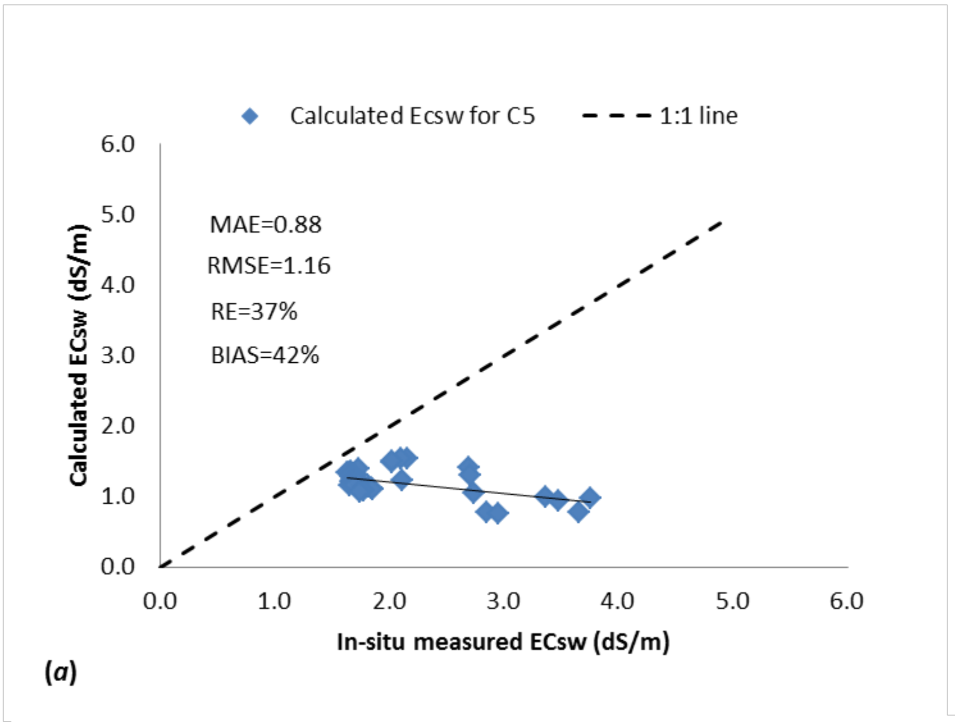


Figure 6.5 Validation of the regressed model for D21 soil for converting EC_{bulk} to calculated $EC_{SW\ (sensor)}$ with in-situ measured $EC_{SW\ (in\text{-}situ)}$ (*a*) for $EC_{SW\ (in\text{-}situ)}$ data ranged between 0.98 and 4.38 dS/m (*b*) for $EC_{SW\ (in\text{-}situ)}$ data ranged between 0.98 and ≤ 2.50 dS/m.



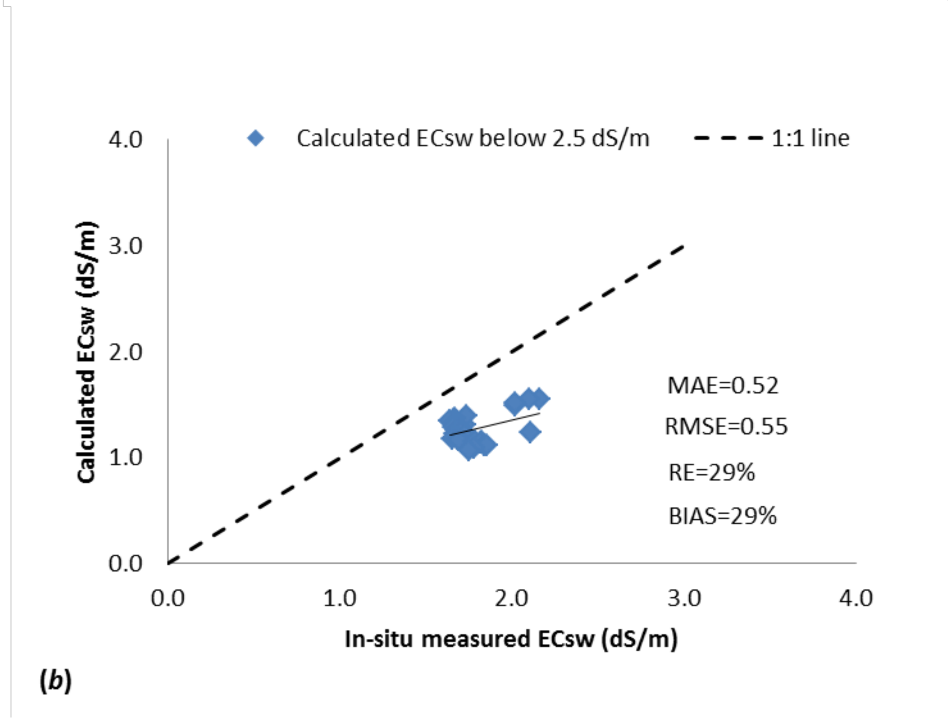


Figure 6.6 Validation of the regressed model for C5 soil for converting EC_{bulk} to calculated $EC_{SW\ (sensor)}$ with in-situ measured $EC_{SW\ (in\text{-}situ)}$ (*a*) for $EC_{SW\ (in\text{-}situ)}$ data ranged between 1.64 and 3.65 dS/m (*b*) for $EC_{SW\ (in\text{-}situ)}$ data ranged between 1.64 and ≤ 2.50 dS/m.

6.5 Application of HYDRUS 1D for modelling salinity in HWRS paddocks

6.5.1 Model parameters

The validated HYDRUS 1D model (as discussed in Section 5.5), was used to predict salt accumulation in D21 and C5 paddocks in field condition. Some of the input parameters are summarised in Table 6.1. The physico chemical parameters (Table 6.1) such as soil type, bulk density, water flow parameters, initial VWC and EC_e for D21 and C5 paddock soils are taken from Chapter 4.

The prediction of EC_{SW} was conducted over a period of 20 years (from year 2021 to 2040) with a spin-up period of three years. The spin-up period is provided so that the model will be adequately equilibrated and have a reasonably realistic soil condition (in terms of VWC and EC_{SW}) and climate state at the beginning of the simulation period (such as at the year 2021). For the spin-up period, climate data of 2021 to 2023 was used. The 20 years period from 2021 to 2040 is considered in this study as that was only the data set which was available to the research team.

The daily rainfall and evaporation data of future (2021 to 2040) climatic condition was collected from Sydney Catchment Authority for the weather station (Station number 067021) at Hawkesbury campus, University of Western Sydney. These future climatic data are downscaled data from CSIRO Mark 3.0 global climate model (GCM) using statistical downscaling method to a finer spatial scale (about 5km x 5km) to be used by the forecasting model (Haque et al. 2014). Three future climatic scenarios were proposed by Intergovernmental Panel for Climate Change corresponding to three different greenhouse gas emission conditions, namely, B1 (low emission), A1B (medium emission) and A2 (high emission) (Nakicenovic and Swart 2000). In this study, data from low emission scenario is investigated. It should be noted that the purpose of this study is to quantify salt accumulation using future climatic condition, rather than investigating the impact of climate change (in terms of greenhouse gas emission scenario) on salt accumulation. Therefore, use of any emission scenario (i.e. low emission) is sufficient to serve the purpose of this study. As such, under the low emission scenario, two future climatic scenarios, i.e. minimum and maximum rainfall (based on 20-year total) was selected. In this chapter, they are termed as *low rainfall* and *high rainfall* scenarios. From these two scenarios, a clear picture of minimum and maximum impact of rainfall on salt accumulation is possible to obtain.

Table 6.1 Input parameters of HYDRUS 1D model for modelling salt accumulation in field condition

Description	**D21 Paddock**	**C5 Paddock**
Depth of soil below the soil surface	1.0 m	1.0 m
Simulation period	20 years	20 years
Hydraulic Model	VG-Mualem	VG-Mualem
Soil type	Loamy sand: Sand = 88.1%, Silt = 6.0%, Clay = 5.9%	Loam: Sand = 67.6%, Silt=18.0%, Clay = 14.4%
Bulk Density	1500 kg/m^3	1470 kg/m^3
Water flow Parameters	θ_r = 0.03 m^3/m^3, θ_s = 0.41 m^3/m^3, α =0.006, n = 2.771, K_s= 264.85 cm/day	θ_r = 0.05 m^3/m^3, θ_s = 0.44 m^3/m^3, α =0.005, n = 2.314, K_s= 42.96 cm/day
Longitudinal Dispersivity	20.0 cm^{-1} (Vanderborght and Vereecken 2007)	21.7 cm^{-1} (Vanderborght and Vereecken 2007)
Initial condition	VWC = 0.09 m^3/m^3, EC_{SW}=2*EC_e (Ayers and Westcot 1985; Stevens et al. 2008) , EC_e = 0.375 dS/m	VWC=0.18 m^3/m^3, EC_{SW}=2*EC_e (Ayers and Westcot 1985; Stevens et al. 2008) , EC_e = 0.340 dS/m
Water flow boundary condition	Upper BC: Atmospheric with surface layer Lower BC: Free drainage	
Solute transport boundary condition	Upper BC: Concentration flux Lower BC: Zero gradient concentration	
Type of solute transport model	Equilibrium model	
Molecular diffusion coefficient	1.75 cm^2/day (James and Rubin 1986)	
Irrigation water EC	0.83 dS/m	
Meteorological parameters	Collected from Sydney Catchment Authority	
Root water uptake model	Feddes et al. (1978) model	
Water stress parameter	From HYDRUS 1D built in library for pasture suggested by Wesseling et al. (1991)	
Plant solute uptake	Not considered	

An irrigation schedule was calculated based on Smith et al. (2012) for rye pasture by taking the daily rainfall into account. The soil moisture deficit was calculated based on readily available water (share of the difference between field capacity and permanent wilting point, which is above the soil moisture limit without leading to water stress) in the root zone. The maximum amount of irrigation water to be applied per irrigation was calculated based on the product of the average water holding capacity of the soil and root depth of rye pasture. For loamy sand (D21) and loam (C5) soil, water holding capacity was 55 mm/m (SARDI 2014) and 80 mm/m (Allan et al. 1997), respectively. The average root depth of rye pasture was assumed as 0.35 m (Allan et al. 1997). In each irrigation event, 19.25 mm and 28 mm of irrigation water was used for D21 and C5 paddock soil, respectively. A crop factor of pasture was used for different months varying between 0.4 and 0.7 (Allan et al. 1997). Using Smith et al. (2012) method, total number of irrigation events per year varied with the rainfall, which is shown in Table 6.2 for D21 and C5 paddocks. Detailed irrigation scheduling per month for the study period is shown in Table C4 and Table C5 in Appendix C, for D21 and C5 paddock, respectively. Variation of rainfall and ET_0 over the study period is shown in Figure 6.7.

As discussed in Section 5.6.1, in HYDRUS 1D, daily potential evaporation (E_p) and transpiration (T_p) are required as input data. The future pan evaporation data (obtained from GCM) was converted to potential evapotranspiration (ET_0) by multiplying a factor 0.8 (Yiasoumi et al. 2008) suitable for paddocks in Hawkesbury campus. ET_0 was then divided into potential transpiration (T_p) and evaporation (E_p) using Beer's Law (Wang et al. 2009) (discussed in Section 5.6.1), which was then entered into HYDRUS 1D. The potential transpiration and evaporation varied in the range of 0.1 to 11.3 mm/d and 0.02 to 2.8 mm/d, respectively. The model then converts them into actual evaporation (E_a) and transpiration (T_a) based on the available soil moisture content.

Table 6.2 Irrigation scheduling based on soil moisture deficit in the root zone

Year	Total number of irrigation per year	
	D21 paddock	C5 paddock
2021	20	11
2022	19	15
2023	25	16
2024	21	13
2025	23	16
2026	20	13
2027	19	12
2028	16	11
2029	21	12
2030	23	17
2031	18	13
2032	21	15
2033	21	14
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2035	20	12
2036	19	11
2037	22	13
2038	24	14
2039	16	9
2040	15	11

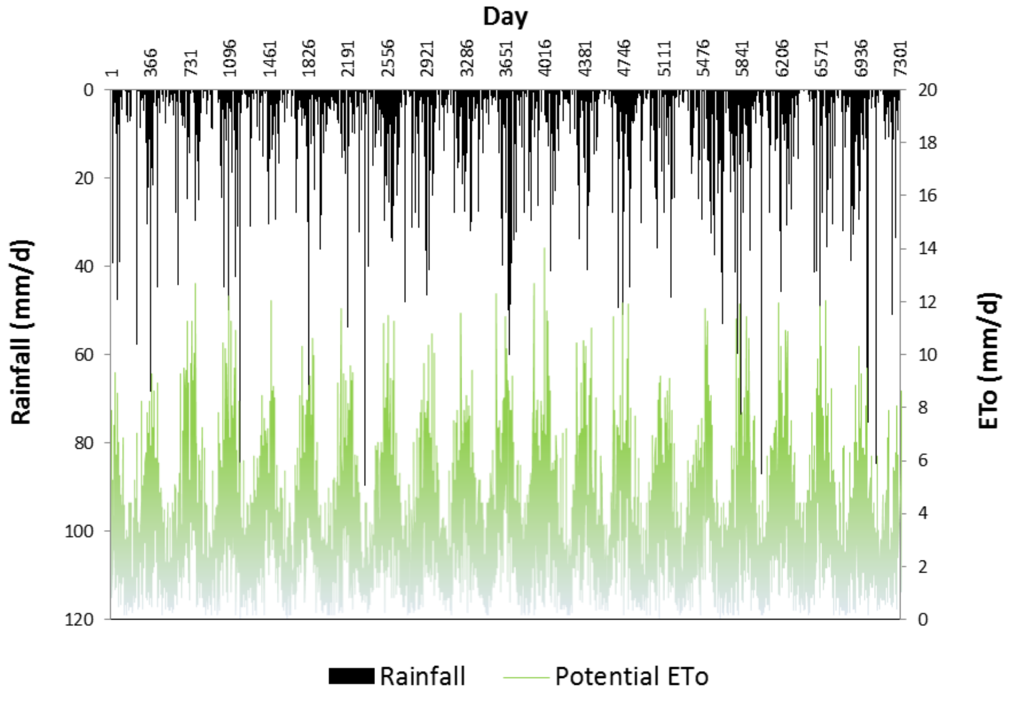
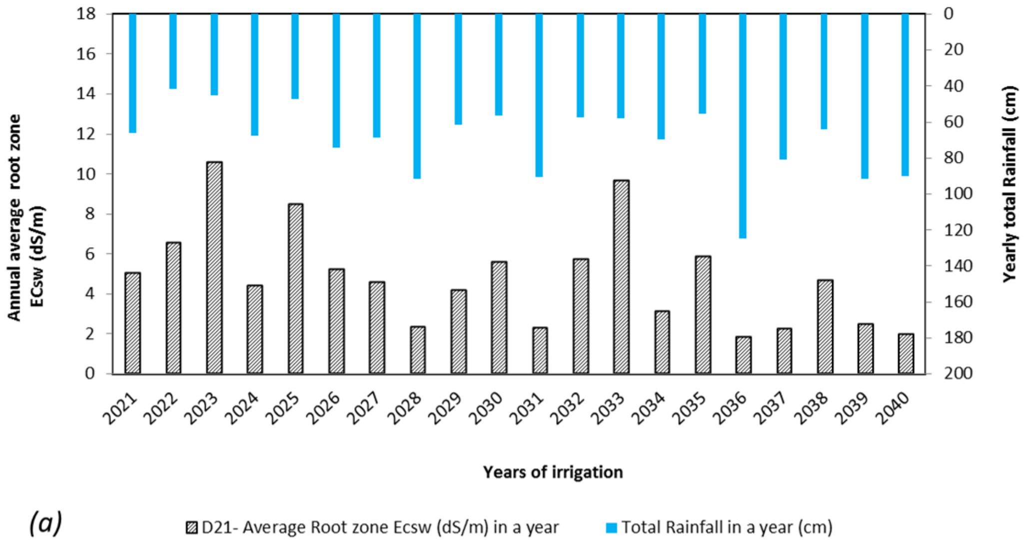


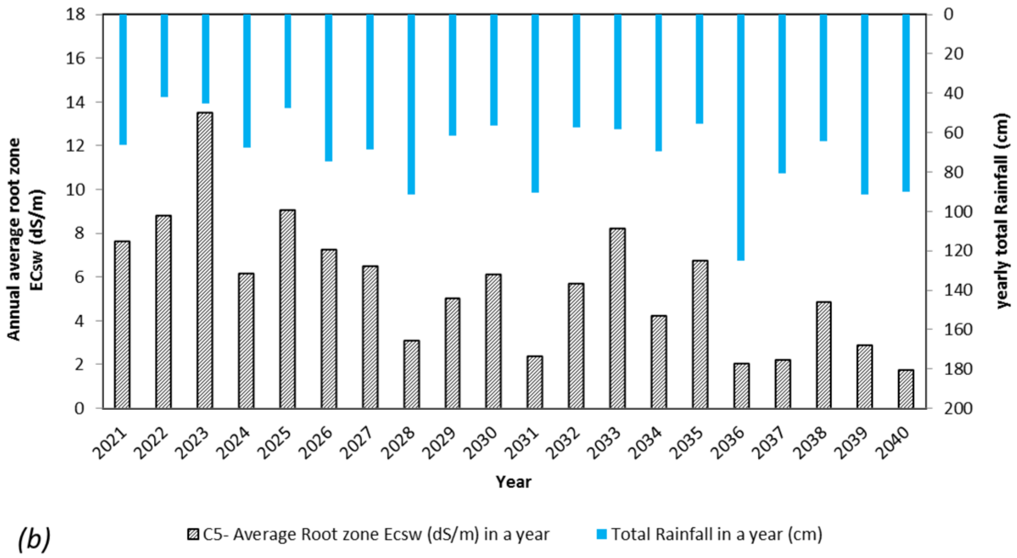
Figure 6.7 Variation of rainfall and ET_0 over the study period

6.5.2 *Rainfall intensity and risk of salt accumulation*

As explained earlier, the HYDRUS 1D model was applied for studying the possible impacts of recycled water irrigation on salt movement and accumulation in the paddocks over the period of 20 years for low and high rainfall scenarios under low emission category. The results obtained from the simulation of 20 years of recycled water irrigation for low rainfall scenario are presented in Figure 6.8 for D21 and C5 paddocks.



(a)



(b)

Figure 6.8 Impact of rainfall on salt accumulation in (*a*) D21 and (*b*) C5 paddock (rainfall represents total rainfall in a year under low rainfall scenario).

The reported salinity represents average root zone (from surface to 0.4 m) EC_{SW} over the entire year. As expected, the root zone salinity shows a cyclical pattern (alternatively increasing and decreasing with time, as discussed in Section 5.6.2). From Figure 6.8 it is evident that salt accumulation in root zone varies with rainfall. Higher yearly rainfall amount resulted in lower salt accumulation (Selle et al. 2010). However, the change of salt accumulation from one year to the next is not proportional to the amount of change in rainfall. For example, for D21 paddock (Figure 6.8*a*), from year 2034 to year 2035, rainfall was decreased by 20% and the salt accumulation increased by 90% (from 3.1 to 5.8 dS/m). From year 2035 to year 2036, rainfall increased by 125% which reduced the salt accumulation by about 69% (5.8 to 1.8 dS/m). Similar pattern was observed for C5 paddock (Figure 6.8*b*), where salt accumulation increased by 60% (from 4.2 to 6.7 dS/m, from year 2034 to 2035) and decreased by about 70% (from 6.7 to 2.0 dS/m, from year 2035 to 2036) for a corresponding decrease and increase of rainfall of 20 and 125%.

6.5.3 Salt accumulation under low and high rainfall scenario

Figure 6.8 showed the dependence of root zone EC_{SW} on variation of rainfall, however to get a clear range of variation of salt accumulation, impact of low and high rainfall scenarios on root zone salt accumulation need to be investigated. The results of the simulation for D21 and C5 paddocks are shown in Figure 6.9. There was significant difference among the amount of total yearly rainfall under the low and high rainfall scenarios (not shown in Figure 6.9). This caused low salt accumulation in high rainfall scenario than under low rainfall scenario (Figure 6.9). As shown in Figure 6.9, the highest difference in the EC_{SW} between high and low rainfall scenarios were in 2023. In this year, total annual rainfall under high rainfall scenario was 2.7 times higher than the low rainfall scenario (451 mm in low rainfall scenario and 1215 mm in high rainfall scenario). Reduction in rainfall caused 6.6 times (from 1.6 to 10.5 dS/m) increase in EC_{SW} in 2023 for D21 paddock and 9.6 times (from 1.4 to 13.5 dS/m) increase for C5 paddock in the same year. The results indicate that for the GCM projected rainfall condition (for both low and high rainfall scenarios) from the year 2021 to 2040, salt accumulation in D21 paddock varies between 1.1 and 10.5 dS/m. On the other hand, for C5 paddock, the salt accumulation varied from 1.0 to 13.5 dS/m.

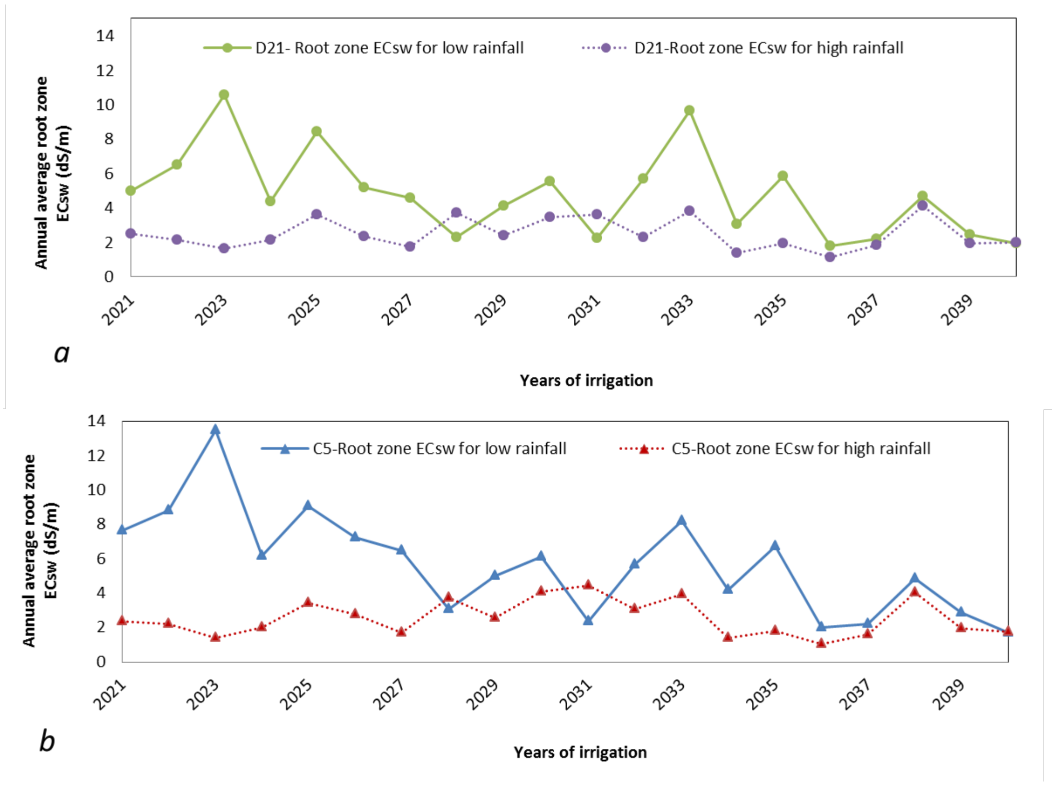


Figure 6.9 Effect of yearly total rainfall on annual average root zone EC_{SW} of two paddocks under low and high rainfall scenarios (*a*) D21 paddock (b) C5 paddock

As shown in Figure 6.9, large variations in EC_{SW} under the low rainfall scenario were observed for both the paddocks. Under the low rainfall conditions, the rate of increase of salt accumulation was more for the amount of recycled water applied. This accumulated salt leached out of the root zone when there was even a small amount of rainfall. This was the reason for large variations in the accumualted salt within the root zone.

6.5.4 Impact of soil type on salt accumulation

Given that higher amount of salt accumulated during low rainfall scenario, it would be justified to use this scenario to compare the maximum impact of rainfall on salt accumulation for two types of soil of the paddocks (i.e. loamy sand of D21 and loam of C5 paddocks). Figure 6.10 shows the salt accumulation in D21 and C5 soils under the low rainfall condition. Over the simulation period, in most of the simulation years, higher amount of salt accumulated in C5 paddock compared to D21 paddock.

Maximum salinity in C5 paddock was simulated as 13.5 dS/m, which was 28% more than that of D21 paddock; both occurred in the year 2023. Among other years, in 2021, salt accumulation in C5 paddock was 7.6 dS/m, which was 53% more than that of D21 EC_{SW}; and in the year 2037, salt accumulation in C5 paddock was 2.2 dS/m, which was about 1% more than that of D21 EC_{SW}. The result shows the range of percent increase of EC_{SW} in C5 compared to D21 paddock. When averaged over 20 years, salt accumulated 24% more in C5 paddock compared to D21 paddock. The variation of salt accumulation in the root zone for both type of soil in a certain year is also evident, which is represented as error bar in Figure 6.10. The error bar represents maximum and minimum root zone EC_{SW} occurred in a year. However, these maximum EC_{SW} sustained for short duration of time and should not have considerable impact on plant growth (Warrence et al. 2002).

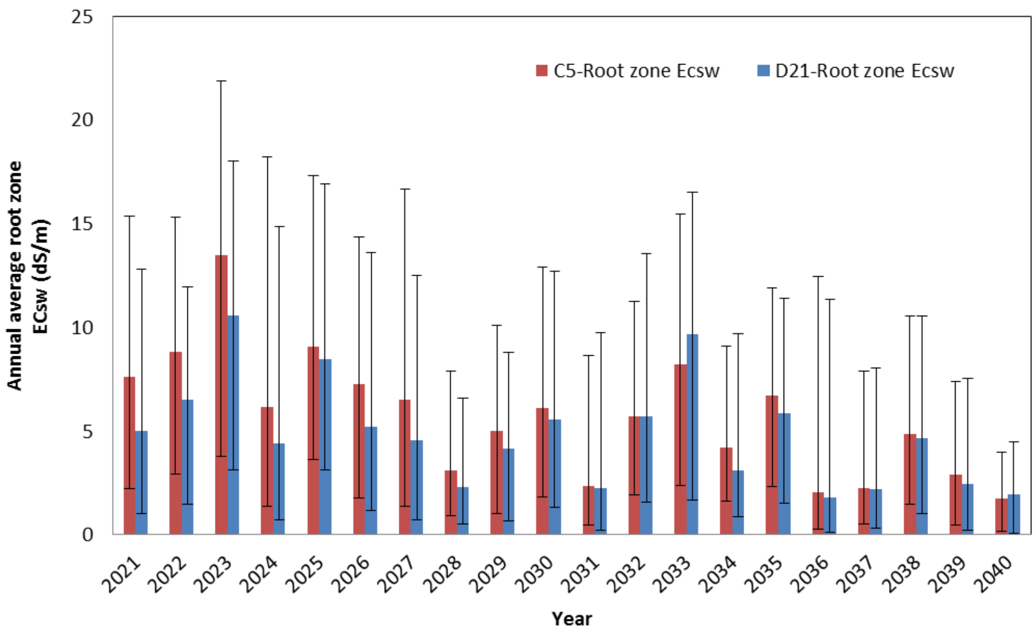


Figure 6.10 Salt accumulations in D21 paddock compared to C5 paddock under low rainfall condition. The error bar indicates the minimum and maximum root zone EC_{SW} occurred over a year.

From the above discussion, it is clear that soil type plays an important role in salt accumulation in the root zone. Soil texture is associated with its capability to infiltrate water, to hold available water (i.e. water holding capacity), and the soil's ability to exchange ions (Hillel 1980). Clayey type soils generally comprise of more cation exchange sites because of having more surface area (Hillel 1980), and therefore able to accumulate salt or more specifically accept excess sodium which contribute to the increase of soil water salinity. A coarse texture soil, on the other hand, has less total surface area, fewer exchange sites, and salt is easily transported downward through its larger particle size (Hillel 1980; Wang et al. 2009). Therefore, the variation of salt accumulation in C5 and D21 paddock soil can be attributed to the clay content of respective soil. As shown in Figure 6.10, the salt accumulation within the soil which contains more clay (C5 soil) appears to be higher compared to the soil which has more sand content (D21 soil). The C5 soil used in this study contains about 41% more clay content than that of D21 soil (Table 4.1). Contrary to the results discussed above, in some simulation years (such as 2033 and 2040), root zone EC_{SW} of D21 paddock were found higher than that of C5 paddock.

6.5.5 Impact of soil type on leaching

Over the simulation period, amount of leaching in D21 paddock was more than that of C5 paddock. On average, annual total amount of leaching from D21 paddock was 161.8 mm with a range of 25 to 449 mm (Figure 6.11). This wide range of leaching is because of the variation of yearly rainfall. Rainfall of adequate intensity and duration may flush the soil water and salts contained in it from upper to bottom layers of soil profile (Selle et al. 2010; Levy et al. 1999; Hardy et al. 1983; Agassi et al. 1981). As discussed in the previous section, clay type soil has more water holding capacity and less capability to drain water because of its smaller pore diameters. On the other hand, coarse texture soil's water holding capacity is less and water drains fast because of its larger pore diameters. Consequently, leaching occurs more in coarse texture of soil than clayey type soil. Similar observations were made from the simulation in current study for the soil of D21 (loamy sand) and C5 (loam) paddocks (Figure 6.11). Compared to D21 paddock, C5 paddock produced about 21% less amount of leachate. The simulated leached amount for the two paddocks also conforms to the findings obtained in the laboratory experiment (Figure 6.1*c*). The study of leaching amount from paddocks is important especially, if it includes underlying shallow aquifer. This is because the washed out salt from the root zone may end up contaminating groundwater aquifers. From Figure 6.11 it is evident that salt was leached more than overall average in some simulation years and this is more predominant in D21 paddock. As shown in the figure, in the years 2036 and 2040, where, total yearly leached amount from both the paddocks was 2 to 3 times more than the respective overall average leached amount. Therefore, continuous irrigation using recycled water over a long period of time may impact on the salinity levels of the groundwater in the perched aquifer situated at D21 paddock.

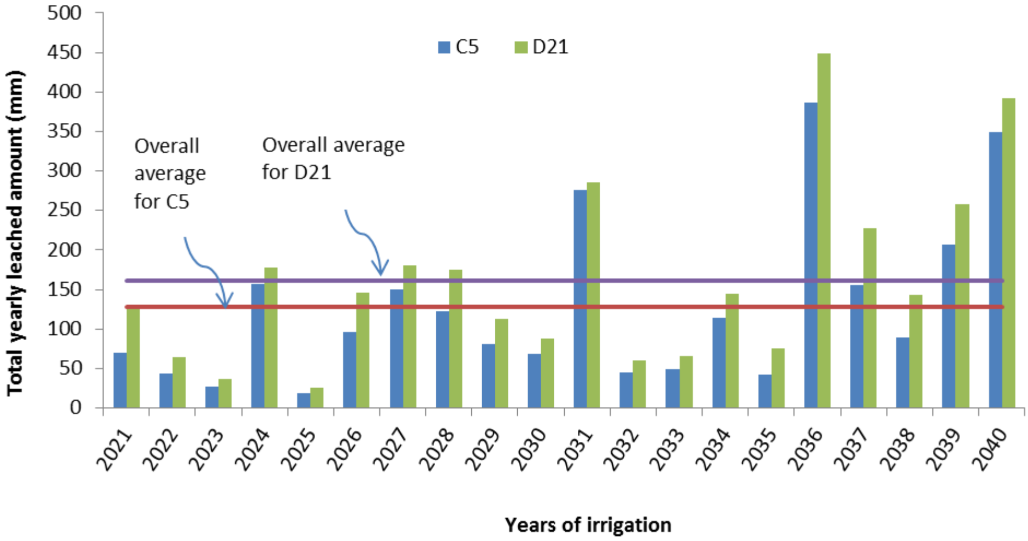


Figure 6.11 Variation of leaching of salt in D21 and C5 paddock for low rainfall condition

6.5.6 Impact of soil type on seasonal variation of root zone salt accumulation

The importance of seasonal variation in the root zone salinity and the classification of seasons in the study area are highlighted in Chapter 5. In this section, variability of salt accumulation due to variability in soil type will be investigated.

The seasonal variation of root zone EC_{SW} in D21 and C5 paddocks is shown in Figure 6.12. EC_{sw} values plotted in Figure 6.12 are the average values over the season. Comparison among seasonal salt accumulation was conducted for the year 2023. This particular year was selected because of its highest yearly EC_{SW} over the simulation period (Figure 6.10).

The root zone EC_{SW} in both D21 and C5 paddocks was found to be higher than salinity tolerance thresholds for pastures (in terms of EC_{SW}) including clovers and rye. According to NRMMC-EPHC-AHMC (2006) the threshold varies from 3.0 to 5.0 dS/m. The root zone EC_{SW} of C5 paddock was found more than EC_{SW} of D21 paddock for all four seasons. As shown in Figure 6.12, the winter season showed highest amount of salt accumulation compared to other seasons, which is because the winter season had lowest rainfall in the year 2023. Summer, autumn and spring season of the year 2023 had 2.4, 1.8 and 2.8 times more rainfall than winter season in this year. The EC_{SW} of C5 paddock in summer, autumn, winter and spring season exceeds the maximum salinity threshold limit by 2.2, 2.4, 3.3 and 2.9 times, respectively. In D21 paddock, root zone EC_{SW} exceeds the threshold by 2.2, 1.9, 2.2 and 2.1 times in summer, autumn, winter and spring seasons, respectively. The exceedance of root zone EC_{SW} of the maximum threshold limit salinity tolerance in both the paddocks may lead to the detrimental circumstances to the yield of pastures irrigated with recycled water in these paddocks. Management scenarios controlling root zone salt accumulation discussed in Chapter 8 may help reduce and control the root zone salt accumulation in these paddocks.

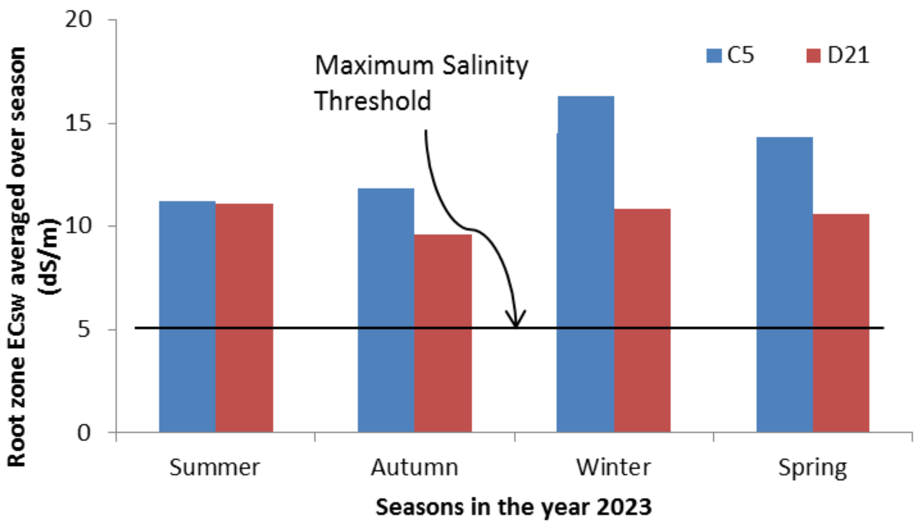


Figure 6.12 Seasonal variation of salt accumulation in D21 and C5 paddocks during the maximum salt accumulation year 2023

Generally, the findings of this study, such as experimental and simulated salt accumulation in two different types of soil, complies with the mechanism of salt accumulation, leaching, and seasonal variation of EC_{SW} reported in literature. The significance of this chapter, however, lies in explaining the impact of salinity due to recycled water irrigation under changing climate conditions, particularly under low rainfall scenarios. Also, the chapter discusses the impact of soil type on salt accumulation when recycled water is used for irrigation. This study will help the farm managers to plan for managing salinity in root zone as well as the underlying perched aquifer while using recycled water for irrigation.

6.6 Summary

A column study incorporating real-time monitoring of salinity in soil profile was conducted to investigate the salt accumulation in the soil of paddocks (D21 and C5) in Hawkesbury, NSW, which uses recycled water for irrigation. Based on the observed experimental results, it can be concluded that:

1. Soil type had little impact on salt mass balance of soil profile; amount of leachate was higher in loamy sand soil (D21) compared to that of loamy soil (C5), however, concentration of leachate was higher in loamy soil compared to loamy sand soil.
2. Sensor measured VWC was highly dependent on amount of applied water and sensor measured EC_{bulk} on the VWC. Dependence of EC_{bulk} on soil type was not evident. In-situ measured EC_{SW} was found higher in loamy sand soil compared to loamy soil, which may be attributed to not considering rainfall during the experimental study period. Calibration equation between EC_{bulk} and EC_{sw} was found to be good for D21 soil. However, C5 soil the equation provided a very poor fit.

The validated HYDRUS 1D model was applied to investigate the impact of recycled water irrigation on salt accumulation in the D21 and C5 paddocks for the years 2021 to 2040. Climatic data was obtained using Global Climate Model. Based on the predicted results, it can be concluded that:

1. Salt accumulation showed a cyclical pattern because of the variations in the rainfall and evapotranspiration.

2. Salt accumulation in terms of EC_{SW} was dependent on the soil type. When averaged over 20 years, salt accumulation in the root zone was found 24% higher in C5 paddock compared to D21 paddock.

3. Compared to C5 paddock, D21 paddock leached 27% more leachate, which may pose a salinity risk to the ground water table if there is a perched aquifer (<1 m depth below the surface) in field.

4. Seasonal variation of salt accumulation shows average root zone salinity exceeds the maximum salinity threshold limit in both D21 and C5 paddocks. Compared to D21 paddock, in C5 paddock root zone EC_{SW} was 1, 24, 51 and 35% higher in summer, autumn, winter and spring season, respectively.

Overall, the evidence from laboratory experiment and long-term modelling with future climate data presented in this chapter indicates that the salt accumulation in the soil depends on the soil type, which particularly appears to be important under low rainfall condition.

CHAPTER 7

IMPACT OF IRRIGATION WATER SALINITY ON SOIL SALINISATION

The following conference paper is a partial reproduction of this chapter

[1]Rahman, M.M., [1]Hagare, D., [2]Maheshwari, B. (2014). Impact of recycled water use compared to town water in urban irrigation: A long-term column study. Proceedings of International conference on Peri-urban landscapes: water, food and environmental security (PERI-URBAN2014), July 8-11, NSW, Australia

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7.1 Introduction

In Chapters 5 and 6, variation of salt accumulation with depth and impact of soil type on different aspects of salt accumulation is discussed for only one type of irrigation water (recycled water). In this chapter, impact of using different quality of irrigation water (in terms of salinity) on salt accumulation is investigated. This investigation is important in the sense that if the consequence of using different salinity of irrigation water on salt accumulation is available, this will help field managers to better manage the irrigation scheme. Three different types of irrigation water were used in a laboratory column study to see the impact on salt accumulation, namely, tap water, recycled water and synthetic saline water. As discussed in Section 3.5.3, the tap water is the town water that is commonly used for drinking, recycled water is the treated water used in the HWRS, and the synthetic water is saline water prepared in the laboratory. The impact of three types of irrigation water is investigated for two types of soils from paddocks of HWRS, namely, D33 and Yarramundi, which are of the texture of silty loam and loamy sand, respectively.

7.2 Methodology

The procedure of the continuous column study using tap, recycled and synthetic saline water is described in Section 3.5.4.3. Impact of irrigation water salinity on salt accumulation is firstly analysed by:

- calculating salt mass balance across the soil column, as per Section 5.2.1, for all three types of irrigation water for both D33 and Yarramundi paddock soil columns; and
- real-time monitoring of salinity at the average root zone depth (0.2 m from the surface of the soil column);

Later, results of the analysed soil samples, collected from every five centimetres, are presented in terms of $EC_{1:5}$, EC_e and soluble cations. The results project the status of salt accumulation at the end of the study period at different depths of the soil profile while comparing to their initial value. The initial values of $EC_{1:5}$, EC_e, soluble cations and SAR for D33 and Yarramundi paddock soils are discussed in Section 4.2.5.

7.3 Impact of irrigation water salinity on the salt mass balance

Figure 7.1 (*a*) shows the average salt stored in D33 paddock soil columns due to tap water (TW), recycled water (RW) and synthetic saline water (SW) irrigation. Stored salt load in columns using tap water varied with a standard deviation of 0.04 to 3.88 g/m^2. Similarly, for recycled water, they were 0.78 to 7.7 g/m^2 and 0.79 to 12.82 g/m^2 for synthetic saline water. This variation is due to the packing of the columns as discussed in previous chapters. During the study period, total cumulative salt mass stored in both RW and SW irrigated columns showed distinct increasing pattern within 21 days (Figure 7.1*a*). However, the salt accumulation pattern was different for TW irrigation, showing a negative salt accumulation at the beginning of the study period. The applied town water leached considerable amount of salt from the D33 soil profile starting from day 2 causing negative cumulative stored salt mass till 134 days. From day 135, a positive salt accumulation occurred and continued to increase throughout the study period. As expected, in SW irrigated columns more accumulation occurred compared to RW and TW irrigated columns. At the end of the study period of 330 days, SW irrigated columns showed 16.2 times more salt accumulation compared to TW irrigated columns, and 2.5 times more accumulation compared to RW irrigated columns. When compared between RW and TW irrigated columns, RW irrigated column showed 6.4 times more salt accumulation than TW irrigated column. Thus the results discussed above are indicative of increase of salinity in the D33 paddock soil in the absence of rainfall.

Salinity in the irrigation water had clear impact on the EC of leachate, which is shown in Figure 7.1 (*b*). It is interesting to see that EC of leachate in SW irrigated columns increased with the progression of study period. During the study period, average leachate EC from SW irrigated columns was 8.30 dS/m with a range between 2.18 and 16.03 dS/m; for RW irrigated columns average leachate EC was 3.32 dS/m (range from 1.33 to 8.44 dS/m) and it was 1.12 dS/m (range from 0.29 to 4.85) for TW irrigated columns. Cumulative amount of leachate (averaged over three columns) from SW and TW irrigated columns were almost same, which was recorded as 2.5 L; the value was 0.3 L more than the cumulative amount of leachate recorded from RW irrigated columns. The identical cumulative leachate amount confirms that same procedures were maintained in the operation of all nine columns.

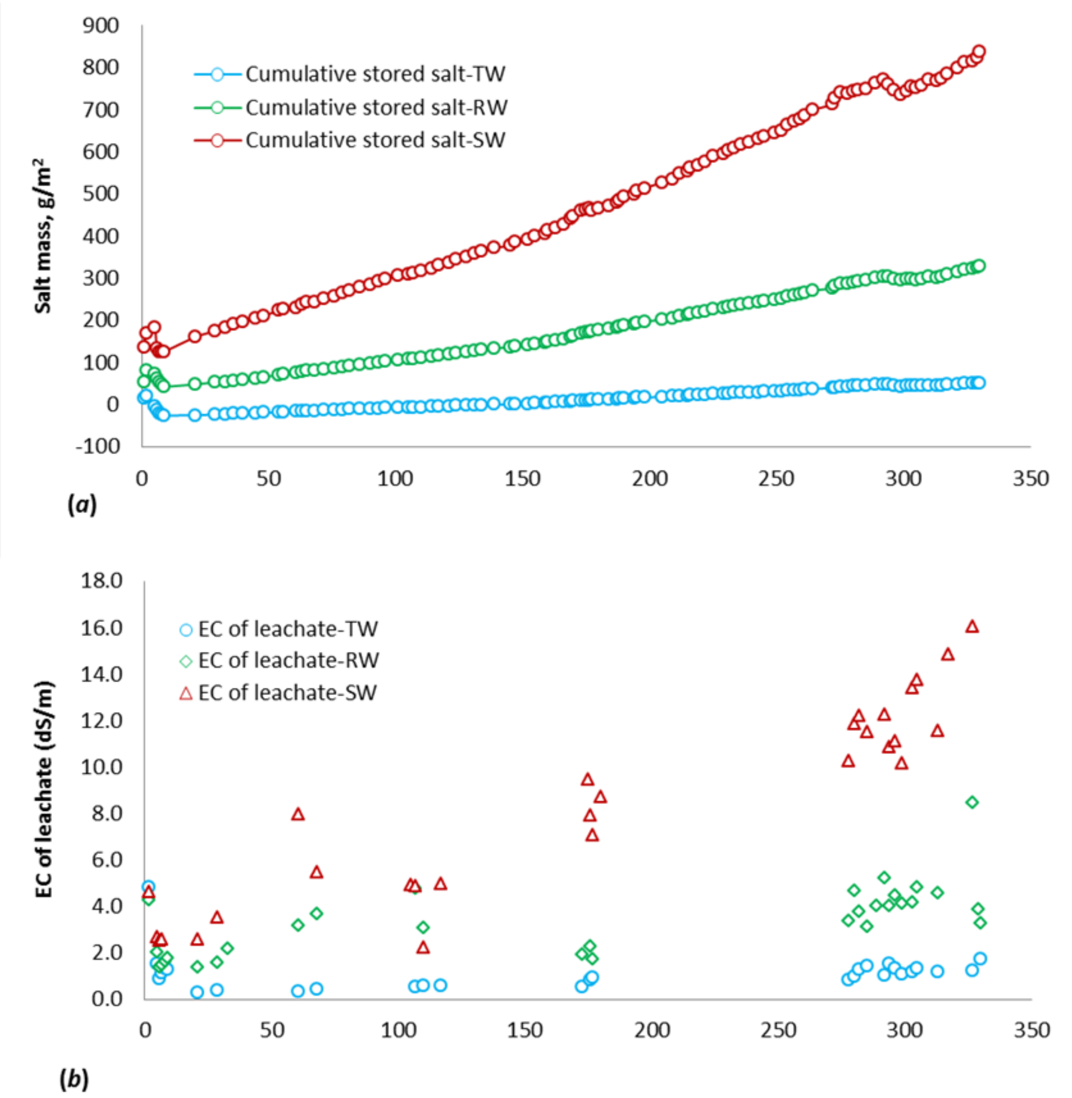

Figure 7.1 (a) Cumulative salt mass stored in columns (averaged over the results from three columns) (b) Variation of electrical conductivity (EC) of leachate during the study period using tap water (TW), recycled water (RW) and synthetic saline water (SW) as irrigation water for D33 paddock soil

Similar observations, as D33 soil columns, were made from results of column study with Yarramundi soil paddock (Figure 7.2). For columns with TW as irrigation water, positive cumulative salt accumulation started at day 76. It is interesting to observe that the negative accumulation of salt sustained in D33 paddock column for longer period of time compared to Yarramundi paddock column, which might be because of the difference in soil texture between these two types of soil and initial salt concentration. The silty loam soil (of D33 paddock) contains higher proportion of clay than loamy sand soil (of Yarramundi paddock), i.e., has low hydraulic conductivity, causing longer time to leach salt from the soil profile. Another reason may be attributed to the irrigation history of D33 paddock, which has 40 years of irrigation history with recycled water compared to zero years of irrigation history for Yarramundi paddock. When the soils were collected at the beginning of the study, the D33 soil had higher saturated electrical conductivity compared to Yarramundi paddock, which were 0.824 and 0.281 dS/m, respectively (Table 4.2).

In Yarramundi soil columns, at the end of the study period, SW irrigated columns showed 10.9 times more salt accumulation compared to TW irrigated columns, and 2.3 times more accumulation compared to RW irrigated columns (Figure 7.2*b*). When compared between RW and TW irrigated column, RW irrigated column showed 4.8 times more salt accumulation than TW irrigated columns. Similar to D33 soil columns, leachate from Yarramundi soil columns showed higher salt concentration as indicated by electrical conductivity (EC). During the study period, average EC for the leachate from SW irrigated columns was 6.40 dS/m with a range between 2.22 and 13.40 dS/m; for RW irrigated columns average EC of leachate was 1.81 dS/m (ranged from 0.83 to 3.06 dS/m), which was 0.66 dS/m (range from 0.15 to 1.67 dS/m) for TW irrigated columns. Electrical conductivity of leachate in Yarramundi soil columns were less when compared to D33 soil columns. The occurrence of leachate from Yarramundi soil columns was also not as frequent as D33 soil columns, especially for SW irrigated columns. In SW irrigated Yarramundi columns, no leachate was observed after 233 days. This unusual circumstance may be the cause of higher salt mass in Yarramundi soil columns compared to D33 soil columns. As shown in Figures 7.1 (*a*) and 7.2 (*a*), up to 233 days, in SW irrigated Yarramundi and D33 soil columns salt mass was closed to each other; 639.67 g/m^2 for Yarramundi and 609.39 g/m^2 for D33 soil columns. However, in the next 97 days, salt load in SW irrigated Yarramundi columns increased by 46%, whereas for D33 soil columns the salt load increased by 35%. This particular incident highlights the importance of leaching to reduce salt accumulation in the soil profile; relationship of salt accumulation with leaching is discussed in Chapters 5 and 6. Results of operation of all columns for D33 and Yarramundi paddocks are shown in Appendix D, Tables D1-D6.

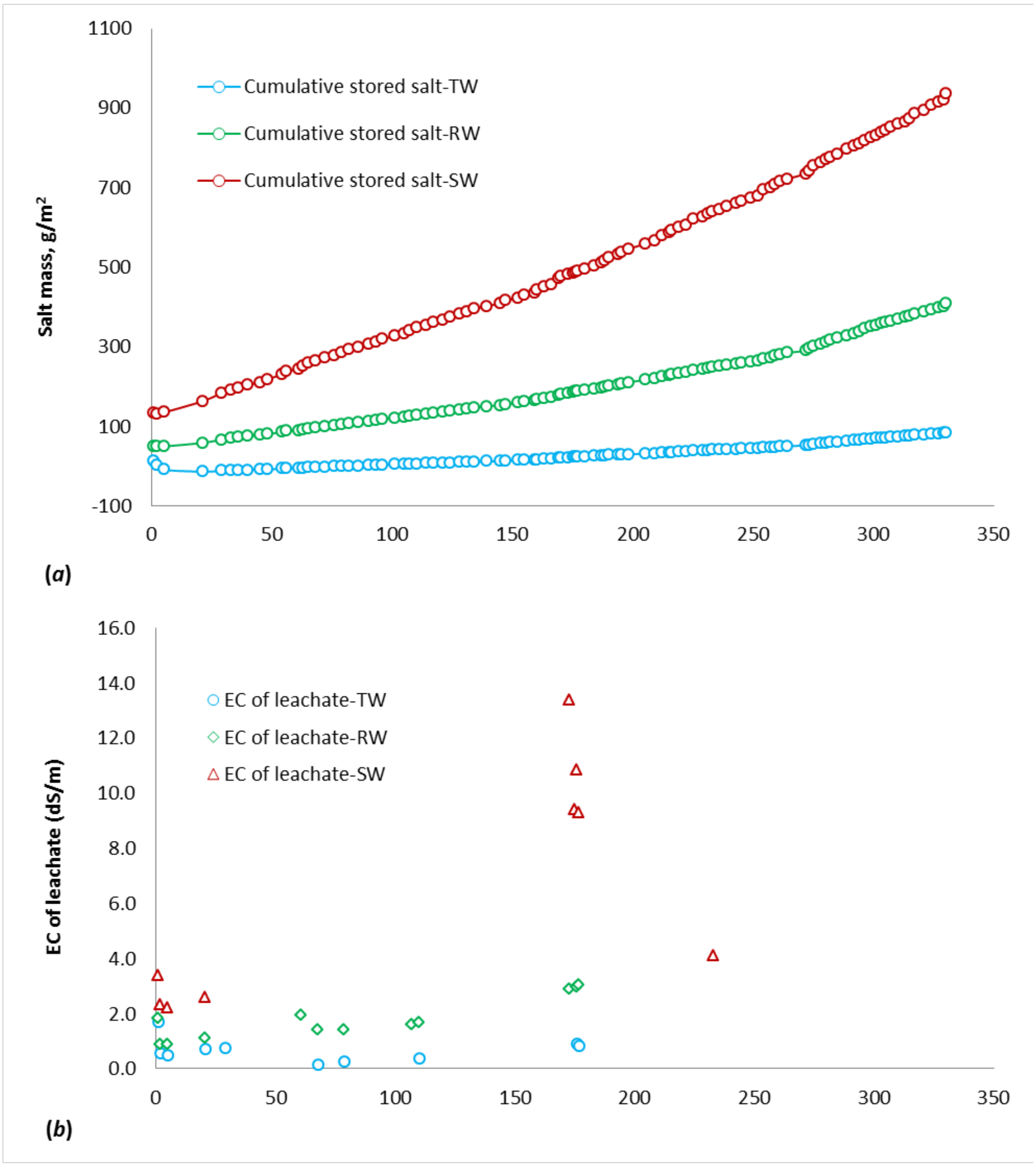

Figure 7.2 (a) Cumulative salt mass stored in columns (averaged over the results from three columns) (b) Variation of electrical conductivity (EC) of leachate during the study period using tap water (TW), recycled water (RW) and synthetic saline water (SW) as irrigation water for Yarramundi paddock soil

7.4 Impact of irrigation water salinity on continuous real-time monitoring of salt accumulation

Results of continuous real-time monitoring of VWC and EC_{bulk} at 0.2 m depth of D33 paddock soil columns are shown in Figure 7.3. Overall, in all three columns the values of VWC at 0.2 m depth was close to each other, which is shown in Figure 7.3 (*a*). The close values of VWC in the columns confirm that the columns performed similarly at the specified depth of 0.2 m. In other words, the column study was replicated reasonably; also, the interpretation of EC_{bulk} was less biased.

From the very beginning of the study period, SW irrigated columns showed higher EC_{bulk} than RW and TW irrigated columns. On average, SW irrigated columns showed 1.9 times more salinity in terms of EC_{bulk} when compared to RW irrigated columns, which was 2.8 times for TW irrigated columns. The RW irrigated column showed 1.5 times more EC_{bulk} compared to the TW irrigated columns. A rapid increase of EC_{bulk} after 270 day was observed for all SW, RW and TW irrigated columns, which is because of the increased application of irrigation water after Day 270. As shown in Figure 7.3 (*a*), during the period between Day 260 and 320, about 1.5 times more water was applied compared to the water applied (68.9 mm/month) during the period between Day 228 and 259. This increased amount of irrigation water was applied to keep the VWC close to 0.25, which is the field capacity of D33 paddock soil determined in Chapter 4 (Figure 4.2).

In the case of Yarramundi soil columns, variation of VWC in RW and TW irrigated columns were close to each other throughout the study period (Figure 7.4*a*). VWC in SW irrigated column varied by about 5% from the VWC in RW and TW irrigated columns over the study period. During most of the days in whole study period the VWC was recorded between 0.2 and 0.31, which was above the field capacity (VWC = 0.16) of the Yarramundi paddock soil, as reported in Chapter 4.

Similar variation of EC_{bulk}, to that observed in D33 columns, was observed for Yarramundi paddock columns. Column irrigated with SW showed higher EC_{bulk} than RW and TW irrigated columns (Figure 7.4*b*). On average, SW irrigated columns showed 3.6 times more salinity in terms of EC_{bulk} when compared to RW irrigated columns, which was 6.1 times for TW irrigated columns. The RW irrigated column showed 1.7 times more EC_{bulk} compared to the TW irrigated columns.

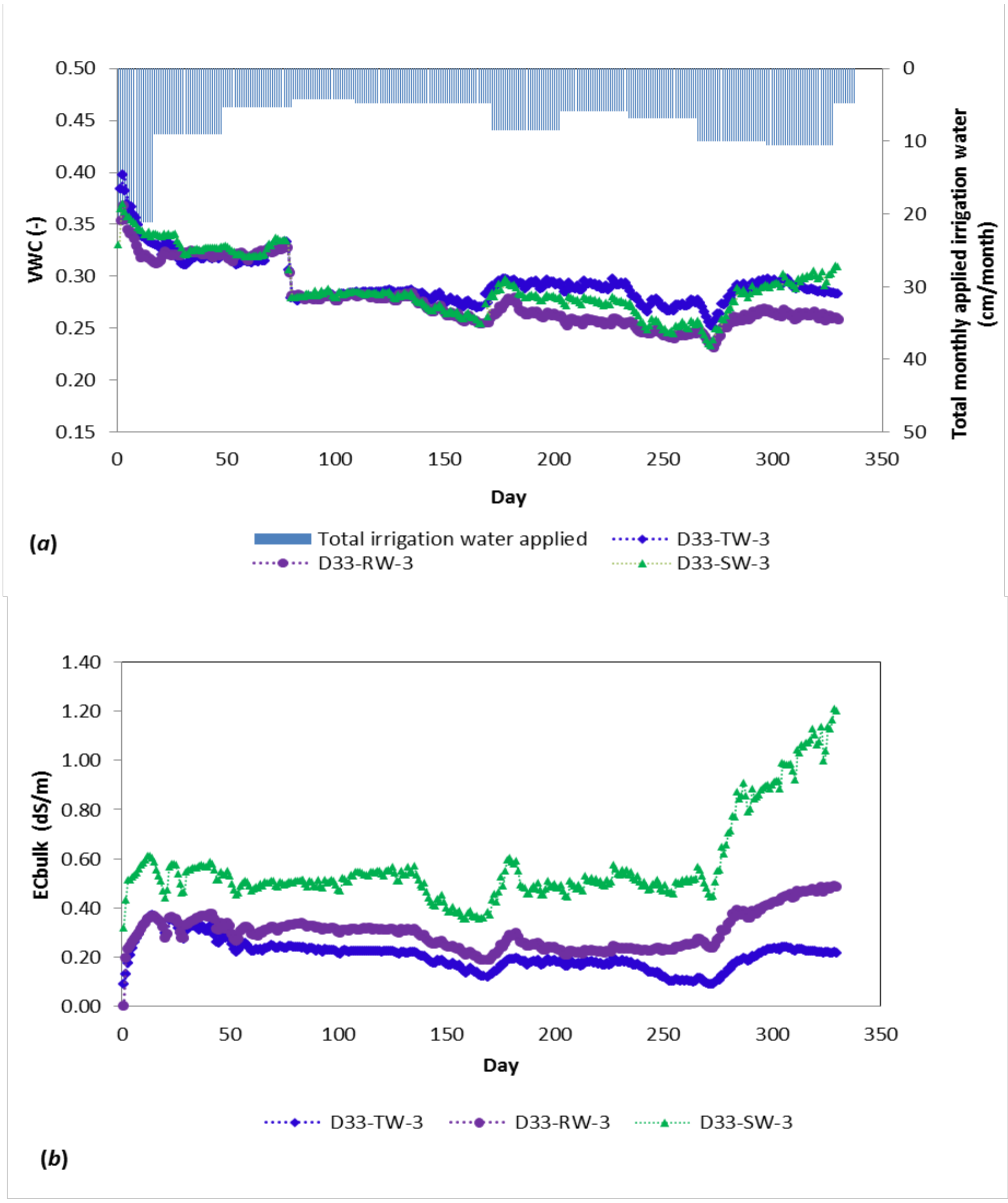

Figure 7.3 **(a) Variation of volumetric water content and (b) bulk electrical conductivity at 0.2 m depth measured by GS3 sensor in D33 paddock soil columns using tap water (TW), recycled water (RW) and synthetic saline water (SW) as irrigation water (VWC and EC_{bulk} averaged over a day).**

It seems, in Yarramundi paddock soil columns at 0.2 m depth, more salt accumulation occurred compared to D33 paddock soil columns; occurrence of the similar phenomenon is discussed in previous chapters (Chapter 5 and Chapter 6) when the column study was conducted in the absence of rain. Sensor measured parameters at the depth of 0.2 m for D33 and Yarramundi paddock columns are shown in Appendix D, Tables D7 and D8, respectively.

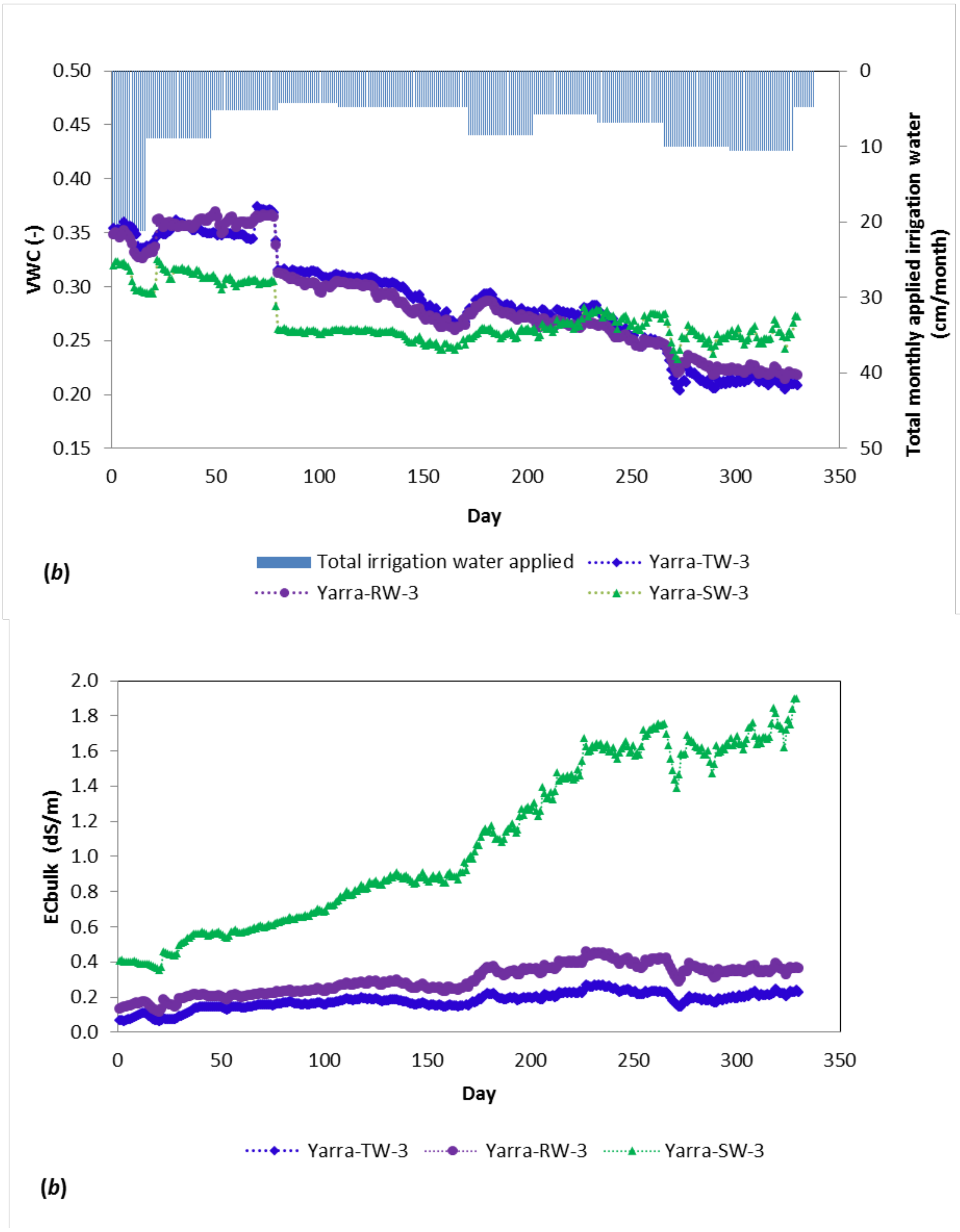

Figure 7.4 (a) Variation of volumetric water content and (b) bulk electrical conductivity at 0.2 m depth measured by GS3 sensor in Yarramundi paddock soil columns using tap water (TW), recycled water (RW) and synthetic saline water (SW) as irrigation water (VWC and EC_{bulk} averaged over a day).

7.5 Impact of irrigation water salinity on $EC_{1:5}$ and EC_e

7.5.1 Salt accumulation in terms of $EC_{1:5}$ and EC_e

Collection of soil samples at different depths and analysis of the same for $EC_{1:5}$ and EC_e are explained in Sections 3.5.4.3 and 3.3.4, respectively. Results of $EC_{1:5}$ at different depths of soil profile in D33 and Yarramundi paddock soil columns are shown in Figure 7.5. It should be mentioned that the results represent the salt accumulation at the end of the column study period of 330 days. As discussed in Section 3.5.4.3, the values of $EC_{1:5}$ at different depths (for each irrigation water type) were averaged over six soil samples. As shown in Figure 7.5 (*a*), most of the salt accumulation occurred between the depths of 0 and 0.1 m from the soil surface. This is expected due to more water evaporation from the upper part of the soil column than its lower part. In the top 0.05 m depth of soil column, SW irrigated columns showed 3.2 times more $EC_{1:5}$ than RW irrigated columns, which is 8.3 times more than TW irrigated columns. Compared to TW irrigated columns, RW irrigated columns showed 2.6 times more $EC_{1:5}$. The results confirm the impact of irrigation water salinity on soil salinity in terms of $EC_{1:5}$ at this depth. At this depth (0-0.1 m), the variation in the quantity of salt accumulated was higher compared to other part of the columns, which is shown by error bars. Especially, this is prominent for SW irrigated columns of D33 paddock soil. The results indicate the heterogeneous nature of salt accumulation at this depth of the D33 soil profile. For the depths between 0 and 0.2 m (i.e. average root zone depth), SW irrigated columns accumulated 2.7 and 6.8 times more salt compared to RW and TW irrigated columns, respectively, which was 2.5 times more in RW irrigated columns compared to TW irrigated columns. The variation of $EC_{1:5}$ was almost constant between depths 0.1 and 0.2 m in columns for all three types of irrigation water. However, the $EC_{1:5}$ increased again between the depths 0.25 and 0.3 m. On average, between depths 0.2 and 0.3 m, SW irrigated columns accumulated 2.4 and 4.9 times more salt compared to RW and TW irrigated columns, respectively, which was 2.0 times more in RW irrigated columns compared to TW irrigated columns. Therefore, from above discussion it can be concluded that with the increase of salinity in irrigation water (i.e. compared to each other), more salt accumulated between depths 0 and 0.2 m than depths 0.2 and 0.3 m in D33 paddock soil columns.

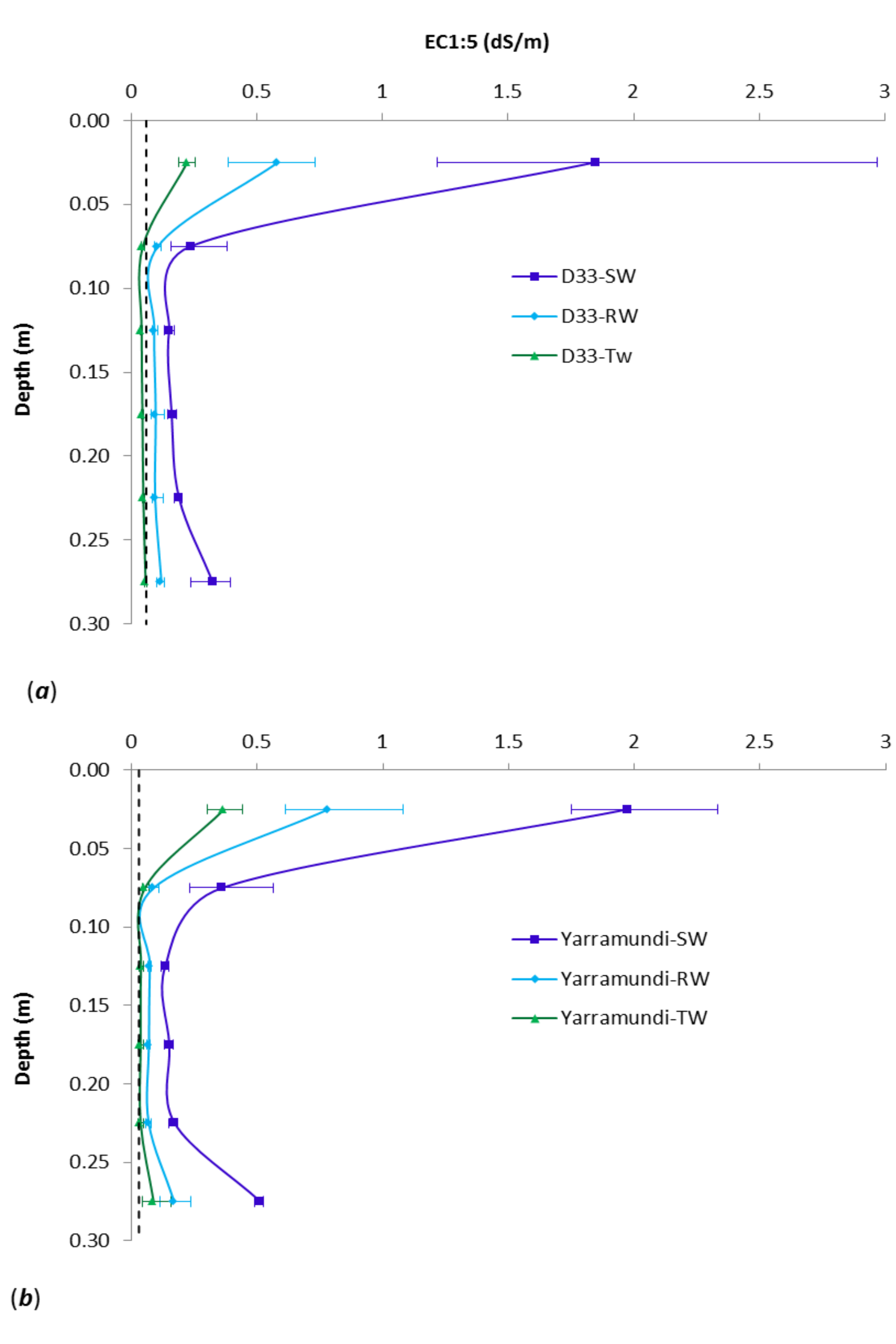

Figure 7.5 **Salinity profile in terms of EC1:5 using tap water (TW), recycled water (RW) and synthetic saline water (SW) as irrigation water in (a) D33 paddock soil columns (b) Yarramundi paddock soil columns after the study period of 330 days. The dotted line shows the initial EC1:5; the error bars show the minimum and maximum value of EC1:5 in columns irrigated with specific irrigation water (see Appendix D, Figures D1-D2 for $EC_{1:5}$ from individual column)**

Figure 7.5 (*a*) also shows the variation of $EC_{1:5}$ compared to its initial value at the start of the column study. Values of $EC_{1:5}$ and EC_e determined in D33 paddock soil before starting the column study is shown in Table 4.2. On average, between depths 0 and 0.2 m, $EC_{1:5}$ in SW and RW irrigated columns increased 10 and 3.7 times, respectively; between depths 0.2 and 0.3 m, the increase was 4.3 and 1.8 times, respectively. In TW irrigated columns, $EC_{1:5}$ increased 3.7 times (from 0.06 to 0.368 dS/m) only in the top 0.05 m of soil column, however decreased than initial value for all other depths. The results are indicative of appropriateness of using less saline water in controlling salinity in the irrigated soil.

Variation of salt accumulation in terms of $EC_{1:5}$ in Yarramundi paddock soil columns are shown in Figure 7.5 (*b*). Almost similar pattern of variation of $EC_{1:5}$ over the depth of the soil profile was observed, as of D33 paddock soil columns. For the depths between 0 and 0.2 m, SW irrigated columns accumulated 2.6 and 5.3 times more salt compared to RW and TW irrigated columns, respectively, which was 2.0 times more in RW irrigated columns compared to TW irrigated columns; the average values of $EC_{1:5}$ were higher than $EC_{1:5}$ observed at this depth of D33 paddock soil columns. On average, between depths 0.2 and 0.3 m, SW irrigated columns accumulated 2.9 and 5.5 times more salt compared to RW and TW irrigated columns, respectively, which was 1.9 times more in RW irrigated columns compared to TW irrigated columns.

When compared the variation of $EC_{1:5}$ to its initial value (Figure 7.5*b*) of Yarramundi paddock soil columns, for each type of irrigation water, $EC_{1:5}$ was higher between depths 0 and 0.2 m than depths between 0.2 and 0.3 m. On average, between depths 0 and 0.2 m, $EC_{1:5}$ in SW, RW and TW irrigated columns increased by 21.8, 8.4 and 4.1 times, respectively, which were 11.4, 4.0 and 2.1 times between depths 0.2 and 0.3 m. It seems, Yarramundi paddock soil columns showed more $EC_{1:5}$ in upper portion of the soil column (from 0 to 0.2 m) compared to $EC_{1:5}$ of D33 soil columns at the same depth. This may be due to the difference in soil type of these two paddocks. As indicated in Chapter 4, silty loam soil has higher water holding capacity compared to loamy sand soil, which may cause less evaporation from D33 paddock soil compared to Yarramundi paddock soil. In this experiment, evaporation is the main mechanism to concentrate salt in the soil; more evaporation was taken place from the Yarramundi paddock soil columns compared to D33 paddock soil columns which led to more salt accumulation in upper part of the Yarramundi soil columns compared to D33 paddock soil columns.

Salt accumulation in terms of EC_e at different depths of soil profile in D33 and Yarramundi paddock soil columns are shown in Figure 7.6. Generally, salt accumulation in terms of EC_e in all the columns followed the typical cyclical pattern of salt accumulation, discussed in Chapters 5 and 6. The cyclical pattern of salt accumulation shown in Figure 7.6 is associated to the variation of evaporation and application of irrigation water, and subsequent downward transportation of salt. Salinity profile in terms of EC_e due to different irrigation water (namely, SW, RW and TW) in D33 and Yarramundi paddock soil was found similar to the salinity profile of $EC_{1:5}$, discussed above; although, they differed quantitatively. Hence, detailed description of the variation of EC_e in the columns is excluded from the discussion.

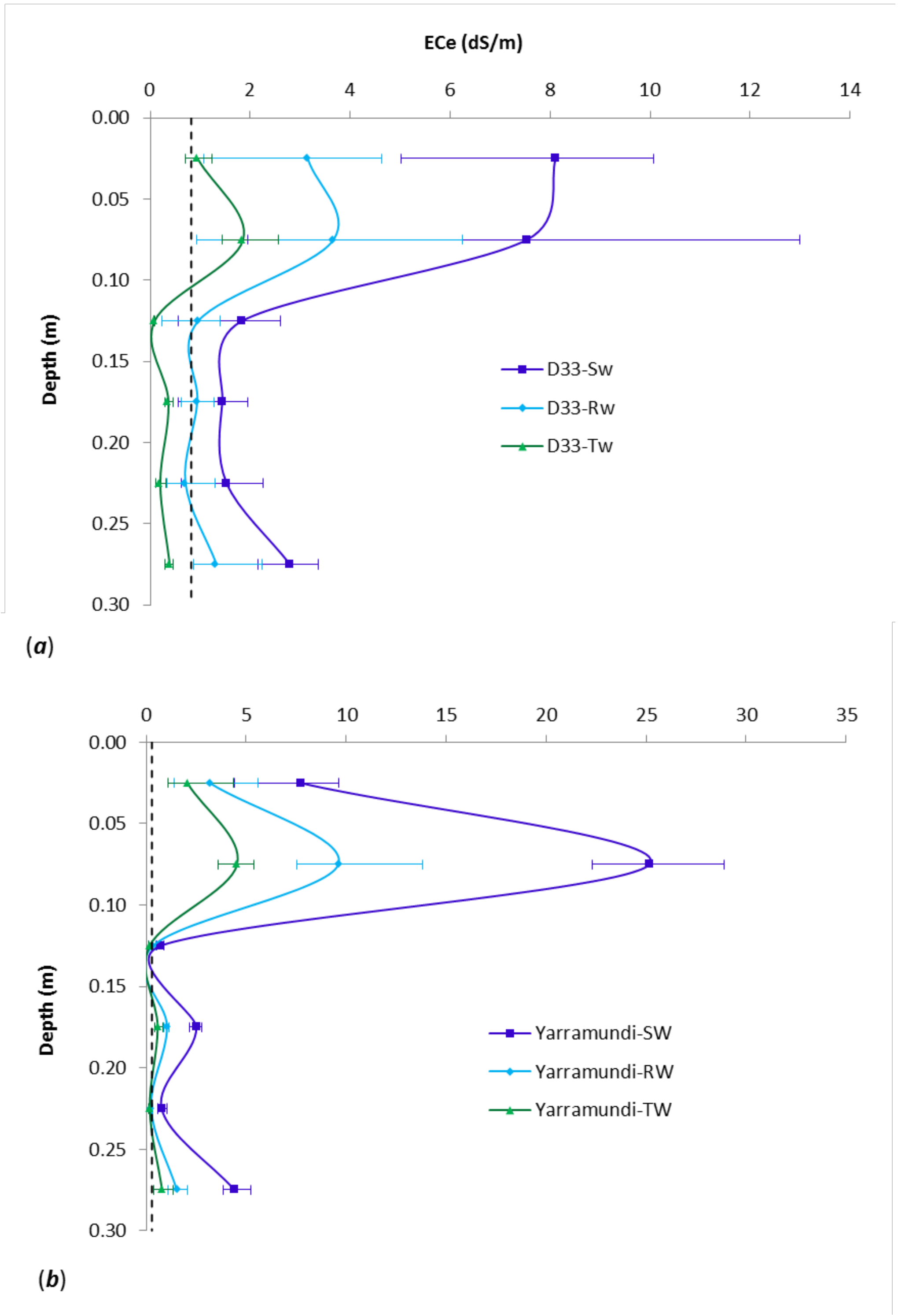

Figure 7.6 **Salinity profile in terms of ECe using tap water (TW), recycled water (RW) and synthetic saline water (SW) as irrigation water in (a) D33 paddock soil columns (b) Yarramundi paddock soil columns after the study period of 330 days. The dotted line and error bars show the initial EC1:5 and the minimum and maximum value of EC1:5, respectively (see Appendix D, Figure D3-D4 for EC_e from individual column)**

7.5.2 Estimation of EC_e from values of $EC_{1:5}$

As discussed in Section 4.2.2, extraction of soil water solution for the determination of $EC_{1:5}$ is quicker and easier than the extraction of soil water solution for EC_e. Therefore, it is advantageous to find EC_e from the given value of $EC_{1:5}$ in denoting salt accumulation using a suitable conversion equation. In this section, a site specific equation for converting $EC_{1:5}$ to EC_e for both D33 and Yarramundi paddocks are proposed.

The relationship between measured EC_e and $EC_{1:5}$ in soil samples from D33 soil columns are shown in Figure 7.7. Data presented in Figures 7.5 (*a*) and 7.6 (*a*) were used to develop the relationship. As shown in Figure 7.7 (*a*), the measured EC_e values in samples from D33 paddock soil columns were found to be poorly correlated with $EC_{1:5}$ when all data were considered. However, the values of EC_e were found to be strongly correlated to $EC_{1:5}$ when values of EC_e > 10 dS/m were omitted (Figure 7.7*b*). The values of EC_e > 10 dS/m were omitted because below the EC_e value of 10 dS/m, highest correlation was achieved between EC_e and $EC_{1:5}$. A simple linear regression equation was proposed, which is:

$$EC_e = 5.63 \times EC_{1:5} + 0.33 \qquad (7.1)$$

The p-value of the predictor variable ($EC_{1:5}$) of the Equation 7.1 was found to be zero, which suggests the predictor as a meaningful entity in the regression equation. The RMSE value shows satisfactory agreement between experimental and regressed values (Figure 7.7*b*). The regressed EC_e determined for soil samples underestimated the experimental EC_e by less than 0.5% which is shown by BIAS in Figure 7.7 (*b*). Therefore, the proposed regressed equation is suitable to measure samples having EC_e values < 10 dS/m and $EC_{1:5}$ values < 1.5 dS/m for D33 paddock soils. The segmentation of observed EC_e and $EC_{1:5}$ values, to develop a suitable relationship between EC_e and $EC_{1:5}$, was also reported by other researchers (He et al. 2013; Agarwal et al. 1961; Visconti et al. 2010).

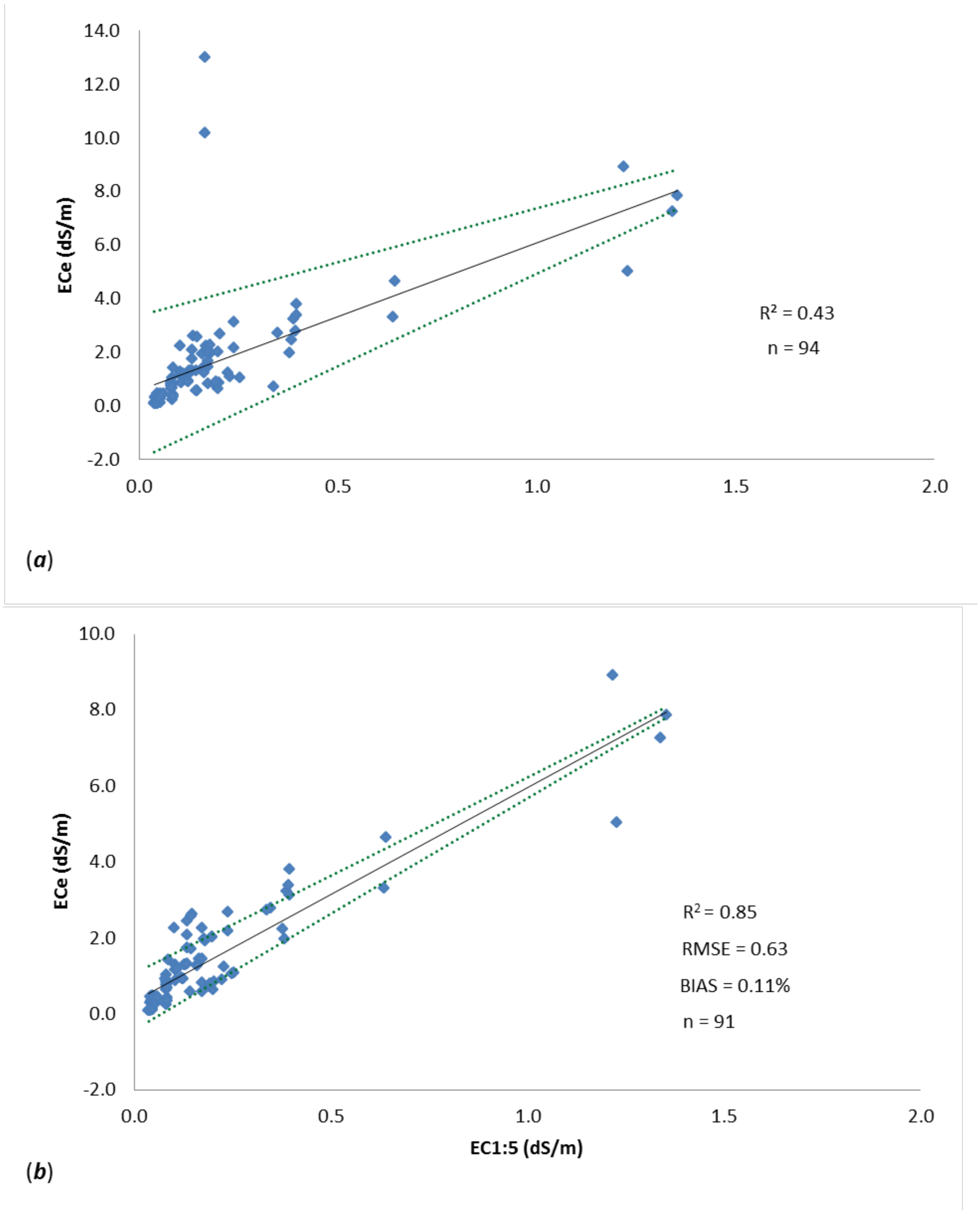

Figure 7.7 Relationships between electrical conductivity of 1:5 soil water extract ($EC_{1:5}$) and saturated paste extract (EC_e) for soil samples collected from depths 0 to 0.3 m after 330 days of column study from D33 paddock soil columns (*a*) for all data (*b*) for EC_e data ranged between 0 and < 10 dS/m and $EC_{1:5}$ data ranged between 0 and < 1.5 dS/m. The dotted lines show upper and lower limit of 95% confidence interval.

Correlation between values of EC_e and $EC_{1:5}$ measured in soil samples from Yarramundi paddock soil columns are shown in Figure 7.8. Data presented in Figures 7.5 (*b*) and 7.6 (*b*) were used to develop the relationship. As shown in Figure 7.8 (*a*), the measured EC_e values in samples from Yarramundi paddock soil columns were found to be poorly correlated with $EC_{1:5}$ when all data were considered. However, the values of EC_e were found to be strongly correlated to $EC_{1:5}$ when values of EC_e > 10 dS/m were omitted (Figure 7.8*b*). A simple linear regression equation was proposed, which is:

$$EC_e = 3.85 \times EC_{1:5} + 0.53 \quad (7.2)$$

The p-value of the predictor variable ($EC_{1:5}$) of the regression equation was found to be zero, which suggests the predictor as a meaningful entity in the regression equation. The RMSE value shows satisfactory agreement between experimental and regressed values (Figure 7.8*b*). The regressed EC_e determined for soil samples overestimated the experimental EC_e by less than 0.5% which is shown by BIAS in Figure 7.8 (*b*). Similar to D33 paddock soil, the proposed regression equation is suitable to measure samples having EC_e values < 10 dS/m and $EC_{1:5}$ values < 2.5 dS/m for Yarramundi paddock soils.

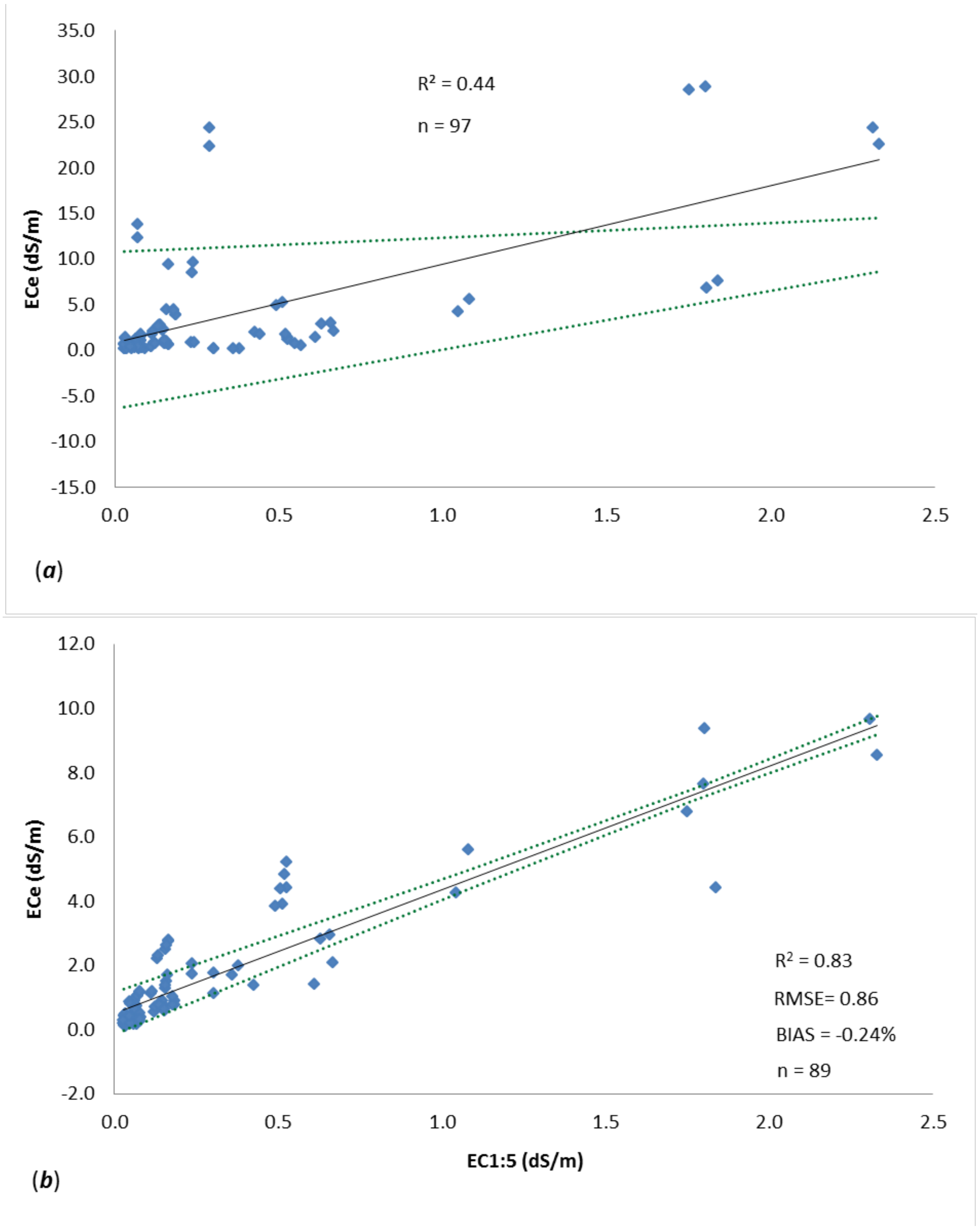

Figure 7.8 **Relationships between electrical conductivity of 1:5 soil water extract ($EC_{1:5}$) and saturated paste extract (EC_e) for soil samples collected from depths 0 to 0.3 m after 330 days of column study from Yarramundi paddock soil columns (*a*) for all data (*b*) for EC_e data ranged between 0 and < 10 dS/m and $EC_{1:5}$ data ranged between 0 and < 2.5 dS/m. The dotted lines show upper and lower limit of 95% confidence interval.**

7.6 Impact of irrigation water salinity on soluble cations

Results of soluble cations in terms of Ca^{2+}, Mg^{2+}, Na^+ and K^+ at different depths of soil profile in D33 and Yarramundi paddock soil columns are shown in Figures 7.9 and 7.10, respectively. The soluble cations were measured in the saturated paste extract (Section 3.5.4.3) according to the procedure mentioned in Section 3.3.6. The general behavior of sodium was found to be similar to that of the EC_e in Figure 7.6. Na^+ increased more in the top 0.1 m depth of soil profile (due to higher evaporation at this depth compared to lower part of the column), however, maintained a cyclical pattern throughout the soil profile. Higher Na^+ concentration at the top part of the columns may also be because of not considering rainfall during the study period. According to Gonçalves et al. (2006), in the absence of rainfall, Na^+ concentration peaked in the upper layer of soil profile, however, reached to the initial condition after occurrence of rainfall; amount of Na^+ in the lower layer increased after the rainfall. In our study, the low values of Na^+ concentration in the lower part of the column may be because of lack of flushing of Na^+ from the top part of the column by rainfall; nominal increase of Na^+ in some depths between 0.15 and 0.3 m may be because of leaching of some Na^+ from upper part (0-0.1 m) and transport to downward due to application of irrigation water.

As expected, Na^+ in soil columns irrigated with synthetic saline water (SW) was higher than columns irrigated with other two types of irrigation water; amount of Na^+ in synthetic saline water was 2.5 times higher than recycled water and 12.3 times higher than tap water. The highest concentration of Na^+ was observed in Yarramundi paddock soil (Figure 7.10*a*) in the top 0.1 m depth, which was almost double of the Na^+ concentration observed in D33 paddock at this depth (Figure 7.9*a*); this may be because of the difference in soil type as discussed in Section 7.5.1. Figures 7.9 and 7.10 also present results for Ca^{2+}, Mg^{2+} and K^+ concentrations. Once again, the general pattern of variation of these cations was similar to that of Na^+.

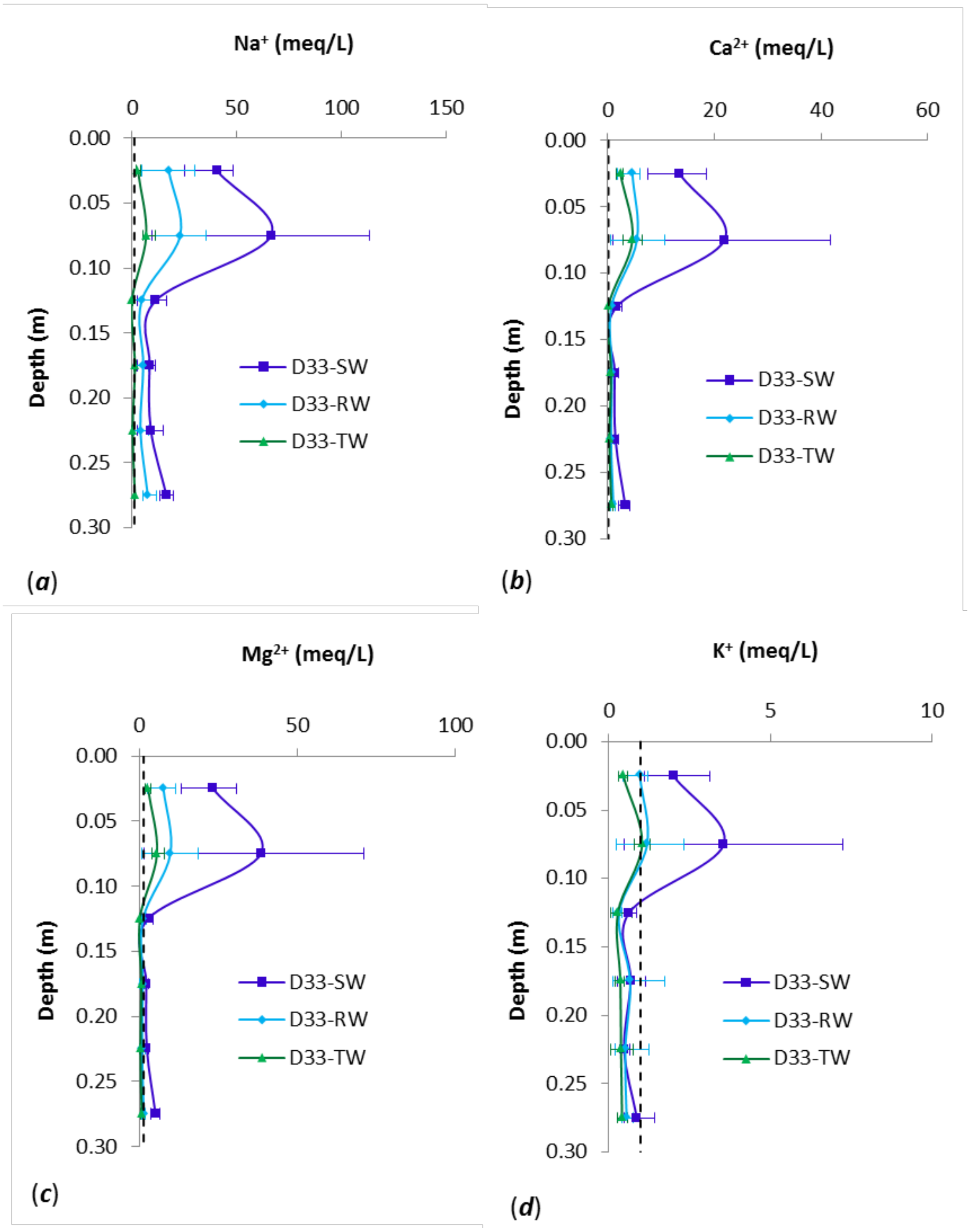

Figure 7.9 Salinity profile in terms of soluble cations (a to d) using tap water (TW), recycled water (RW) and synthetic saline water (SW) as irrigation water in D33 paddock soil columns after the study period of 330 days. The dotted line and error bars show the initial value of cation, and the minimum and maximum values of measured cation, respectively (see Appendix D, Figure D5-D8 for measured soluble cation from individual column)

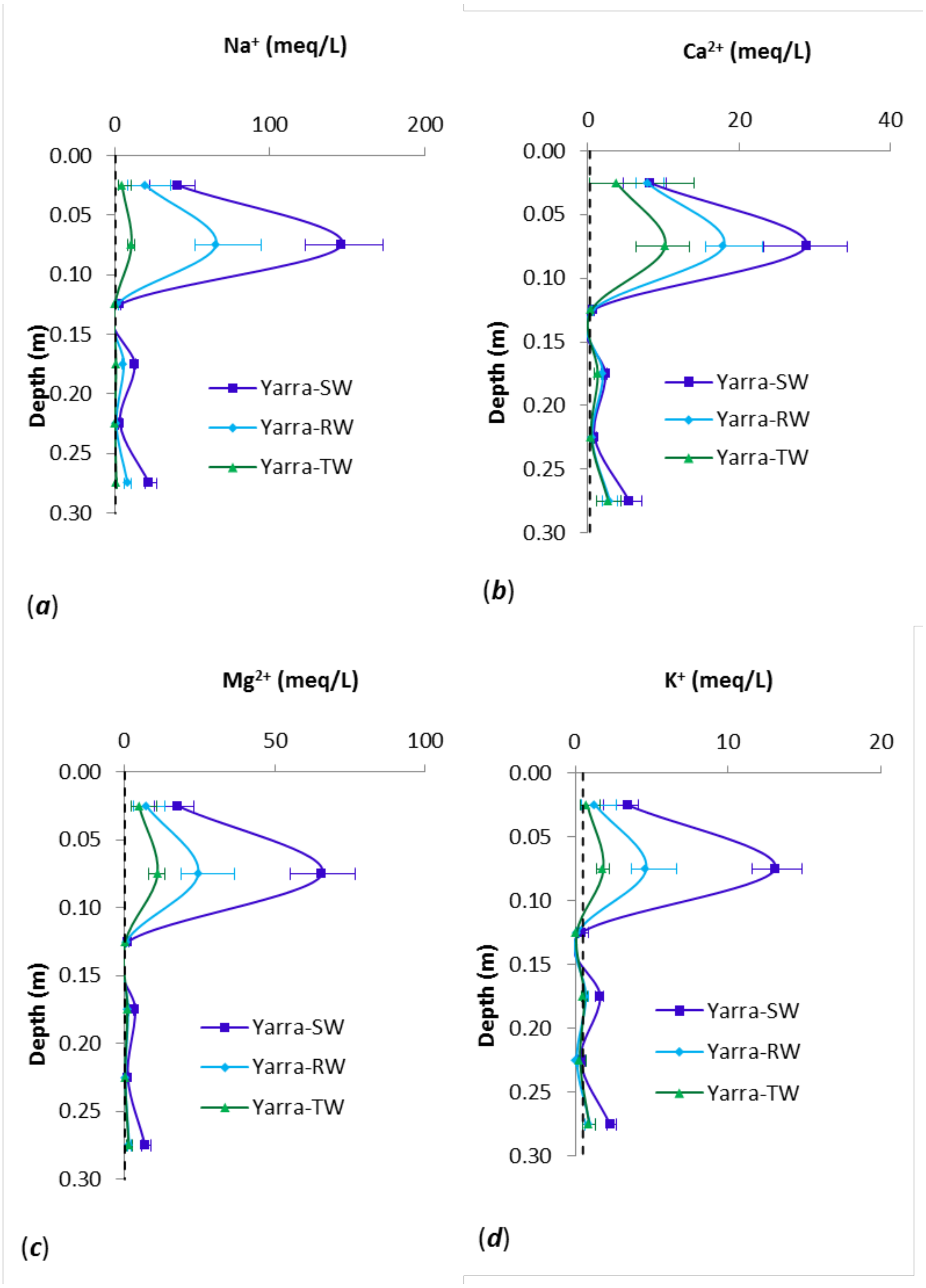

Figure 7.10 Salinity profile in terms of soluble cations (a to d) using tap water (TW), recycled water (RW) and synthetic saline water (SW) as irrigation water in Yarramundi paddock soil columns after the study period of 330 days. The dotted line and error bars show the initial value of cation, and the minimum and maximum values of measured cation, respectively (see Appendix D, Figure D9-D12 for measured soluble cation from individual column)

7.6.1 Sodium adsorption ratio (SAR)

Results of soluble Na^+, Ca^{2+} and Mg^{2+} was used to calculate sodium adsorption ratio (SAR) according to the Equation 2.1. As discussed in Section 2.3, SAR provides information on the comparative concentration of Na^+, Ca^{2+} and Mg^{2+} in soil solutions; the adverse effect of Na^+ is compensated by the presence of Ca^{2+} and Mg^{2+} in the soil solution (Gonçalves et al. 2006). The sodicity profile in terms of SAR is shown in Figure 7.11 for D33 and Yarramundi paddock soil columns. A distinct impact of changing the salinity in the irrigation water was observed on the SAR measured in the saturated paste extract (Figure 7.11); the SAR in both types of soil increased with the increase of salinity in the irrigation water. As expected, the variation of SAR throughout the soil profile followed similar pattern of EC_e.

It should be noted that soluble cation concentrations and SAR presented in Figures 7.9 to 7.11 represents the profile for a single period of time (i.e. at the end of the study period). For getting a representative picture of cyclical nature of cation accumulation in the soil profile, presenting the data in time series is favorable; unfortunately it was not possible in this particular experiment, as saturated paste extract was possible to get only at the end of the experiment. Variation of cations with time and impact of rainfall on cation accumulation was simulated in the laboratory for D21 paddock soil which is presented in Chapter 9.

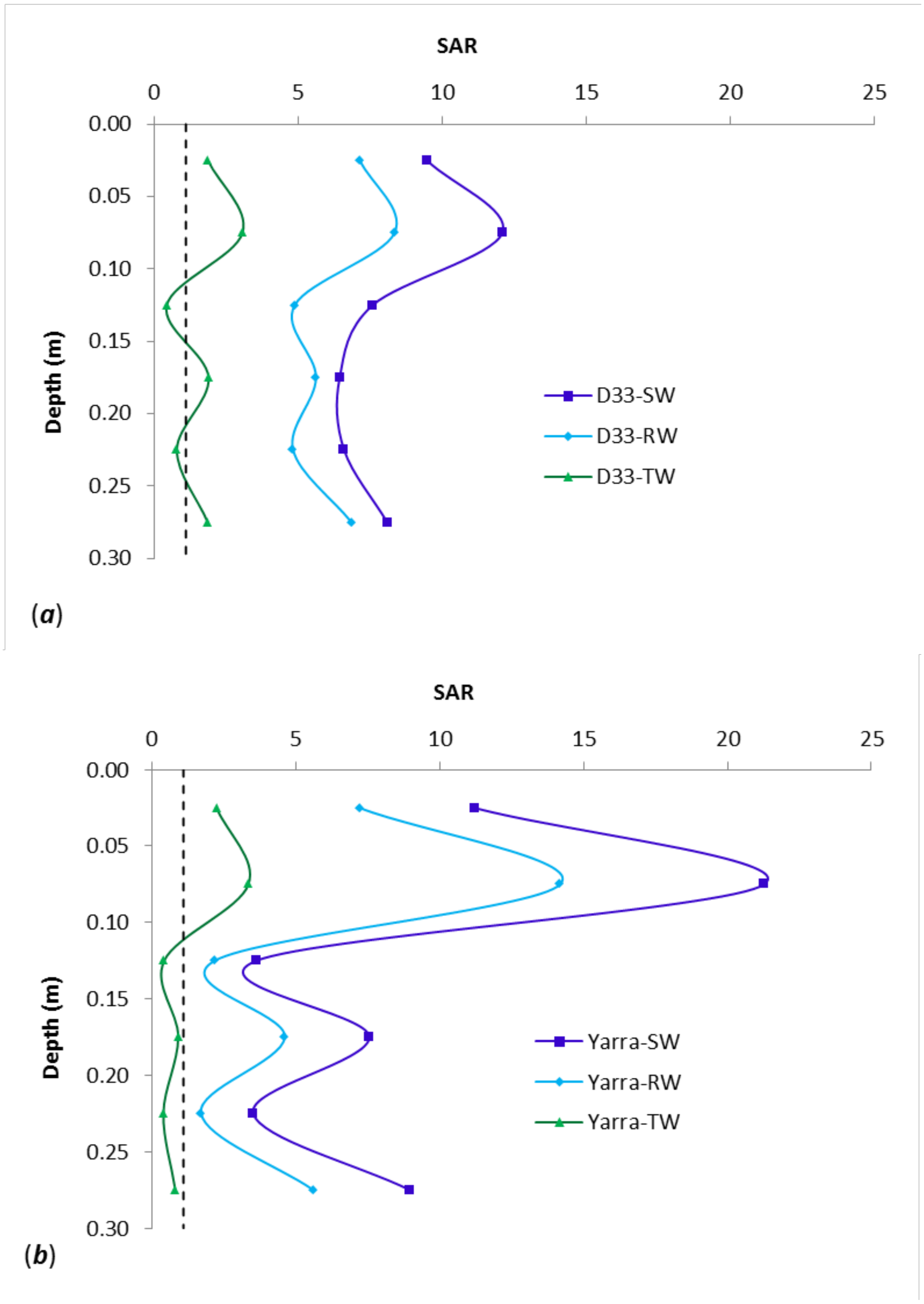

Figure 7.11 Sodicity profile in terms of SAR using tap water (TW), recycled water (RW) and synthetic saline water (SW) as irrigation water in (*a*) D33 paddock soil columns (*b*) Yarramundi paddock soil columns after the study period of 330 days. The dotted line shows the initial SAR.

7.6.2 Relationships of EC_e with soluble cations

Figure 7.12 (*a*) shows the correlation between EC_e and the concentration of total cation ($Na^+ + Ca^{2+} + Mg^{2+} + K^+$, denoted as C_{sum}) measured in the saturated paste extract for samples collected from D33 paddock soil columns. Data presented in Figures 7.6 (*a*) and 7.9 was used to develop the relationships. The values of EC_e and C_{sum} were found to be highly correlated and a regressed equation was proposed (Figure 7.12*a*). The proposed regression equation was developed for EC_e ranged between 0.07 and 13 dS/m; the C_{sum} ranged between 0.5 and 132 meq/L. The equation is suitable to calculate C_{sum} for a given value of EC_e at these ranges for soil similar to D33 paddock. The regression equation between the variables EC_e and C_{sum} was found to be similar to the relationships ($EC_e = 0.1\ C_{sum}$) proposed by Bresler et al. (1982). Similar correlation between EC_e and the concentration of total cation measured in the saturated paste extract for samples collected from Yarramundi paddock soil columns were evaluated and presented in Figure 7.13 (*a*).

Figure 7.12 (*b*) was developed to find relationships of individual cations to C_{sum} in saturated paste extract. In the previous section (Section 7.6.1), SAR provided information on the comparative concentrations of Na^+, Ca^{2+} and Mg^{2+} in the saturated paste extract from samples collected along the depth of the soil profiles. However, relationships of concentration of individual cation (such as Na^+, Ca^{2+}, Mg^{2+} or K^+) to its total cation concentration is useful to assess the impact of individual cation on ionic composition of saturated paste extract (or soil water). This also highlights if any cation is responsible for the nutritional limitations in the root zone soil water, which may impact crop growth (Oanzen and Chang 1988). According to Oanzen and Chang (1988), two phenomena may restrict the crop yield because of salt accumulation in the root zone, which are osmotic stress and nutrition limitation in the soil water. Therefore, relationships of individual cations to the total salinity (in terms of cation concentration) in saturated paste extract are proposed for D33 paddock soil as follows (Equations 7.3 – 7.6):

$$Na^{+} = 0.52 \times C_{sum} + 0.79\ , \qquad p\text{-value} = 0.001 \qquad (7.3)$$

$$Mg^{2+} = 0.29 \times C_{sum} - 0.91\ , \qquad p\text{-value} < 0.0001 \qquad (7.4)$$

$$Ca^{2+} = 0.16 \times C_{sum} - 0.20\ , \qquad p\text{-value} = 0.063 \qquad (7.5)$$

$$K^{+} = 0.02 \times C_{sum} - 0.32\ , \qquad p\text{-value} < 0.0001 \qquad (7.6)$$

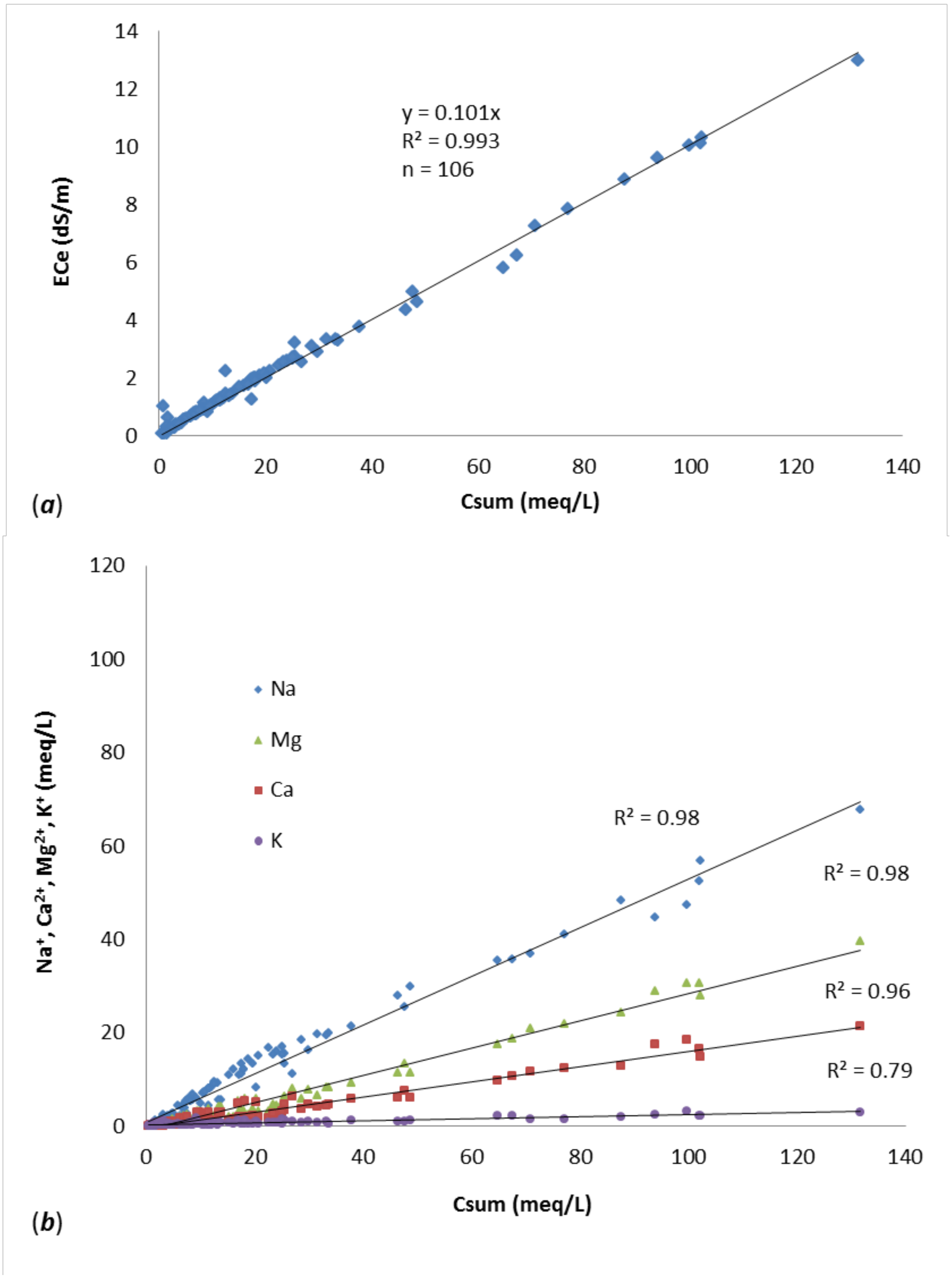

Figure 7.12 Relationships between *(a)* electrical conductivity (EC_e) and concentration of total cation (C_{sum}) (*b*) concentration of individual cation and C_{sum} in the saturated paste extract from soil samples collected from depths 0 to 0.3 m after 330 days of column study from D33 paddock soil columns.

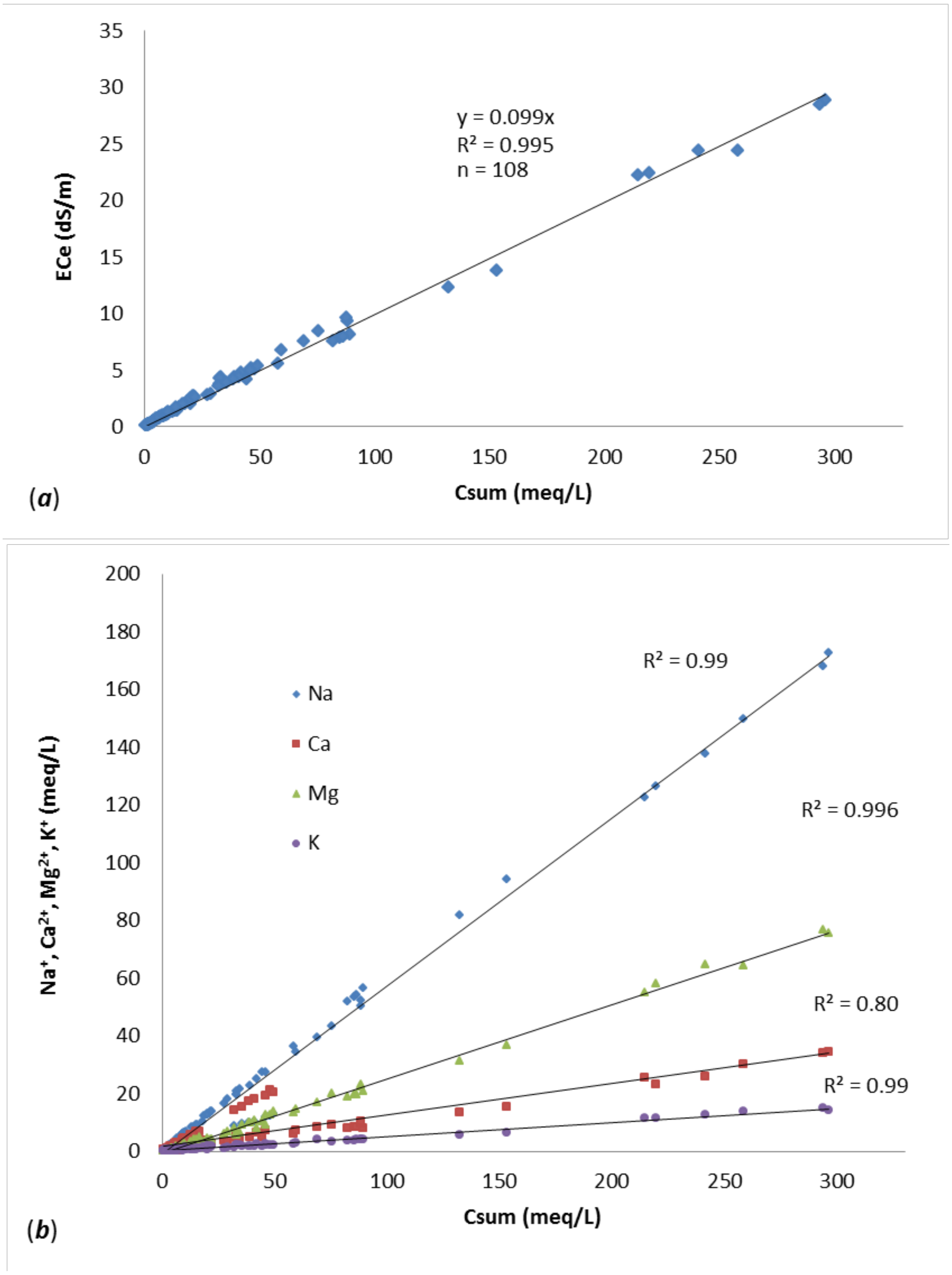

Figure 7.13 Relationships between *(a)* electrical conductivity (EC_e) and concentration of total cation (C_{sum}) (*b*) concentration of individual cation and C_{sum} in the saturated paste extract from soil samples collected from depths 0 to 0.3 m after 330 days of column study from Yarramundi paddock soil columns.

Equations 7.3 – 7.6 can be used to determine the ionic composition of saturated paste extract from D33 paddock soil for a given C_{sum}. It is needless to say for a given EC_e, the total cation concentration can be calculated using the relationship shown in Figure 7.12 (*a*). Similar equations were developed for Yarramundi paddock soil as below (Equations 7.7 – 7.10):

$$Na^{+} = 0.58 \times C_{sum} - 1.03 \,, \qquad p\text{-}value = 0.015 \qquad (7.7)$$

$$Mg^{2+} = 0.26 \times C_{sum} - 0.64 \,, \qquad p\text{-}value < 0.0001 \qquad (7.8)$$

$$Ca^{2+} = 0.11 \times C_{sum} + 1.54 \,, \qquad p\text{-}value < 0.0001 \qquad (7.9)$$

$$K^{+} = 0.05 \times C_{sum} + 0.14 \,, \qquad p\text{-}value = 0.001 \qquad (7.10)$$

The high correlation coefficient between individual and the total cation concentration, and low *p*-values for the developed equations confirm that the developed equations (7.3 – 7.10) are noteworthy.

As shown in Figures 7.12 (*b*) and 7.13 (*b*), all the cation concentrations increased linearly with the increase of total salinity, however, the ratio of soluble cations in soil samples varied. For example, in the case of RW irrigated D33 paddock soil, the soluble cations in the soil sample was found for $Na^+/Mg^{2+}/Ca^{2+}/K^+$ as 0.61/0.22/0.13/0.04, which was recorded initially at the beginning of the study as 0.34/0.37/0.04/0.25, respectively. Similarly, for RW irrigated Yarramundi paddock soil, the ration was found as 0.62/0.22/0.11/0.04, which was recorded initially at the beginning of the study as 0.35/0.11/0.18/0.35, respectively. The change in the ration occurred because of exchanging cations. Due to the presence of high sodium in the recycled water, continued irrigation with recycled water led the increase of Na^+ and decrease of K^+. This will lead to the increase of sodicity in soils and reduction of nutrients available to plants.

7.8 Summary

A column study incorporating real-time monitoring of salinity in soil profile was conducted to investigate the impact of irrigation water salinity on the salt accumulation in the soil of paddocks (D33 and Yarramundi) in Hawkesbury, NSW. Three types of water, such as tap water (0.2 dS/m), recycled water (0.81 dS/m) and synthetic saline water (2.0 dS/m) was used as irrigation water. Based on the observed experimental result, it can be concluded that:

1. Salt mass balance for the entire soil profile of D33 paddock soil columns showed increased salt accumulation with the increase of salinity in irrigation water. Similar observation was also observed in Yarramundi paddock soil columns. Salinity in the irrigation water had clear impact on leachate concentration; higher the salinity in irrigation water, higher salt concentration in leachate was observed for both types of soil.
2. Sensor measured VWC at average root zone depth (0.2 m) was close for all columns, which indicates column study was replicated reasonably. With the increase of salinity in irrigation water, bulk electrical conductivity increased for both types of paddock soil.
3. Salinity in terms of $EC_{1:5}$ and EC_e indicates that with the increase of salinity in irrigation water more salt accumulated in the upper part of the column (0-0.2 m) than the lower part (0.2-0.3). This is because only applied irrigation water was not sufficient to flush salt from upper part of the soil profile. However, when irrigated with low salinity water (TW), $EC_{1:5}$ and EC_e was found close to its initial value over most of the soil profile. The result is indicative of appropriateness of using less saline water in controlling salinity in the irrigation scheme.
4. The values of EC_e and $EC_{1:5}$ were found to be highly correlated for $EC_e < 10$ dS/m and $EC_{1:5}$ values < 1.5 dS/m for D33 paddock soil; for Yarramundi paddock soil, EC_e values < 10 dS/m and $EC_{1:5}$ values < 2.5 dS/m showed high correlation. Regression equation to predict EC_e from $EC_{1:5}$ values was proposed, which predicted the EC_e values accurately (BIAS < ±0.5%), for both types of paddock soils.

5. Sodicity (in terms of SAR) increased above its initial value for RW and SW irrigated columns for both types of paddock soil; in the case of TW irrigated columns, SAR increased within the top 0.1 m and decreased over the rest of the soil profile.
6. EC_e was found to be highly correlated to the total cation concentration for both types of soil. The developed relationship of individual cation concentration (namely, Na^+, Ca^{2+}, Mg^{2+} and K^+) to its total cation concentration will help to assess impact of individual cation on the root solute uptake from the soil water.
7. Ionic composition of saturated paste extract in terms of soluble cations increased with the increase of salinity in the irrigation water in both types of paddock soil. The ratio of soluble cations (Na^+: Mg^{2+}: Ca^{2+}: K^+) in the soil sample changed than its initial ratio at the beginning of the study. The change in the ration occurred because of exchanging cations between soil and the water added for irrigation.

Overall, the impact of irrigation water salinity was distinct for salt accumulation in the soil profile. Data presented in this chapter exposed how the sodium concentration in the soil increases while the potassium decreases with time as the irrigation with recycled water is continued. This aspect requires further research in order to develop appropriate management tools for using recycled water for irrigation.

CHAPTER 8

BAYESIAN BELIEF NETWORK FOR THE MANAGEMENT OF ROOT ZONE SALINITY

This chapter is partial reproduction of the following refereed journal paper:

[1]Rahman, M.M., [1]Hagare, D. and [2]Maheshwari, B. (2015). Bayesian Belief Network analysis of soil salinity in a peri-urban agricultural field irrigated with recycled water. Agricultural Water Management, under review (Impact factor 2.333).

[1] School of Computing, Engineering and Mathematics, Western Sydney University, Australia

[2] School of Science and Health, Western Sydney University, Australia

8.1 Introduction

In Chapters 4 to 7, salt accumulation in the root zone was discussed from different aspects such as soil characteristics, soil type, depth of soil profile and salinity in irrigation water. However, none of the previous chapters considered assessing the salt accumulation in a probabilistic manner. A probabilistic model involves a degree of variability and randomness, which is helpful in quantifying salt accumulation compared to a point value only. In this chapter, a novel methodology incorporating Bayesian belief network (BBN) is proposed to identify the level of treatment needed in recycled water that significantly influence the soil salinity and sodicity within the context of using recycled water for irrigation. Bayesian belief network was applied in this chapter because this method is capable of incorporating uncertainty of associated variables by using marginal probability distributions. The network provides graphical representation of key factors, which portrays a better understanding of the inter-dependent relationships between the factors of the decision process. The main objectives of this chapter are:

- To use a probabilistic method, viz., bayesian belief network, to evaluate the risk of salinity hazard associated with recycled water irrigation in the D21 paddock (D21 paddock was chosen as the column studies carried out with this soil were more elaborate and produced all the data required for BBN analysis); and
- To identify the level of treatment needed to reduce salinity in recycled water for salt accumulation in the soil due to recycled water irrigation over 20 years and to devise management options to reduce salinity in the recycled water.

8.2 Methodology

In this chapter BBN is used as a basis for assessment framework. Background of BBN and essential terminologies such as Bayes' theorem, parent and child nodes, prior and posterior probability, and conditional probability table (CPT) are discussed in Section 3.6.2. Details of the case study area (D21 paddock) and the soil properties of this paddock were discussed in Chapters 3 and 4, respectively. The steps involved in the BBN model development and application are depicted in Figure 8.1. The construction and application of the model was carried out in seven steps, namely,

- Identification of parent and child nodes;
- Collection of Mean and standard deviation of amount and EC of recycled water used, amount of rainfall and potential evapotranspiration recorded during the study period to develop probability distribution of parent nodes;
- Evaluating parent-child relationships from results of continuous as well as batch laboratory experiment;
- Discretisation of the nodes;
- Construction of the model using Hugin-Expert® (Hugin 2013) system;
- Testing the developed model with observed experimental results for child nodes; and
- Likelihood analysis using the constructed model.

8.3 Parent and Child Nodes

The first step in the development of the BBN model is to identify appropriate parent and child nodes. In the proposed model, the nodes represent a particular parameter which is ultimately connected with the probability of salinity in the soil. All the parent and child nodes considered in the proposed BBN model are taken as stochastic variables with normal probability distribution. The nodes are presented in Figure 8.2 which forms the framework for the proposed BBN model. As discussed in Chapter 3 the proposed BBN is essentially a directed acyclic graph, which is a suitable way to represent causal relationships between parent and child nodes.

As stated earlier, salt accumulates in the root zone due to depletion of water from the root zone by leaving the salt behind. The depletion occurs due to extraction of water by roots of plants (i.e., transpiration), evaporation from soil, and percolation or leaching of water from the root zone. The salt that is left behind accumulates on the basis of water flow and solute transport mechanism including parameters related to different hydraulic properties of soil and solute. Salt transport model, such as HYDRUS 1D (Šimůnek et al. 2009) is available and can be used to quantify salt accumulation as a point value. However a probability distribution, providing information on magnitude of salt accumulation along with uncertainty is helpful for field managers, which is easy to implement through the use of BBN.

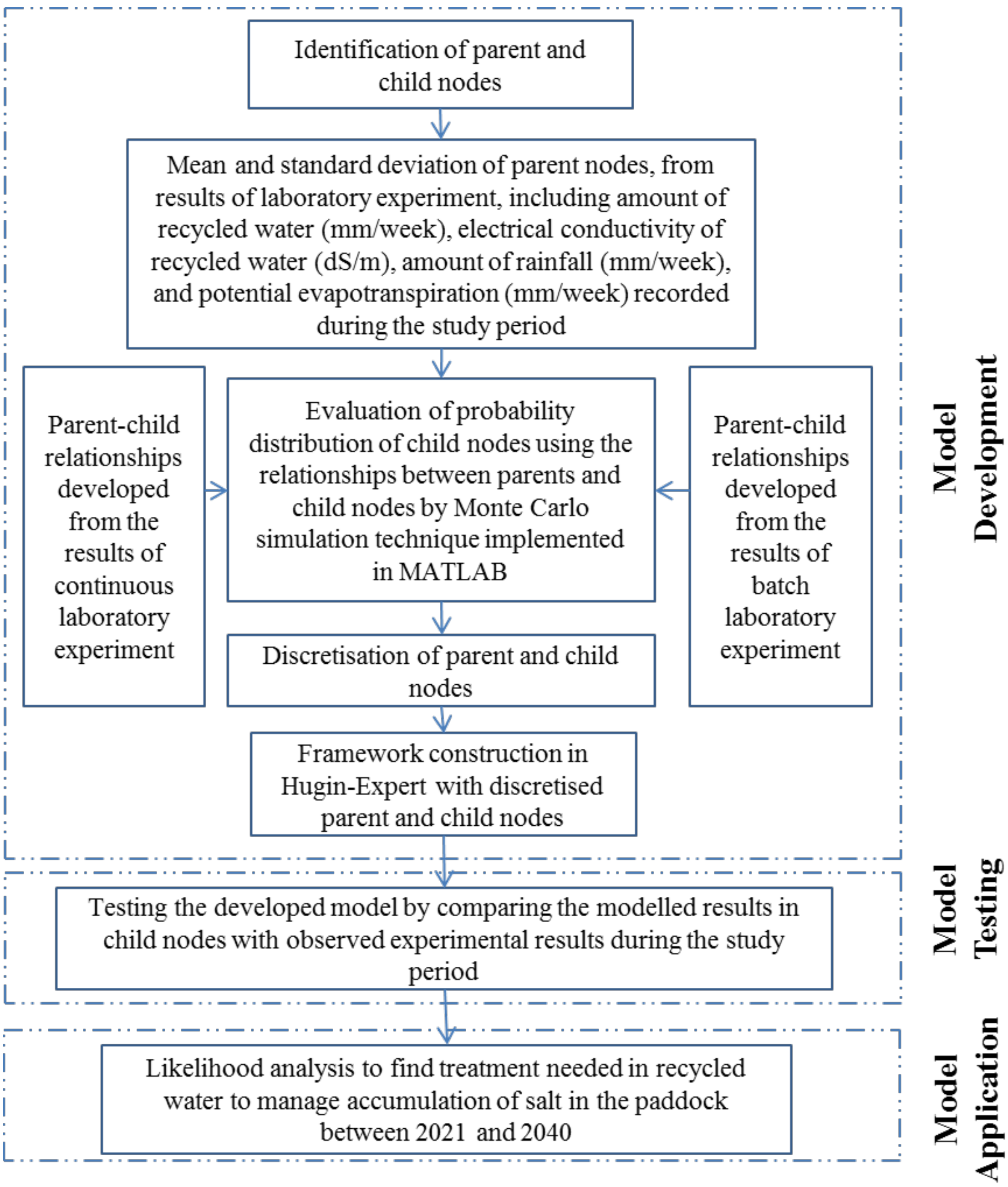

Figure 8.1 Steps for BBN analysis

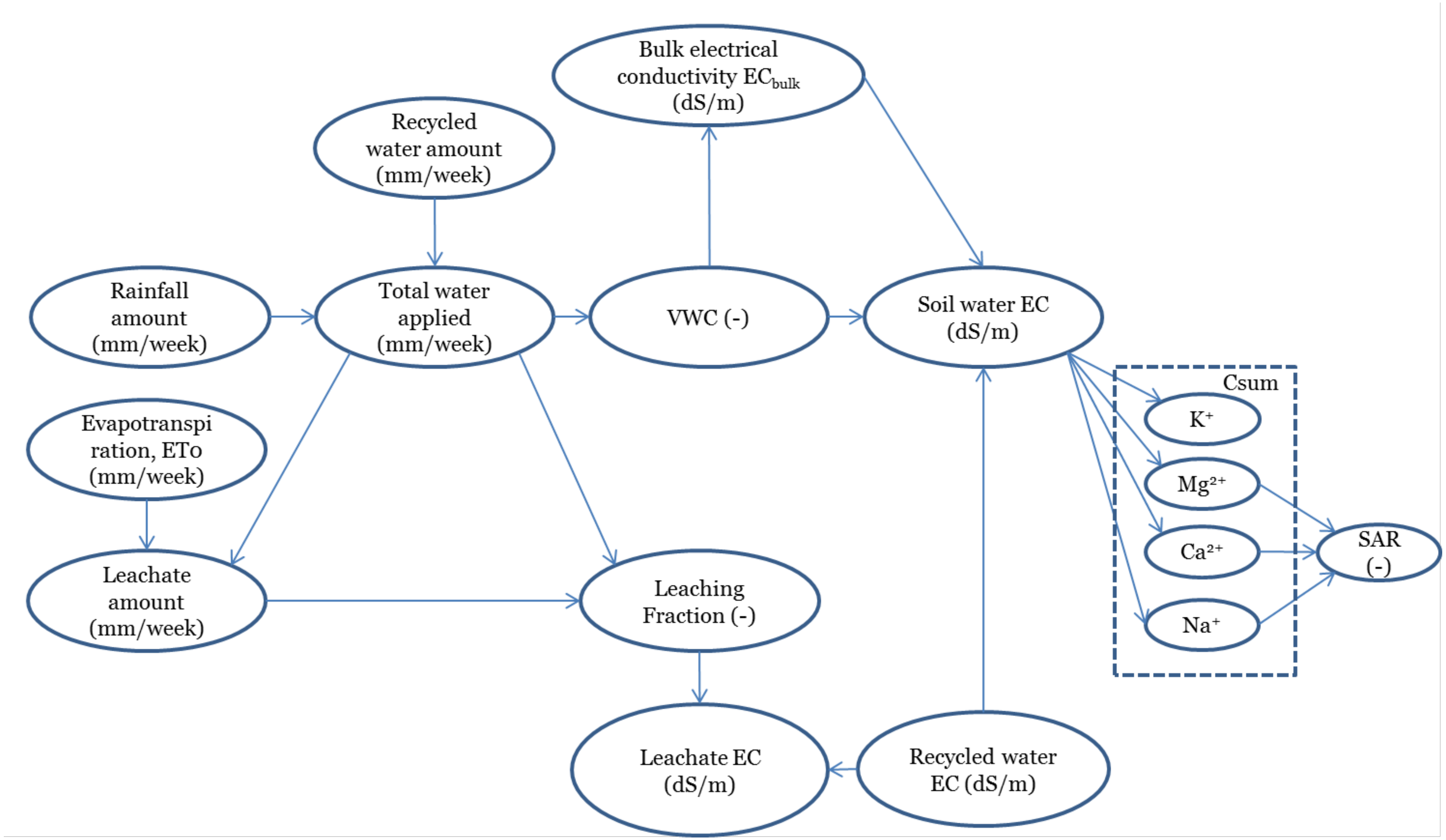

Figure 8.2 The BBN model for salt accumulation in D21 paddock due to recycled water irrigation

The proposed framework (Figure 8.2) is a simplified salt accumulation process where key variables of salt accumulation process are identified and included in the framework. Segregation of the salt accumulation process into different key variables enables the decision makers to decide on the most significant aspects related to management of irrigation in a holistic way. The framework addresses process of salt accumulation in a sensor based irrigation system, where the salt accumulation is reported as average root zone soil water electrical conductivity (EC_{SW} in dS/m). Moreover, the framework includes different variables associated with the calculation of salt mass balance as an indicator of the conventional salt accumulation process (i.e. amount and EC of irrigation water and leachate). Typically, the salt accumulation process starts with the application of irrigation water. In this study recycled water is being used as irrigation water that is stored in a storage dam in Hawkesbury campus (Section 3.5.3). Both the applied recycled water amount and EC of recycled water are considered as separate nodes. This gives greater flexibility to decide which of the two parameters need to be controlled to manage salt accumulation in the root zone. Both of the two nodes are considered as parent nodes (independent variables) in the framework.

The amount of irrigation water depends on the irrigation scheduling. The irrigation scheduling is the process of deciding when and how much water needs to be applied in the field to attain maximum crop productivity (Smith et al. 2012). In this framework, irrigation scheduling was not added as variable; however, recycled water amount was calculated based on the irrigation scheduling (total weekly amount of recycled water based on frequency and amount of irrigation).

Rainfall impacts the salt accumulation process, which is discussed in Chapters 5 and 6. Rainfall is also considered as parent node in the framework. Evapotranspiration plays an important role in calculating the water balance. Evapotranspiration is a combined loss of water to the atmosphere due to evaporation from soil and plant surfaces, and transpiration through plants. Reference evapotranspiration (ET_0) can be used to estimate the evapotranspiration of a specific crop and evaporation losses from field (Allen et al. 1998). In this framework, ET_0 is a parent node. All other nodes (namely, Total water applied, LF, Leachate amount, leachate EC, Bulk EC, VWC, EC_{SW}, C_{sum}, and SAR), except the above mentioned four nodes, are considered as child node in the framework.

The net applied water that enters the soil depends on the amount of rainfall, recycled water irrigation, evapotranspiration, and the amount of leachate. Leachate is the amount of water that exit from the root zone. The net amount of water relates the total water that infiltrates (i.e. rainfall and irrigation water) and the total water that exits from the root zone (i.e. ET_0 and leachate). The amount of leachate can be determined by deducting the amount of water that leaves the root zone by evapotranspiration from the amount of water that infiltrates. Determining the amount of leachate is important because it may percolate deep and increase the depth of water table. In the calculation of net applied water two more parameters, namely runoff and recharge from water table into the root zone are considered in practice. However, these variables were not considered in the framework; runoff from irrigation area was considered zero as allowing runoff of irrigation waters is generally discouraged (Stewart 2006), and no recharge of water table is assumed (as a representation of unsaturated soil condition). Leaching fraction (LF) is considered one of the irrigation management options by field managers (Corwin et al. 2007). Conventionally, in the field, LF is used to calculate the salt buildup in the soil. Hence, LF is included in the framework which then used to calculate EC of leachate with the help of irrigation (recycled) water EC.

All of the variables discussed above are needed to conventionally determine the salt accumulation. However, for sensor based irrigation system (i.e. when sensor is installed in the field to monitor water and salt accumulation status at a certain depth), two more variables named bulk electrical conductivity (EC_{bulk}) and moisture content or volumetric water content (VWC) are needed. In this study GS3 sensors were used (Section 3.5.4.1), which monitor EC_{bulk} and VWC. The measured EC_{bulk} was dependent on VWC (Chapters 5 and 6). The EC_{bulk} increased when the VWC increased and vice-versa. As shown in Section 5.4, EC_{bulk} was not a proper representative of salt accumulation in the soil. Therefore, EC_{bulk} was converted to soil water electrical conductivity (EC_{SW}), with the help of sensor measured EC_{bulk} and VWC data. Besides EC_{bulk} and VWC, the soil water electrical conductivity also depends on the salinity of recycled water; hence, EC_{SW} was represented as a child node of recycled water EC.

The soil water electrical conductivity gives an indication of overall salinity, however information on ionic composition of soil water (especially for cations) is useful to calculate sodium adsorption ratio (SAR) with the help of Na^+, Ca^{2+} and Mg^{2+} concentration in liquid phase. The SAR when evaluated along with soil water electrical conductivity helps to understand the permeability problem in soil (Pedrero et al. 2010) and thus, the risk of growth and yield of plant, irrigated in a saline-sodic soil.

8.4 Relationships between parent and child nodes

In this study, the relationships were evaluated based on experimental result. The evaluated relationships using soil from specific site of interest better represents the relationships than constructing them with data from literature. The site specific relationships between variables were mainly established using two types of experiments:

- Batch study to establish relationships between amount of irrigation water, EC of irrigation water, VWC, EC_{bulk} and EC_{SW} (details of the batch study were discussed in Sections 3.4 and 4.3). These relationships are shown in Table 8.1.
- Continuous column study to establish relationships among ET_0, applied water and leachate, and EC_{SW} and ionic composition of soil water (details of the column study was discussed in Section 3.5.4.1 and results of first 103 days out of 264 days, were discussed in Chapter 5)

The derived relationship between parent and child nodes and the marginal probability of parent nodes were used to generate a model for the conditional probability of the child nodes. For this purpose, a Monte Carlo simulation technique (Nguyen 1995) implemented under MATLAB® (MathWorks 2013) was used. In Monte Carlo simulation technique, using the mean (μ) and standard deviation (σ) of parent node and assuming that the parent node has normal distribution, the distribution of child node was determined by applying the relationship between parent and child nodes. The number of iterations used for determining the distribution of the values for child node was 10,000. With the distribution thus determined, mean (μ) and standard deviation (σ) of the child node was calculated. More information on the application of Monte Carlo simulation technique can be found in Nguyen (1995).

All the nodes in the BBN are continuous; however for the purpose of this study they were discretised. As discussed in Section 2.5.1.3, the purpose of discretisation is to subdivide a continuous space of a variable into a set of different intervals; the discretisation approach may be according to equidistant split points, equal frequency or supervision (Bayraktarli 2009). In the current study, supervised discretisation is followed which is further detailed in the following sections. It is expected that the discretisation chosen in this study will not drastically affect the accuracy of the model output. It should be noted that the detailed analysis of impact of discretisation on the accuracy and computational efficiency is out of the scope of this research.

8.4.1 Relationships developed by batch study

Results of the batch study are shown in Figure 8.3 and the developed regression equations in Table 8.1. This should be noted from Figures 8.3 (*a*) and 8.3 (*b*) that VWC depends on applied amount of water and EC_{bulk} depends on VWC. Figure 8.3 (*c*) shows more dependency of EC_{SW} on the recycled water EC (EC_{rw}) compared to other two parameters (i.e. VWC and EC_{bulk}). This is also reflected by the p-value (Table 8.1), where high p-value of EC_{bulk} makes it less significant in the regression equation. However, this variable is needed in the equation to represent the sensor measured salinity monitoring system.

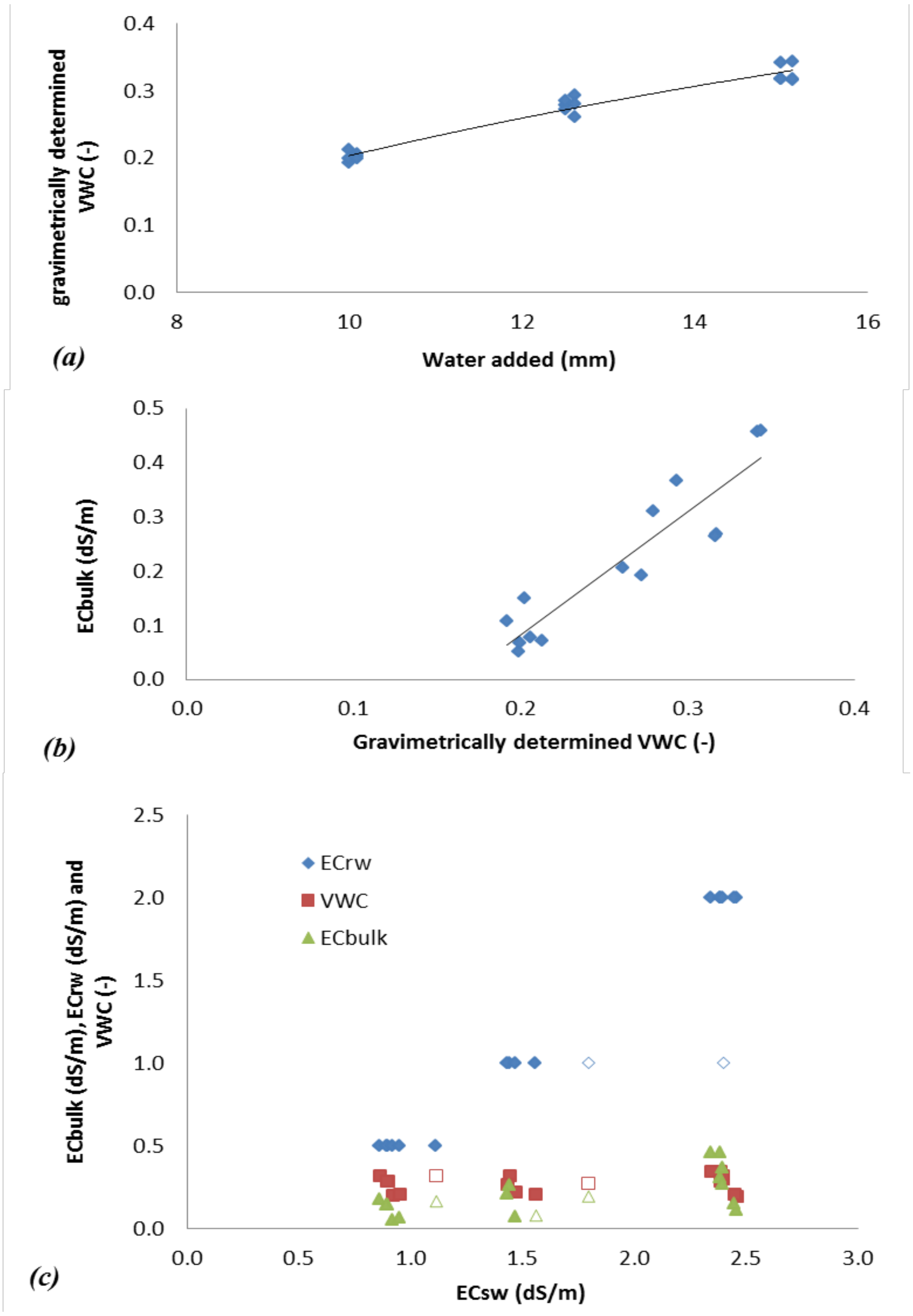

Figure 8.3 Results from the batch study used to find relationships among variables (a) VWC vs amount of applied water (b) ECbulk vs VWC (c) ECbulk, ECrw, VWC Vs ECSW (the non-filled points were excluded from the regression analysis)

Table 8.1 Models connecting child and parent nodes evaluated from batch study

Child Node	Associated parent nodes	Model connecting child and associated parent nodes	R^2	p-value	States generated from Monte Carlo simulation output
VWC (-)	Applied water (mm)	$0.307 \times ln(Applied\ water) - 0.504$	0.96	<0.0001	0.05-0.1, 0.1-0.15, 0.15-0.2, 0.2-0.3
EC_{bulk} (dS/m)	VWC (-)	$2.285 \times (VWC) - 0.375$	0.85	<0.0001	0.01-0.05, 0.05-0.1, 0.1-0.15, 0.15-0.35
EC_{SW} (dS/m)	VWC (-), EC_{bulk} (dS/m), EC_{rw} (dS/m)	$0.187 - 0.261 \times \ln(VWC) + 0.0501 \times \ln(EC_{bulk}) + 0.973 \times EC_{rw}$	0.99	0.079 0.354 <0.0001	1-1.1, 1.1-1.3, 1.3-3.2

VWC = Volumetric water content, EC_{bulk} = Bulk electrical conductivity
EC_{SW} = Soil water electrical conductivity, EC_{rw} = Recycled water electrical conductivity

8.4.2 Relationships developed by continuous column study

Results from the continuous column study are shown in Figure 8.4. As shown in Figure 8.4 (*a*), at first week of the study period, higher amount of irrigation water was applied. As discussed in Chapter 5, this higher application was required to soak the soil in the column. However, this unusually high amount was not considered to calculate prior probability of recycled water amount. Generally, leachate amount as well as leaching fraction increased with the application of rainfall (Figure 8.4*b*). An increasing pattern of EC_{SW} over time was observed till the application of rainfall (Figure 8.4*c*). The average root zone EC_{SW} increased by about 2.9 times above its initial value (from 1.0 to 2.9 dS/m). EC_{SW} increased substantially between 2nd and 8th week then stabilised, and increased again from 14th week till the application of rainfall. Further details can be found in Chapter 5. The rainfall reduced the average root zone ECsw about 2 times (from 2.7 to 1.4 dS/m). The VWC (denoted as θ in Chapter 4) was calculated based on Equation 4.1. The variation of VWC and EC_{bulk} throughout the study period was related to ECsw, as discussed in Section 8.4.1. The variations of observed concentrations of soluble Na^+, Ca^{2+}, Mg^{2+} and K^+ in soil water (measured up to 31st week), closely followed the root zone EC_{SW} (Figure 8.4*d*). The SAR increased by 1.7 times of its initial value during the study period. It should be noted that the decrease of SAR due to simulated rainfall was delayed than cations. According to Gonçalves et al. (2006), this delayed decrease may be because of slower movement of SAR front than the concentration fronts of non-reactive solutes (such as Cl^-) due to the effect of cation exchange. Data from the column study was used to generate prior probabilities (μ and σ) of parent nodes, namely, recycled water amount (μ = 18.38 mm/week, σ = 5.97 mm/week), rainfall amount (μ = 4.22 mm/week, σ = 5.21 mm/week), potential ET_0 (μ = 6.16 mm/week, σ = 1.55 mm/week) and electrical conductivity of recycled water (μ = 0.83 dS/m, σ = 0.02 dS/m). It should be mentioned that the distribution (μ and σ) of rainfall was calculated based on the entire period of the column study.

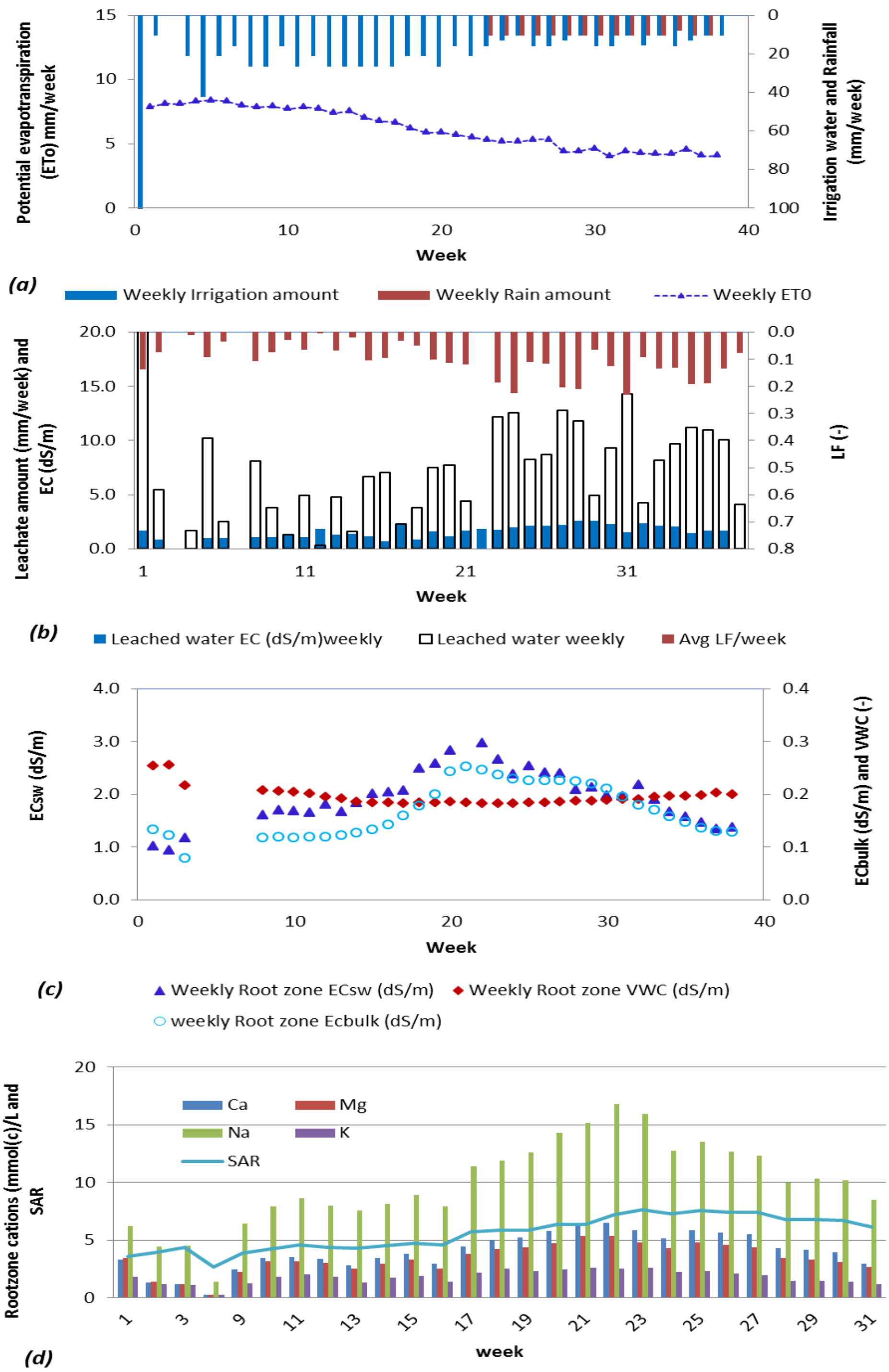

Figure 8.4 Results from continuous column study (a) applied irrigation amount and rainfall, and observed potential ET_0 (mm/week) (b) measured leachate amount (mm/week), leachate EC (dS/m) and leaching factor (c) observed root zone ECsw (dS/m), VWC (-), and EC_{bulk} (dS/m), which were averaged over 0.1 and 0.35 m (d) measured weekly root zone cations (mmol(c)/L and SAR (-)

The relationships developed from results of the continuous column study are shown in Table 8.2. It is worth mentioning that the relationship of leachate amount with application water and potential ET_0 was developed considering results from the entire study period (38 weeks). However, relationships of cations with root zone EC_{SW} were developed with data from 31 weeks (due to availability of data for the last 7 weeks). All the relationships reported in Table 8.2 have high correlation coefficient and low p-value. The low p-value suggests the predictors as a meaningful entity in these regression equations.

Relationship among leachate amount (mm/week), LF and leachate EC (dS/m) was taken from Ayers and Westcot (1985) as below:

$$LF = \frac{Depth\ of\ water\ leached\ below\ the\ rootzone}{Depth\ of\ water\ applied\ at\ the\ surface}$$

$$= \frac{EC_{Applied\ water}}{EC_{Leachate}} \tag{8.1}$$

The relationship of SAR with Na^{+}, Ca^{2+} and Mg^{2+} was taken from Equation 3.5. The states generated from Monte Carlo simulation output for LF were 0.05-0.1, 0.1-0.15, 0.15-0.2, 0.2-0.3 and for leachate amount were 1.1-2, 2-2.75, 2.75-3.5 mm/week; states of SAR were 1.5-3, 3-6 and 6-10.

Table 8.2 Models connecting child and parent nodes evaluated from continuous column study

Child Node	Associated parent nodes	Model connecting child and parent nodes	R^2	p-value	States generated from Monte Carlo simulation output
Leachate amount (mm/week)	Applied water (mm/week) ETo (mm/week)	$10.6 + 0.249 \times Applied\ water - 1.68 \times ET_0$	0.93	<0.0001 <0.0001	0-5, 5-10, 10-15
Soluble K^+ (mmol(c)/L)	EC_{SW} (dS/m)	$2.1603 \times ln(EC_{SW}) + 0.3458$	0.81	<0.0001	0.3-0.5, 0.5-1, 1-3
Soluble Mg^{2+} (mmol(c)/L)	EC_{SW} (dS/m)	$4.0993 \times ln(EC_{SW}) + 0.6918$	0.87	<0.0001	0.5-1, 1-2, 2-5
Soluble Ca^{2+} (mmol(c)/L)	EC_{SW} (dS/m)	$5.2551 \times ln(EC_{SW}) + 0.5439$	0.88	<0.0001	0.5-1, 1-2, 2-6
Soluble Na^+ (mmol(c)/L)	EC_{SW} (dS/m)	$11.934 \times ln(EC_{SW}) + 2.0981$	0.87	<0.0001	1.5-3, 3-10, 10-15

EC_{SW} = Soil water electrical conductivity

8.5 BBN model based on prior belief from laboratory experimental results

The model developed is applied using Hugin-Expert® system. Prior probability distribution for all the nodes were obtained using Hugin and the same is presented in Figure 8.5. Each box in the figure represents a variable (either parent or child) containing three columns. The first and second columns represent the discretised probability distribution graphically and numerically, respectively. The third column represents different states of the probability distribution. A close examination of Figure 8.5 indicates that the mean and variance for the parent nodes closely match with that of raw data given in preceding sections. This indicates that the relationships between parent and child nodes and discretised probability distributions for each of the nodes are acceptable.

Bayes' theorem (Equation 3.19) was used to find the changes in state probabilities of parent variables based on the evidence entered in the child node. In other words, entering a known probability distribution in child node was changes the distribution in parent nodes. This is called *backward propagation* (Tanji and Grattan 2007). Similarly, entering a known probability distribution in parent node changes the distribution in child nodes and is called *forward propagation*.

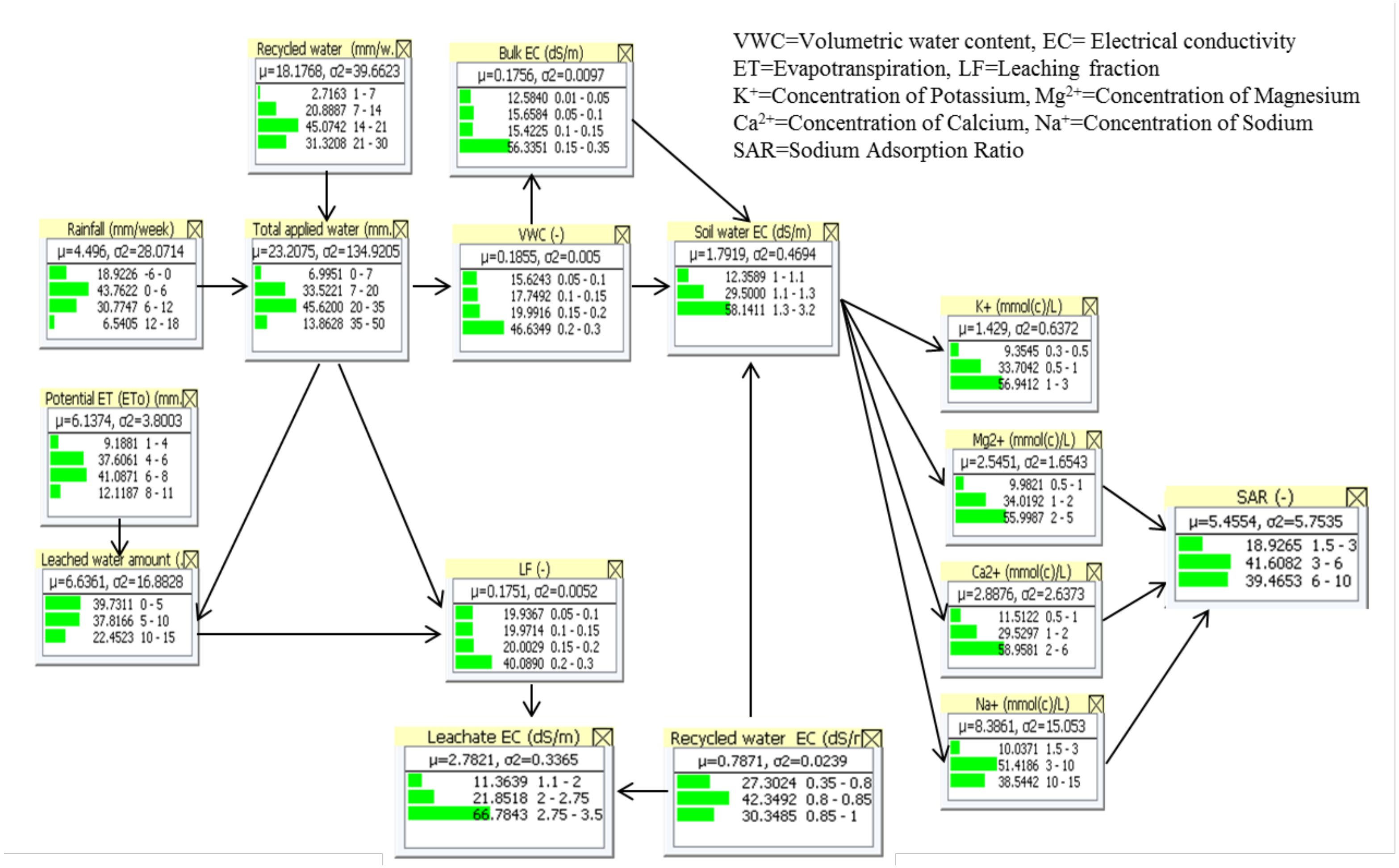

Figure 8.5 Probability distribution in different nodes of BBN model based on prior belief from laboratory experimental result

8.5.1 Testing the developed network

Testing of the developed BBN model was conducted to logically validate the results it produces. The testing of the network demonstrates that the result of a variable changes logically with the variations experienced by other related variables. The testing was conducted in two ways:

- Scenario analysis; and
- Sensitivity analysis

In the scenario analysis, the developed BBN model was tested against the observed data over the period of continuous column study. The recycled water EC, ET_0 and rainfall were kept constant assuming they lie in the range of 0.8 - 0.85 dS/m, 1 - 4 mm/week, and 6 - 12 mm/week, respectively. The observed values of recycled water EC, ET_0 and rainfall were within the specified range during the continuous column study period (Figure 8.4). The amount of recycled water was changed to find the effect of this variable on probability distribution of EC_{SW}, soluble Na^+ concentration, SAR, leachate amount and leachate EC, LF, VWC and EC_{bulk}. To achieve this, a forward propagation was carried out using the discretised probability distribution of recycled water amount (which is considered as evidence) assuming that the entire recycled water amount lies in the range of 1-7 mm/week (which is the first state value considered). Similarly, forward propagation of the constructed BBN model was run for three additional states considering all recycled water amounts lie in the range of 7-14, 14-21 and 21-30 mm/week. The results from this forward propagation are presented in Figure 8.6 to compare with the observed experimental result.

It is obvious from Figure 8.6 that mean (μ) of the posterior probability distribution of root zone EC_{SW} matched well with the observed experimental root zone EC_{SW} occurred, when the recycled water amount was in the range of 7-14 and 14-21 mm/week. The mean (μ) of the posterior probability distribution of root zone for other two ranges, i.e., 1-7 and 21-30 mm/week of recycled water amount did not occur during the study period, hence could not be compared. Similarly, mean (μ) of the posterior probability distribution of Na^+, SAR, leachate amount and leachate EC, LF, VWC and EC_{bulk} was within the observed value.

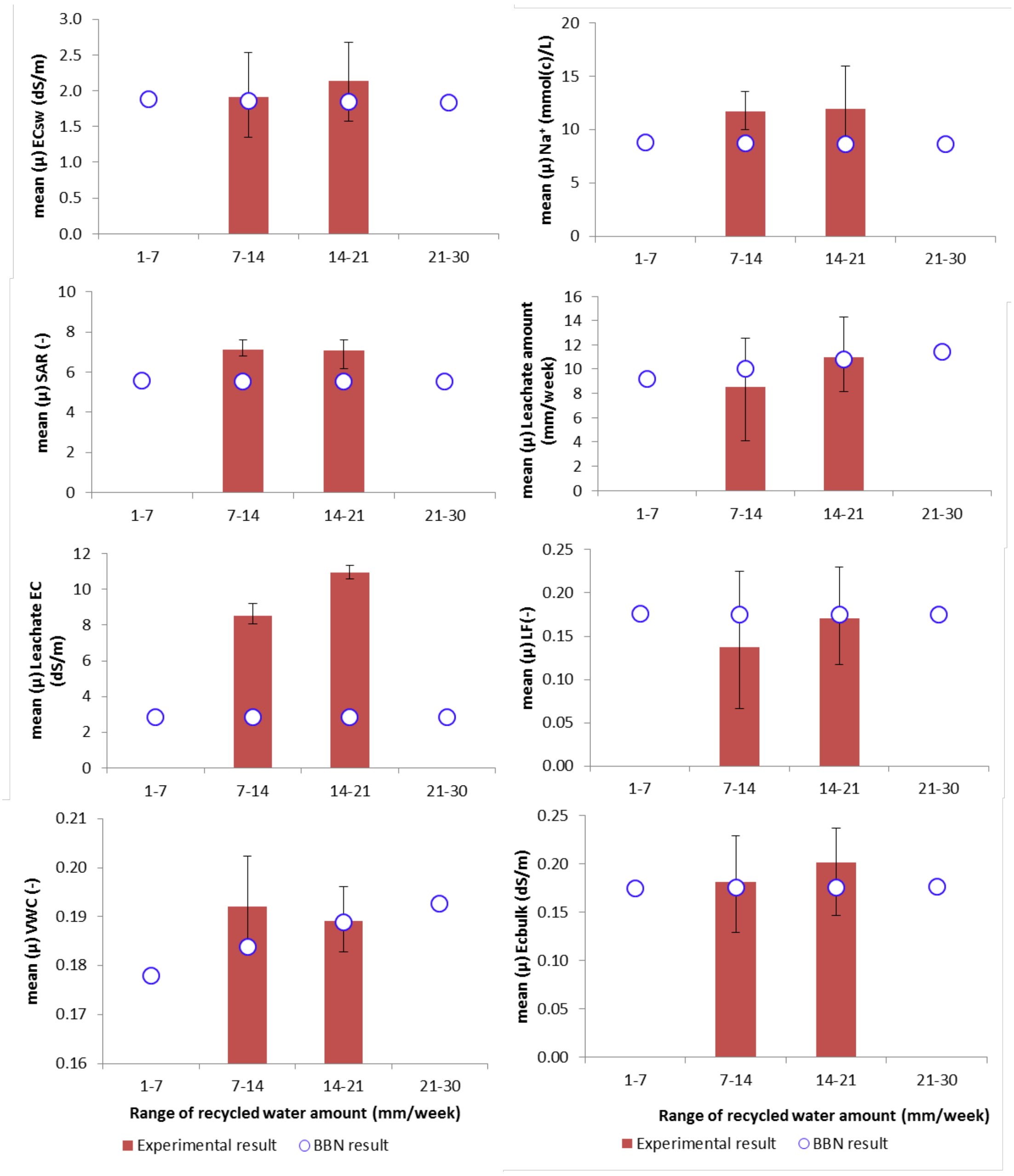

Figure 8.6 Comparison of results from BBN model and observed values of different variables for the scenario tested on the developed BBN

Scenario analysis described above (Figure 8.6) compared the BBN result with the experimental data. However, to determine the influence of parent nodes (i.e. recycled water amount, rainfall, total applied water, potential ET_0, leachate amount, leachate EC, LF, VWC, EC_{bulk} and recycled water EC) on the child node (soil water EC_{SW}), sensitivity analysis was performed. This helped to further explore the significant variable that would influence the accumulation of salt in the root zone. To perform sensitivity analysis, the distribution of mentioned nodes were adjusted to reflect ±50% of the prior mean. Figure 8.7 shows the variation in EC_{SW} under different distributions for the parent nodes.

It is clear from the sensitivity analysis (Figure 8.7) that the EC_{SW} is mostly sensitive to EC of recycled water and VWC. About 18% increase in prior mean of recycled water EC node resulted in 12% increase of posterior mean of EC_{SW}. As shown in Figure 8.7, about 18% increase in prior mean of recycled water concentration node resulted in 12% increase of posterior mean of EC_{SW}. Similarly, as shown in Figure 8.7, the prior mean of VWC was increased by 35%, which resulted in the decrease of ECsw by about 11%. For rest of the variables, posterior mean of EC_{SW} changed less than 1% (Figure 8.7), thereby indicating insignificant effect of these parameters on ECsw. It should be noted in this regard that rainfall did not affect the EC_{SW} directly however it influenced via the *total amount of water,* which is a total amount of rainfall and recycled water, and VWC. For EC of recycled water and VWC, variance reduced by 7.9% and 8.85%, respectively; for rest of the variables, variance reduced by less than 1%. The variance reduction means that the uncertainty associated with the variable will be reduced (Stiber et al. 1999).

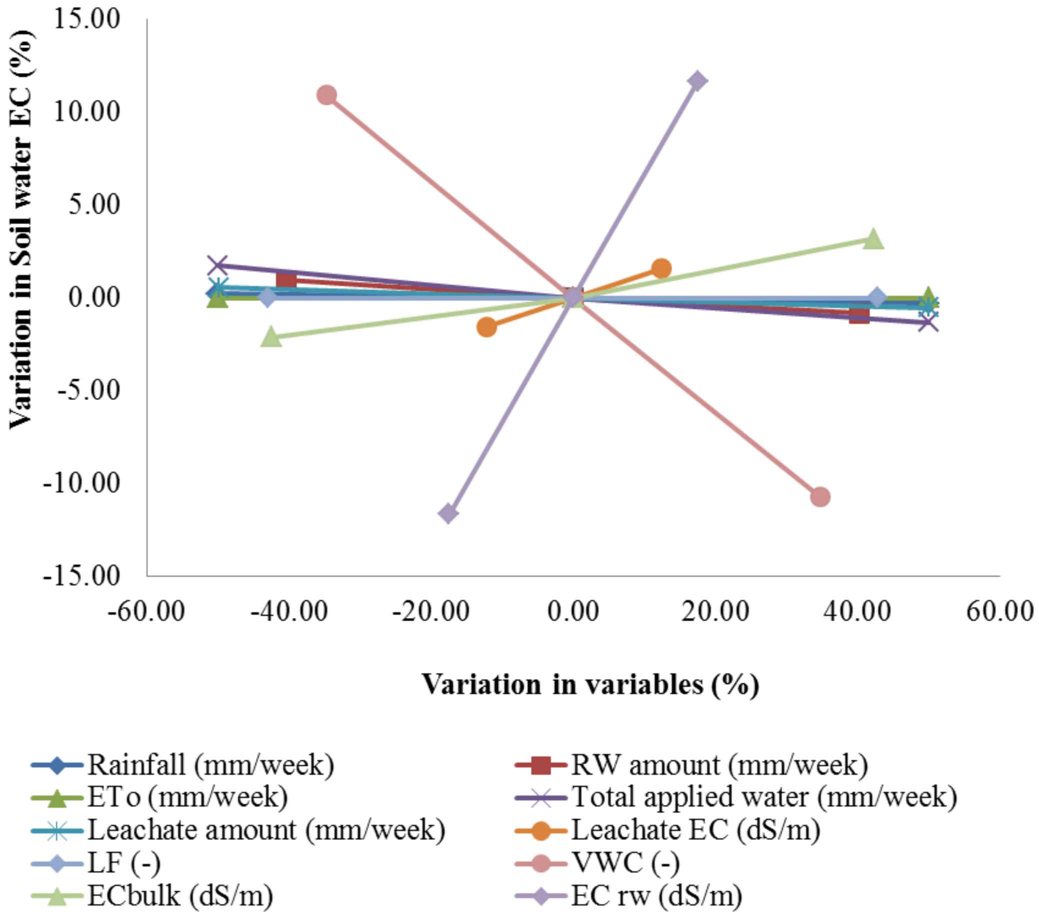

Figure 8.7 Variation of ECsw in soil under different parent node distributions

8.6 Application of the BBN model in field condition

The BBN model developed with laboratory experimental result (BBN_{Lab}) described in preceding sections, was applied to the field condition (of D21 paddock) by keeping the same relationships among nodes discussed in Section 8.4. However, prior probabilities in parent nodes were updated based on the field data. For distinguishing the BBN model developed for the field condition from that of lab condition, the updated model to field condition is denoted by BBN_{Field}. With the updated field data, Monte Carlo simulation discussed in Section 8.4 were used to evaluate the discretised states in child nodes (Table 8.3). In the field application, no sensor was considered; hence, in the BBN_{Field} model, EC_{bulk} node was excluded. The relationship of EC_{SW} with VWC and recycled water EC was updated using the data from batch study (Section 3.4) as follows:

$$EC_{sw} = 0.604 - 0.673 \times VWC + 0.999 \times EC_{rw} \quad (8.2)$$

The p-value for VWC was 0.004 and for EC_{rw} was <0.0001 with R^2 = 99.7%.

It should be mentioned here that the batch experiment was conducted in the laboratory (Section 3.4) with different EC of water, which subsequently generated the relationship between three parameters (i.e. EC_{SW}, VWC and EC_{rw}) as given in Equation 8.2. However, the field condition is different than the laboratory condition (where the experiment was conducted). Especially, in the field, the changes of EC_{SW} occurs due to the root water uptake (i.e. transpiration), evaporation from soil and leaching of salt. In the laboratory condition, when developing the Equation 8.2, to calculate EC_{SW}, effect of root water uptake and leaching of salt was not considered. Therefore, the developed relationship from laboratory batch calibration study underestimates the EC_{SW} that would occur in the field study. To take into account the above mentioned parameters not considered in developing this relationship, a multiplication factor was required (Rahman et al. 2014). The multiplication factor was evaluated (detailed in the later part of this section) by comparing the average weekly EC_{SW} recorded over the laboratory column study of 264 days to the simulated average weekly EC_{SW} over the 20 year simulation period (2021 to 2040). It is needless to say that average EC_{SW} from the continuous column study was used to find the multiplication factor because priors of all parent nodes in the BBN_{Lab} were also averaged over this period (264 days).

The continuous prediction of root zone salt accumulation by HYDRUS 1D in D21 paddock for the years 2021 to 2040 was discussed in detail in Section 6.5. Details of model input parameters, irrigation scheduling, variation of rainfall and ET_0 over the period of 2021 to 2040 are also discussed in Section 6.5. For the evaluation of the above mentioned multiplication factor, 20 years simulation results reported in Section 6.5 was used. As discussed in Chapter 6, Section 6.5, in some of the simulation years between 2021 and 2040, root zone EC_{SW} in D21 paddock exceeded the maximum threshold for salinity tolerance of rye pasture (which is 5.0 dS/m). Particular simulation years showing higher average weekly EC_{SW} than maximum threshold includes 2022, 2023, 2025, 2026, 2030, 2032, 2033 and 2035 (Figure 6.10); highest average weekly root zone EC_{SW} was observed in the simulation year of 2023. Besides using to calculate multiplication factor, the simulation result helped upgrading the prior probabilities (μ and σ) of parent nodes of BBN_{Field} (Figure 8.8) The updated prior probability distributions of parent nodes in field condition includes recycled water amount (μ = 7.31 mm/week , σ = 9.72 mm/week), recycled water EC (μ = 0.827 dS/m, σ = 0.04 dS/m), rainfall amount (μ = 13.68 mm/week, σ = 23.42 mm/week) and potential ET_0 (μ = 23.43 mm/week, σ = 10.67 mm/week).

The multiplication factor was calculated as the ratio of mean root zone EC_{SW} obtained by 20 years simulation period under the field conditions to the mean root zone EC_{SW} observed during the laboratory continuous column study:

$$EC_{sw\ at\ field} = a \times EC_{sw\ at\ lab} \quad (8.3)$$

Where, $EC_{sw\ at\ field}$= Mean simulated weekly root zone ECsw over 20 years in field condition (dS/m);

$EC_{sw\ at\ lab}$ = Mean observed weekly root zone ECsw observed over 264 days in the laboratory;

a = multiplication factor;

$EC_{sw\ at\ field}$ was taken as 4.81 dS/m which is the average weekly root zone EC_{SW} over the study period at field (Figure 6.8*a*) and $EC_{sw\ at\ lab}$ was taken as 1.98 dS/m which is the average weekly root zone EC_{SW} over the continuous column study in the laboratory (Figure 8.4*c*). The multiplication factor 'a' was estimated as 2.43.

The obtained multiplication factor indicates that the field condition is quite different from experimental conditions. However, the multiplication factor proposed in Equation 8.3 is expected to take into account the differences in the field and experimental conditions. Equations 8.2 and 8.3 were used to generate CPT for the node “Soil water EC”. The node was discretised using the output of Monte Carlo simulations according to procedure described earlier. This discretised node along with other updated discretised nodes (i.e. all parent and child nodes) are summarised in Table 8.3. Distribution of all child nodes were updated by generating new CPT using the relationships mentioned in Table 8.1 and Table 8.2. Probability distribution of updated BBN model based on field condition is shown in Figure 8.8.

Table 8.3 Description of updated parent and child nodes in field condition

Parent node	States generated from Monte Carlo simulation output	Child node	States generated from Monte Carlo simulation output
Recycled water amount (mm/week)	5-10, 10-20, 20-30, 30-40	Total applied water (mm/week)	0-10, 10-30, 30-50, 50-70
Recycled water EC (dS/m)	0.1-0.8, 0.8-1.0, 1.0-1.6	Leachate amount (mm/week)	0-5, 5-15, 15-25
Rainfall (mm/week)	0-5, 5-10, 10-25, 25-65	Leachate EC (dS/m)	0.05-1.0, 1.0-2.0, 2.0-3.5, 3.5-15
Potential ET_0 (mm/week)	5-15, 15-30, 30-40, 40-55	LF (-)	0.05-0.1, 0.1-0.15, 0.15-0.25, 0.25-0.30
		VWC (-)	0.05-0.1, 0.1-0.15, 0.15-0.2, 0.2-0.25
		Root zone EC_{SW} (dS/m)	1.5-3.0, 3.0-5.0, 5.0-8.0, 8.0-25.0
		K^+ mmol(c)/L	1-3, 3-6, 6-8
		Mg^{2+} mmol(c)/L	4-6, 6-10, 10-15
		Ca^{2+} mmol(c)/L	4-6, 6-10, 10-15
		Na^+ mmol(c)/L	5-15, 15-20, 20-30, 30-35
		SAR	3-5, 5-8, 8-10, 10-12

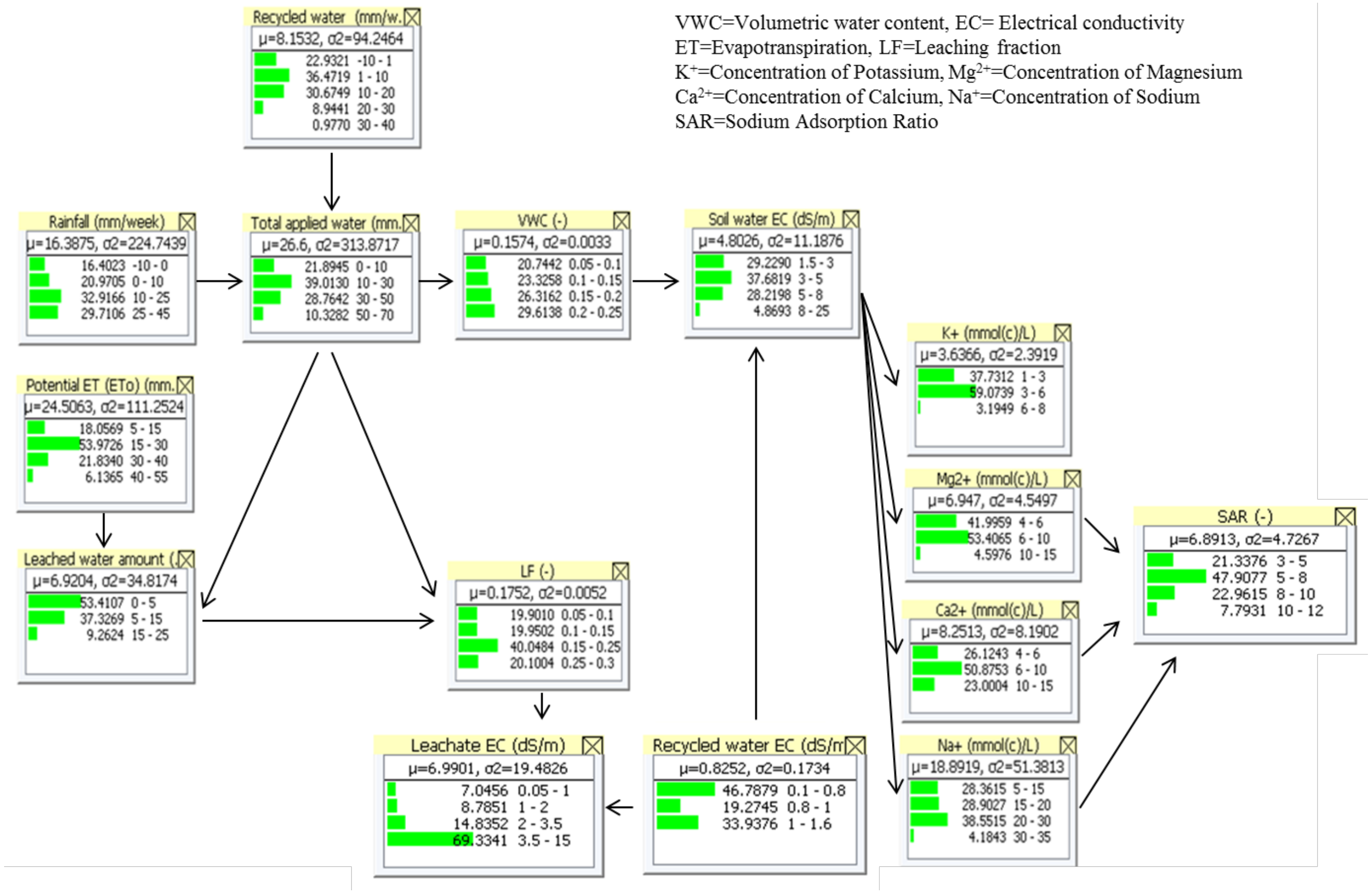

Figure 8.8 **Probability distribution in different nodes of updated BBN model based on field condition**

8.6.1 Likelihood analysis of Na^+ and SAR in the root zone

The main objective of constructing the BBN_{Field} was to determine the probability distribution of Na^+ concentration and SAR in the root zone and electrical conductivity in recycled water (EC_{rw}) for a given or desired probability distribution in the root zone EC_{SW} (that is, to determine the value of $P\left(Parent\ or\ Child\ nodes_{Concentration} \middle| Soil_{Rootzone\ ECsw}\right)$). This would aid to quantify the quantity (mean) and uncertainty (probability) associated with these nodes (Na^+, SAR and EC_{rw} node) which are not possible to get from a deterministic salt transport model.

In the first instance a forward propagation analysis was carried-out (as discussed in Section 8.5.1) using the discretised probability distribution of root zone EC_{SW} assuming that all the EC_{SW} lies in the range of 1.5 to 3 dS/m (which is the first state value considered – Table 8.3). The exercise is repeated for other three states of this node, which are 3-5, 5-8, and 8-25 dS/m. The results of this analysis are presented in Figure 8.9, which shows the posterior mean (μ) and predicted probability of root zone Na^+ concentration and SAR within the study period of 2021 to 2040. It is clear from Figure 8.9*a* that mean (μ) root zone Na^+ concentration increases with the increase of mean (μ) EC_{SW}; also the cause of obvious increase in root zone SAR (Figure 8.9*c*). In the case of predicted probability of Na^+ concentration (Figure 8.9*b*), for a root zone EC_{SW} of 2.25 dS/m (which is the minimum EC_{SW} considered in the framework), it is 92% probable that the root zone Na^+ concentration would be in the range of 5-15 mmol (c)/L. Also, for a root zone EC_{SW} mean of 16.5 dS/m (which is the maximum EC_{SW} considered in the framework), there is 86% probability that the root zone Na^+ concentration would be in the range of 30-35 mmol (c)/L. It should be mentioned that probabilities of occurrence of Na^+ concentrations are 70% and 99% in the range of 15-20 mmol (c)/L and 20-30 mmol (c)/L, respectively.

In the case of SAR, for higher root zone EC_{SW} (such as 6.5 and 16.5 dS/m) it is more likely that SAR would be in the range of 8-10 (Figure 8.9*d*). For lower root zone EC_{SW}, such as 2.25 and 4 dS/m, probabilities of occurrence of SAR are 57% and 61% in the range of 3-5 and 5-8 (not shown in the figure), respectively.

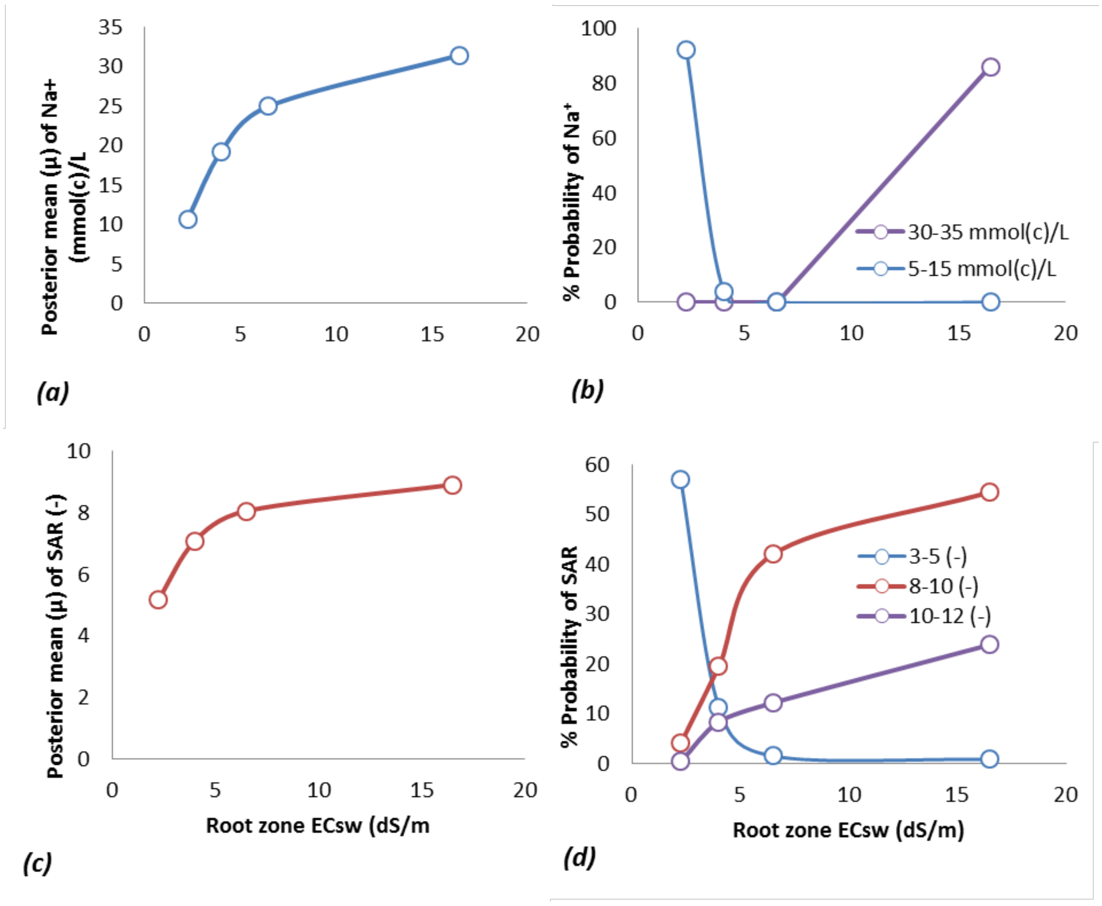

Figure 8.9 **Impact of root zone EC_{SW} on root zone Na^+ concentration and SAR over the period of 2021 to 2040 (*a*) variation of posterior mean of Na^+ concentration (mmol(c)/L) (*b*) predicted probability of Na^+ concentration (mmol(c)/L) to be in certain range (*c*) variation of posterior mean of SAR (-) over the study period (*d*) predicted probability of SAR (-) to be in certain range.**

8.7 Management scenarios to control salinisation

It is recognised from the above discussion and salt transport modelling results presented in Chapters 5 and 6 that long-term irrigation with recycled water may progressively increase the salt accumulation in the root zone in D21 paddock. Increased levels of salinity in the root zone may affect plant response in terms of leaf xylem water potential, tissue moisture content and color of grass in open space (Lockett et al. 2008). Rengasamy (2006) and Grewal and Maheshwari (2013) observed that salinity in root zone reduces the root water uptake by plants, which reduces plant growth and hence, reduces crop yield. This necessitates an examination of possible management options which can relieve the salt accumulation due to long-term irrigation using recycled water.

The problem of root zone salinity due to recycled water irrigation is possible to tackle with the implementation of the proposed BBN_{Field}. The management option considered in this chapter is to reduce the salt level in recycled water before using it in the irrigation. Investigation with the help of BBN_{Field} was carried out to find suitable amount of salt reduction in the recycled water, so that the salt accumulation in the root zone remains sustainable (i.e. below the maximum salinity threshold limit), by irrigation using recycled water.

A backward propagation was carried out to find out the impact of changes of EC_{SW} on the EC_{rw} (Figure 8.10). It can be seen from the figure that root zone EC_{SW} depends on the recycled water EC, which also supports the findings of sensitivity analysis conducted for BBN_{Lab} (Section 8.5.1). Over the study period of 20 years, the probability that the recycled water EC of 0.1 to 0.8 dS/m range will cause root zone EC_{SW} of 2.25 and 4 dS/m is 59.7 and 48.9%, respectively (Figure 8.10 *a* - *b*). However, high root zone $EC_{SW,}$ such as 6.5 and 16.5 dS/m will be caused by recycled water EC from 1-1.6 dS/m range with a probability of 44.8 and 62.3%, respectively (Figure 8.10 *c* - *d*). In other words, if the posterior mean of recycled water EC can be reduced by 13% (from μ=0.92 dS/m to μ=0.8 dS/m), there is 48.9% probability that the recycled water is from the range of 0.1-0.8 dS/m, however, there is 31% possibility that the EC_{rw} is from the range of 1-1.6 dS/m. Interestingly, the amount of reduction in EC_{rw} brings the average root zone EC_{SW} down from 6.5 dS/m to 4 dS/m, which is within the salinity threshold limit of 3.0 to 5.0 dS/m for rye pasture (NRMMC-EPHC-AMC 2006).

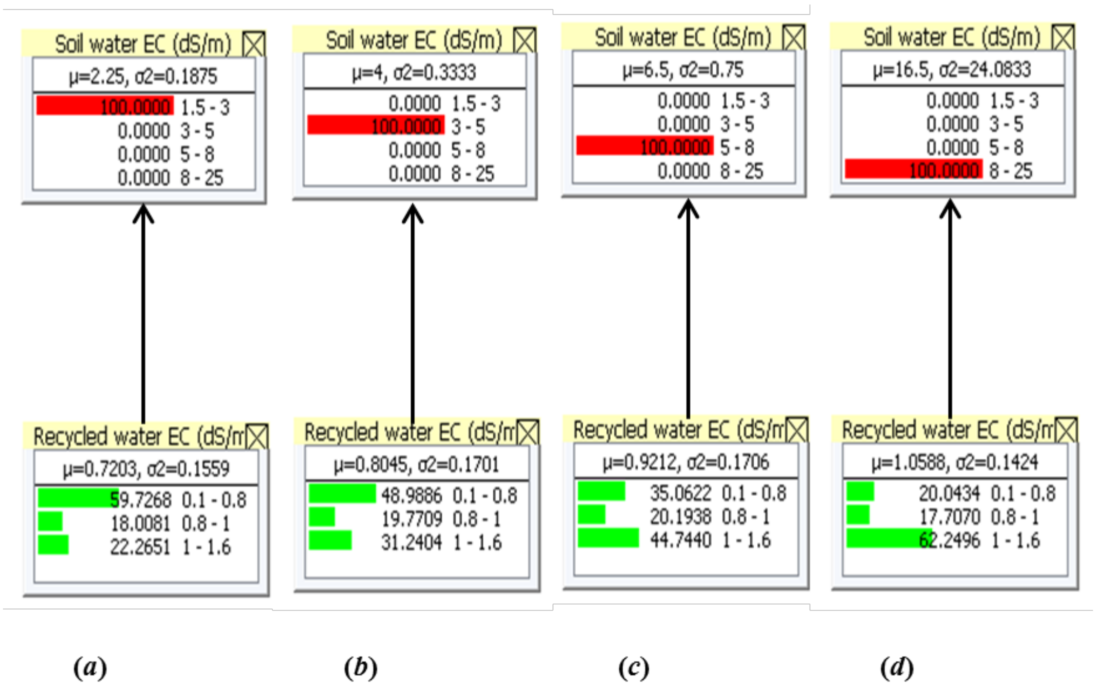

Figure 8.10 Backward propagation showing impact of root zone soil water EC (EC_{SW}) on recycled water EC (EC_{rw}) over the period of 2021 to 2040, assuming all the EC_{SW} lies in the range of (*a*) 1.5-3 dS/m (*b*) 3-5 dS/m (*c*) 5-8 dS/m and (*d*) 8-25 dS/m

Given that conventional treatment system is unable to remove salinity from recycled water (Rebhun 2004), it may be necessary to install tertiary treatment system comprising reverse osmosis (RO) process to remove salt from the recycled water. Also, it is not necessary to treat all the recycled water to treat with reverse osmosis process. For example, by blending or mixing recycled water treated using reverse osmosis with the equal amounts of recycled water that is not treated using recycled water can yield 50% salt reduction in the irrigation water. It should be mentioned that the reverse osmosis process is costly; however, research shows that farmers are willing to pay more for higher quality water (Brahim-Neji et al. 2014).

Thus the proposed management option of partially treating recycled water using reverse osmosis process may be an appropriate solution to reduce salinity impacts on the ground water table, especially for the perched aquifer situated under this paddock in HWRS. Beveridge (2006) monitored the ground water table at this site from January 2004 to April 2005 and reported that the depth of the water table of the perched aquifer was between 1.4 to 2.4 m. Therefore, continuous irrigation using 100% recycled water over a long period of time may impact on the salinity levels of the groundwater in the perched aquifer.

Instead of using RO treated recycled water to blend with untreated recycled water, it is possible to blend harvested stormwater with untreated recycled water. Stormwater harvesting involves collecting, storing and treating stormwater from urban areas, which can then be reused (Sydney Water 2013a). Stormwater is expected to contain relatively less salt levels (electrical conductivity of 0.17 to 0.34 dS/m) as compared to the recycled water (Sharpin 1995). A well-designed and managed stormwater management scheme, such as wetland and urban lake, may be able to supply required quantity of water for blending with recycled water.

However, care should be taken to maintain the quality of the stormwater to be used. Especially, during the prolonged drought period (root zone salinity due to drought condition is discussed in Chapter 5) the quality of detained stormwater should be monitored for possible increase of salinity. Moreover, during drought conditions, sufficient stormwater may not be available for use in the blending, which may be available during normal condition (root zone salinity in normal condition is discussed in this chapter and Chapter 6). Furthermore, economic feasibility must be considered before deciding to establish the stormwater harvesting scheme (Knights and McAuley 2009).

It is understood that conventional management options such as leaching fraction might be used to reduce the salt build-up as explained in Section 5.3, because leaching fraction is highly correlated with salt build-up in the soil profile. Leaching fraction based salinity management was reported to have helped in reducing high salinity level in open space in the lower Colorado River basin (Devitt et al. 2007). However, the leaching fraction was not considered as the sustainable option in this study because increased leaching flushes considerable amount of salt out of the root zone and into the groundwater aquifer (Khan et al. 2007); in the case of using blended recycled water, less amount of salt will be leached. Therefore, mixing treated (using RO) and untreated recycled water before applying as irrigation water is considered to be more sustainable. This solution was also recommended by

Grewal and Maheshwari (2013) for continuous long-term irrigation using recycled water.

8.8 Summary

Results presented in this chapter reports a new approach incorporating bayesian belief network model, to analyse the soil salinisation due to application of recycled water for irrigation. The proposed model allows for back calculating the level of treatment needed to reduce salinity in recycled water while considering the stochastic nature of the parent and child nodes. Probability distributions for different variables of a simplified salt accumulation process were developed from relationships evaluated in the laboratory experiment. The developed framework provides distribution of ionic composition in root zone and overall salinity in irrigation water with a range and corresponding probability for the desired salt concentration (EC_{SW}) in the soil.

Through BBN analysis the level of treatment of recycled water needed was determined to keep the root zone EC_{SW} within the sustainable limit. The management option of blending recycled water with RO treated water before using it as irrigation water will help in securing sustainability in agricultural irrigation given the increasing reliance on recycled water. The proposed management option is resilient for advanced countries like Australia because water authorities in different major cities in Australia are currently utilising RO treated recycled water to maintain river health and urban open space irrigation (Sydney Water 2013b; Port Macquarie Hastings Council 2013). Further research may warrant identifying appropriate way of implementing the management option proposed in this study to reduce the risk for salt accumulation in the root zone with longer-term recycled water irrigation. Further, it is apparent that while irrigating with recycled water, besides monitoring soil moisture, it is necessary to monitor salt levels in the soil.

CHAPTER 9

MANAGEMENT OF SOURCES CONTROLLING SOIL SALINITY

This chapter is partial reproduction of the following refereed journal paper:

[1]Rahman, M.M., [1]Hagare, D. and [2]Maheshwari, B. (2014). Framework to assess sources controlling soil salinity resulting from irrigation using recycled water: An application of Bayesian Belief Network. Journal of Cleaner Production, In Press (Impact factor 3.590). http://www.sciencedirect.com/science/article/pii/S0959652614004259

DOI: 10.1016/j.jclepro.2014.04.068

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9.1 Introduction

In Chapter 8 management of root zone salinity due to recycled water irrigation was discussed, where controlling salinity in the recycled water was emphasised as a management option. However, controlling salinity at its source may help to reduce salinity in the recycled water if salinity load in the sewage can be prevented before entering the treatment plant. Sewage from domestic sources contains several contaminants including detergents, floor cleaners, medicines, toothpaste, chlorine bleaches, hand lotions, mouthwash, shampoo, cosmetics, disinfectants, hair-dyes and tints, skin ointment, shaving cream and general cleaners (Munoz 1994). Particular contaminant that is of concern for this study is salts. The main contributors to salinity from the domestic sources are sodium based detergents and other chemicals used in washing clothes and utensils, and sodium based salts used in food preparation (Patterson 2004; Stevens et al. 2011). In a typical household, major appliance which contribute salt load to the grey water include dishwasher, washing machine, shower, kitchen and bathroom sink. In general, the salt along with other household waste (faeces, paper and food scraps) is discharged into sewer system and finally to the sewage treatment plant (Patterson 2004). As discussed in Chapter 8, while most organic matter is removed by various wastewater treatment processes, the majority of mineral salts pass through the wastewater treatment system unaffected, unless reverse osmosis is used as one of the treatment processes.

Source control includes the identification and monitoring of contaminants, with a view to reduce or eliminate these, before entering the sewer system. This is critical in order to protect the sewage collection infrastructure, workers at sewerage systems, efficiency of treatment processes, effluent quality, and the receiving environment. In addition, source management, in particular, is becoming important in the context of sustainable management of resources, as the potential pollutants are prevented from entering into the environment. Similarly, source control in the case of controlling the salt in the wastewater can yield more sustainable use of recycled water for irrigation purposes.

The Vayesian belief network (BBN) methodology developed and validated in Chapter 8, is used in this chapter to identify the sources that significantly influence the soil salinity and sodicity within the context of using recycled water for irrigation.

The proposed methodology is implemented in a sporting oval, namely Greygums oval. Details of the case study area are discussed in Section 3.2.2. Applying the same BBN methodology in paddocks as well as in sporting ovals demonstrates the versatility of the proposed methodology for analysing salt accumulation in the soil. However, the methodology proposed in Chapter 8 is modified in this chapter by the addition and omission of several nodes to appropriately represent the case study; also by updating parent child relationships. In the case of functionality both methodologies (proposed in this chapter and Chapter 8) are similar; however they are different in terms of manifestation. Moreover, in this chapter soil salinity is expressed as Total Dissolved Solid (TDS) instead of EC_{SW}. This is because salinity from domestic sources was calculated as “salt load, g/d” rather than “concentration, g/L”. This was achieved by converting the literature reported EC data (dS/m) to TDS (g/L) using a multiplication factor of 640 (Stevens et al. 2008; Tchobanoglous and Burton 1991). The main objectives of this chapter are:

- To identify the salt sources which have maximum influence on the salinisation of the soil;
- To discuss possible options to control the salt load from the sources which are important in terms of salinisation of the soil.

9.2 Methodology

Background of BBN and essential terminologies used during the analysis of BBN are discussed in Chapter 3, Section 3.6.2. The steps involved in the BBN model development and application are depicted in Figure 9.1. The construction and application of the model was carried out in six steps, namely,

(i) Identification of parent and child nodes;
(ii) Collection of mean and standard deviation of salinity loads in terms of TDS and Na^+ from literature to develop probability distribution of parent nodes (i.e. sources of salinity);
(iii) Evaluating parent-child relationships;
(iv) Discretisation of the nodes;
(v) Construction of the model using Hugin-Expert® (Hugin 2013) system; and
(vi) Likelihood analysis using the constructed model.

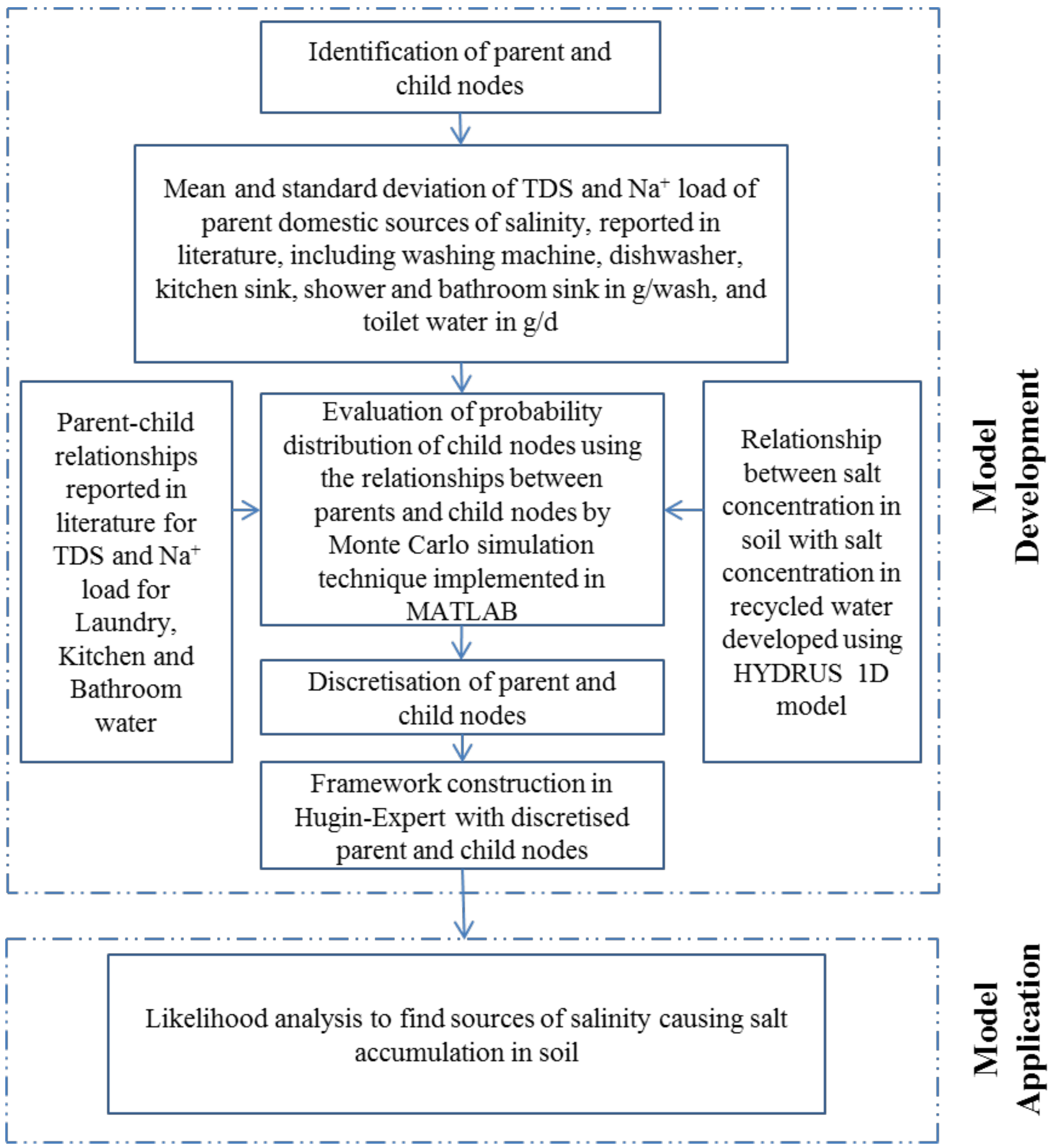


Figure 9.1 Steps for BBN analysis

9.3 Parent and Child Nodes

In the proposed model, the nodes represent a particular parameter which is ultimately connected with the probability of salinity in the root zone soil. All the parent and child nodes considered in the proposed BBN model are considered to be stochastic variables with normal probability distribution. The parent and child nodes are identified under four phases, which include:

- Salt generation phase – consists of domestic appliances (salt sources) that contribute towards the salt load in the wastewater.
- Wastewater phase – consists of various wastewater streams including different streams of grey and black water.
- Treatment phase – consists of treatment plant that produces recycled water.
- Salt accumulation phase – includes the process of salt accumulation in the root zone due to recycled water irrigation.

All the nodes and the phases are presented in Figure 9.2, which forms the framework for the proposed BBN model. Typically, salt load that enters the wastewater treatment plant mainly comes from residential, commercial and industrial sources and to a lesser extent from stormwater, infiltration and inflows. However, in the current BBN model, only the residential sources are considered. Commercial, industrial and other sources are not included in this study due to lack of data. Within the residential, five different sources of salt loads (in terms of TDS and Na^+) from various appliances at home were considered, namely, washing machine (WM), dishwasher (DW), kitchen sink (KS), shower water (SW) and bathroom sink (BS). These were considered as the main contributors to the salt loads in grey water by Diaper et al. (2008). These five nodes of the first phase are considered as parent nodes.

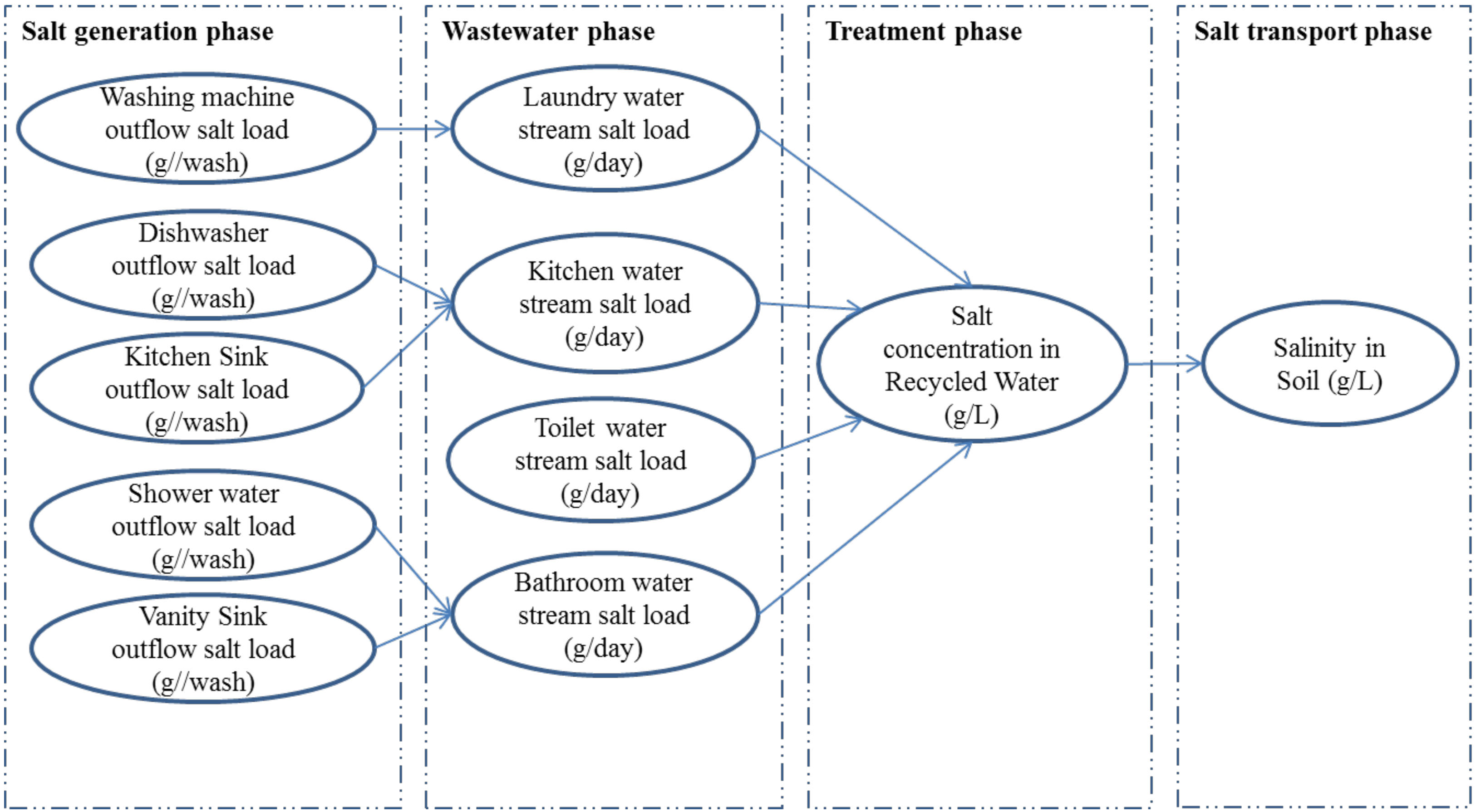


Figure 9.2 The BBN model for source management of Greygums oval irrigated with recycled water

Each of the sources of first phase contributes to the second phase (wastewater phase) of the respective grey water streams. Laundry water (LW), kitchen water (KW) and bathroom water (BW) streams were connected to respective parent nodes contributing to salinity loads. These three streams of this phase are considered as child nodes. The main reason for selecting individual streams of grey water is for identifying the significant stream which will have a maximum impact on the soil salinity. The knowledge of grey water composition is essential for its treatment and the management of treated grey water for reuse purposes, particularly for crops or urban irrigation (Huang et al. 2012; Naylor et al. 2012). The black water stream from toilets (TW) is considered as a parent node in the wastewater phase, as the raw data related to the salt load that is entering toilet water stream was not available.

The grey and black water streams (Figure 9.2) are considered separately and are connected to the third phase of the pathway consisting of wastewater treatment plant to produce recycled water. The recycled water that is used in this oval is produced at Penrith Sewage Treatment Plant. The wastewater received by this plant undergoes preliminary treatment, primary treatment, secondary treatment (biological treatment and intermittently decanted aerated lagoon treatment) and tertiary treatment. The tertiary treatment comprises flash mixing (addition of Alum for flocculation), filtration (by deep bed sand filter) and disinfection (by chlorine).

The fourth phase of the pathway includes the salinity levels in the root zone soil. The accumulation of salt in the root zone is quantified by using HYDRUS 1D (Šimůnek et al. 2009). This model (HYDRUS 1D) plays an important role in the overall Bayesian network. Governing equations for water and solute transport modelling implemented in HYDRUS 1D is discussed in Chapter 3, Section 3.6.1

9.4 Relationships between parent and child nodes

In this study, the relationships between parent and child nodes are taken from literature except the relationship between the recycled water salt concentration and salt accumulation in soil, which was determined using HYDRUS 1D. The derived relationship between parent and child nodes and the marginal probability of parent nodes were used to generate a model for the conditional probability of the child nodes. For this purpose, a Monte Carlo simulation technique implemented under MATLAB was used. Details of the process of Monte Carlo simulation and node discretisation are discussed in Chapter 8, Section 8.4.

9.4.1 Salt generation phase

The parent nodes in the salt generation phase of the exposure pathway are formulated from information reported in Diaper et al. (2008). The authors simulated the field conditions in a controlled laboratory experiments to find out physicochemical properties of the effluent from different appliances including washing machine, dishwasher, shower head, bathroom sink and kitchen sink using different types of cleaning products (the detailed description of the cleaning products is available in Diaper et al. (2008). The study reported effluent quantity and pollutant concentrations (i.e. TDS and Na^+) in the effluent for single use of the above appliances. The effluent quantity and pollutant concentrations were measured at the outlet of respective appliances by collecting multiple samples at the time of effluent discharged by the appliances. For washing machine, each top loading and front loading types were run for two different combinations of cold and warm wash cycles. Each combination was run with five different types of washing powder and liquids. The dishwasher was tested for two modes, the normal and rapid modes. The normal mode includes a pre-wash, a wash and two rinses whereas the rapid mode does not have a pre-wash in the program. In the study the dishwasher was run with no dishes. A low flow and a high flow shower head were used to observe the different outlet flow and pollutant concentration profiles from different shower heads. The low flow head used on average 10 L/min and the high flow shower head was measured to use 13.5 L/min. Showers were run for 4 minutes to simulate a complete bath using a leading brand roll-on deodorant, liquid soap, shampoo and conditioner. For the bathroom sink, three products were used: liquid soap hand wash, toothpaste and mouthwash, which were used as per the behaviour of the male experimenter. For the kitchen sink experimentation, a leading brand of washing detergent was dissolved in a sink filled with water.

As explained above, the experimental study was well designed and can be reproduced if desired. Further details on the experimental design and measurements can be obtained from Diaper et al. (2008). Data presented by the authors of this experiment represent the amount of salt (TDS and Na^+) that is generated from different appliances of a single person household located in an urbanised area. Table 9.1 shows the marginal probabilities (μ and σ) for each of the five nodes (Figure 9.2) in this phase for TDS and Na^+ as calculated using the data given in Diaper et al. (2008).

It should be noted that the total load of salt from the household will vary according to the number of persons in a household and their usage pattern. Also, the survey conducted by Roberts (2005) for calculating frequency of appliance use is based on neighbouring state Victoria, which may be slightly different from the user pattern of inhabitants residing in the study area. To account for the above factors a multiplication factor was developed. More details on the same are given in Section 9.4.2.

Table 9.1 Marginal probability and output states of parent nodes in salt generation phase

Node	TDS (g/wash)		Na^+ (g/wash)	
	μ, σ*	Output states	μ, σ*	Output states
Washing machine Outflow load	μ= 46.73, σ=31.13	0-35, 35-70, 70-105, 105-140	μ= 49.08, σ=30.35	0-35, 35-70, 70-105, 105-140
Dishwasher Outflow load	μ= 20.37, σ=9.51	0-10, 10-20, 20-30, 30-40, 40-50	μ= 16.54, σ=9.67	0-10, 10-20, 20-30, 30-40, 40-50
Kitchen sink Outflow load	μ= 0.57, σ=0.34	0-0.4, 0.4-0.8, 0.8-1.2, 1.2-1.6	μ= 0.143, σ=0.04	0-0.09, 0.09-0.135, 0.135-0.18, 0.18-0.27
Shower water Outflow load	μ= 2.48, σ=0.86	0-0.9, 0.9-1.8, 1.8-2.7, 2.7-3.6, 3.6-5.4	μ= 0.493, σ=0.16	0-0.32, 0.32-0.48, 0.48-0.64, 0.64-0.8, 0.8-1.12
Bathroom sink Outflow load	μ= 1.93, σ=0.3	1.05-1.4, 1.4-1.75, 1.75-2.1, 2.1-2.45, 2.45-2.8	μ= 0.05, σ=0.01	0.018-0.036, 0.036-0.045, 0.045-0.054, 0.054-0.063, 0.063-0.081

Note: μ= mean, σ= standard deviation
*Diaper et al. (2008)

9.4.2 Wastewater and treatment phases

Data on TDS and Na^+ loads were used to calculate the contribution of load from different appliances to the respective grey water streams for single person household based on the frequency of uses. For example, the daily salt load for the laundry water stream was calculated by multiplying the salt load per wash (data from Diaper et al. 2008) with the number of uses of washing machine per day (data from Roberts 2005). Similarly, the daily salt loads for kitchen water stream were calculated from dishwasher and kitchen sink salt loads, and similarly, the daily salt loads for bathroom water stream from shower water and bathroom sink loads.

The relationships between the child and parent nodes are shown in Table 9.2 for TDS and Na^+ loads. Data on TDS and Na^+ loads for toilet water stream were taken from experiment conducted by Tjandraatmadja et al. (2009). The experimental setup used in this study was similar to the one discussed in Section 9.4.1. Three of the four nodes in this phase are child nodes (except toilet water) and need a CPT to connect to respective parent nodes of salt generation phase. The output from Monte Carlo simulation technique for each child node was then appropriately discretised into several intervals of state values, as explained in Chapter 8. The state values, thus created, are shown in Table 9.2 for all the nodes in wastewater phase.

Total salt load (g/day) for each of the four wastewater streams was needed to be converted into salt concentrations, so that this can be linked with the recycled water concentration node. This was achieved by dividing the total salt load by the total wastewater flow rate (Table 9.3). Total wastewater flow rate was taken for a single person household (Roberts 2005). In the treatment phase, it was assumed that the conventional treatment process was unable to remove TDS from wastewater (NRMMC-EPHC-AMC 2006). Therefore, the concentration of salt in the recycled water is assumed to be same as the one entering the treatment plant. However, as explained in Section 9.4.1, a multiplication factor was developed to take into account the variation in the user habits between the site at which the salt load data was collected and the site at which the salt load is being applied and multiple persons household. The multiplication factor also helps to include other sources (such as commercial, industrial and stormwater), not explicitly considered in Tables 9.1 and 9.2, as a function of known salt loads. The multiplication factor was calculated as the ratio of mean TDS concentration of recycled water that was applied on the site considered in this study to that of wastewater TDS entering the treatment phase (as explained above):

$$RW_{TDS} = a \times WW_{TDS} \qquad (9.1)$$

Where, RW_{TDS} = Recycled water TDS concentration leaving the treatment phase (g/L)

WW_{TDS} = Wastewater TDS concentration from domestic sources entering the treatment phase (g/L)

a = Multiplication factor

RW_{TDS} was taken as 0.54 g/L which is the average TDS concentration measured in the applied recycled water over the study period (Table 9.4) and data reported in Table 9.3 was used to calculate WW_{TDS} as 0.32 g/L. The multiplication factor 'a'was estimated as 1.72 for TDS and 0.35 for Na^+ concentrations. The values obtained for the multiplication factor 'a' indicate that while TDS concentration in the actual recycled water used in the case study is higher than the one observed in the experimental studies conducted by Diaper et al. (2008). On the other hand the Na^+ concentration is significantly lower in the actual recycled water compared to the experimental studies conducted by Diaper et al. (2008). This means that the field conditions can be quite different from experimental conditions. However, the multiplication factor proposed in Equation 9.1 is, to some extent, expected to take into account the above differences in the field and experimental conditions. The relationship shown in Equation 9.1 was used to generate CPT for the node in the third phase. The node was discretised using the output of Monte Carlo simulations according to procedure described earlier. The discretised state values for this node are 0-0.18, 0.18-0.36, 0.36-0.72, 0.72-1.08 g/L for TDS concentration, and 0-0.035, 0.035-0.105, 0.105-0.14, 0.14-0.21 g/L for Na^+ concentration.

Table 9.2 Description of nodes in wastewater phase and the relationships of child nodes with parent nodes, used to generate conditional probability table

Node	Model connecting child and parent node*	States generated from Monte-Carlo simulation output	
		TDS Load (g/d)	Na^+ Load (g/d)
Laundry water stream (g/d)	$0.43 \times WM_{Load}$	0-16, 16-32, 32-48, 48-64	0-16, 16-32, 32-48, 48-64
Kitchen water stream (g/d)	$0.26 \times DW_{Load} + 1.5 \times KS_{Load}$	0-2.75, 2.75-5.5, 5.5-8.25, 8.25-11, 11-13.75	0-2.75, 2.75-5.5, 5.5-8.25, 8.25-12
Bathroom water stream (g/d)	$0.76 \times SW_{Load} + 2 \times BS_{Load}$	3-4, 4-5, 5-6, 6-7, 7-9	0.14-0.28, 0.28-0.42, 0.42-0.56, 0.56-0.7, 0.7-0.84
Toilet Water stream (g/d)		0-10, 10-20, 20-30, 30-40	3.5-10.5, 10.5-17.5, 17.5-21, 21-28

Where, *WM* = Washing machine, *DW* = Dish washer, *KS* = Kitchen sink, *SW* = Shower water, *BS* = Bathroom sink

*Roberts (2005); Tjandraatmadja et al. (2009)

Table 9.3 Flow rate and calculated salt load of wastewater streams

Wastewater stream	TDS load (g/day)	Na^+ load (g/day)	Flow rate (L/day)
Laundry water	20.03	21.03	40
Kitchen water	6.09	4.47	3
Toilet water	15.02	15.42	30
Bathroom water	5.76	0.47	49
Kitchen sink and bathroom basin*			27
Total	46.90	41.40	149

*Kitchen sink and bathroom sink salt load is included in kitchen water and bathroom water stream

Table 9.4 Recycled water usage and applied salt load in Greygums oval during the study period

Data logging date	Average TDS of irrigation water (mg/L)	Amount of irrigation water (kL)	Calculated salt load* (TDS concentration x volume of irrigation water) (kg/ha/month)
31/1/2008-26/2/2008	604	23	6
26/2/2008-25/3/2008	621	21	6
25/3/2008-22/4/2008	506	0	0
22/4/2008-23/5/2008	552	3	1
23/5/2008-24/6/2008	533	256	59
24/6/2008-29/7/2008	511	256	56
29/7/2008-29/8/2008	512	85	19
29/8/2008-23/9/2008	564	171	42
23/9/2008-24/10/2008	563	435	105
24/10/2008-19/12/2008	485	870	91
19/12/2008-12/2/2009	478	870	90
12/2/2009-16/4/2009	501	870	94
16/4/2009-19/6/2009	495	890	95
19/6/209-20/5/2010	525	3480	73
20/5/2010-21/10/2010	523	2500	114
21/10/2010-20/1/2011	563	1048	85
20/1/2011-14/4/2011	562	1236	100
14/4/2011-23/6/2011	552	11	1

* Monthly average salt load is calculated based on the amount of irrigation water used between consecutive months.

9.4.3 Salt accumulation phase

Quantification of salt accumulation in the soil depends on, besides the salt concentration in the irrigation water, the meteorological conditions including rainfall and evapotranspiration, soil type, irrigation practice and the model parameters, such as, boundary conditions, and hydraulic and solute transport parameters. As stated, HYDRUS 1D was used to analyse the salt accumulation in this phase. The model parameters are summarised in Table 9.5. Textural distribution of soil was carried out for samples collected from the oval and the texture was determined as sandy loam. The bulk density of the top soil (0 – 0.25 m) from the study area was less than the usual range of 1100 to 1600 kg/m3 (Table 9.5) because recycled organics were mixed with the soil in this depth to increase its porosity (detailed analysis of physico-chemical characteristics is shown in Table E1-5 of Appendix E).

Atmospheric boundary conditions were specified using meteorological data. From these data, daily values of the reference evapotranspiration rate (ET_0) were calculated using Penman-Monteith method by HYDRUS 1D (Šimůnek et al. 2009). Daily values of ET_0 were in the range of 0.3-8.5 mm/day. Meteorological data were collected from nearest weather station of Penrith Lakes (station number 067113), 4 km from the Greygums Oval (Scanlon 2004). Annual rainfall during year 2008 was 867.2 mm which is around 20% more of mean annual rainfall of 715.9 mm in the study area. Annual rainfall in the study area during year 2009, 2010 and 2011 were 537.6 mm, 722.8 mm and 704.6 mm, respectively. Variation of rainfall, irrigation rate and ET_0 over the study period is shown in Figure 9.3.

Greygums Oval has an above ground automatic watering system consisting of Rainbird Eagle E900 sprinkler heads. A submergible pump operates the irrigation system from a 25,000 L tank. The monthly use of recycled water is based on Penrith City Council Groundsman’s logbook for the period between January 2008 and June 2011 (Table 9.4). From January 2008 to February 2009 the irrigation frequency was three days per week but the irrigation scheduling was decreased to two days per week from March 2009 to June 2011. Irrigation frequency was used to convert monthly recycled water usage data reported in Table 9.4 to daily application rate. Average monthly irrigation application rate and salt loading were 13.4 mm and 59.4 kg/ha respectively. As seen in Table 9.4, there is only a marginal variation in the recycled water TDS concentration (varying between 500 and 600 mg/L). On the other hand, there are large variations in the applied salt loads, which can be mainly attributed to the variation in the applied quantity of recycled water.

Table 9.5 Input parameters of HYDRUS 1D model for modelling salt accumulation in Greygums oval

Input parameters		**Values**
Depth of soil below the soil surface		1.0 m
Simulation period		1277 days
Hydraulic Model		VG-Mualem
Soil type		Sandy loam: Sand = 74.6%, Silt=9.5%, Clay=15.9%
Bulk density	Depth 0 to 0.25 m	763 kg/m^3
	Depth 0.25 to 1.0 m	1355 kg/m^3
Water flow Parameters	Depth 0 to 0.25 m	θ_r = 0.0675 m^3/m^3, θ_s = 0.6244 m^3/m^3, α =0.0338, n = 1.341, K_s= 214.13 cm/day
	Depth 0.25 to 1.0 m	θ_r = 0.0608 m^3/m^3, θ_s = 0.4418 m^3/m^3, α =0.0274, n = 1.5327, K_s= 86.59 cm/day
Longitudinal dispersivity	Depth 0 to 0.25 m	17.5 cm^{-1} (Vanderborght and Vereecken 2007)
	Depth 0.25 to 1.0 m	5.5 cm^{-1} (Vanderborght and Vereecken 2007)
Initial condition		VWC=0.2 m^3/m^3, EC_{SW}=2*EC_e (Ayers and Westcot 1985; Stevens et al. 2008) , EC_e=0.296 dS/m (Maheshwari 2011)
Water flow boundary condition		Upper BC: Atmospheric with surface layer Lower BC: Free drainage
Solute transport boundary condition		Upper BC: Concentration flux Lower BC: Zero gradient concentration
Type of solute transport model		Equilibrium model
Molecular diffusion coefficient		1.75 cm^2/day (James and Rubin 1986)
Irrigation water EC		0.54 g/L
Meteorological parameters		Bureau of Meteorology 2012
Root water uptake model		Feddes et al. (1978) model
Water stress parameter		From HYDRUS 1D built in library for Turfgrass
Plant solute uptake		Not considered

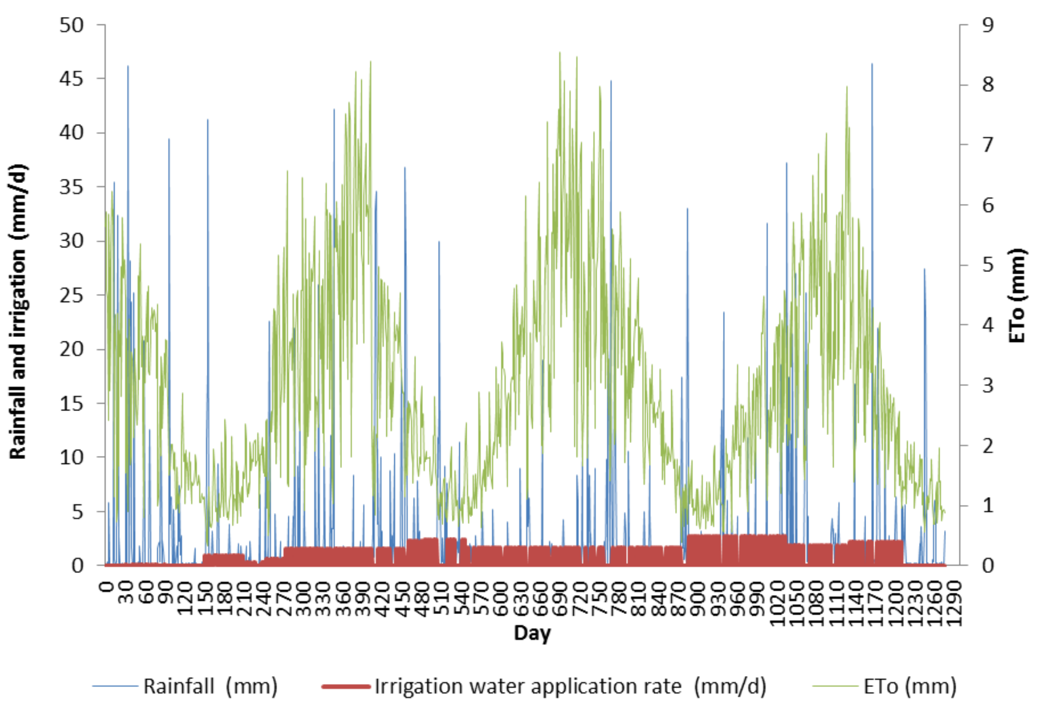


Figure 9.3 Variation of rainfall amount, reference evapotranspiration (ET_0) and amount of irrigation water applied

The hydraulic parameters reported in Table 9.5 including residual water content (θ_r), saturated water content (θ_s), shape parameters (α and n) and saturated hydraulic conductivity (K_s) were determined from the particle size distribution and bulk density of the soil with Rosetta model, which is implemented in HYDRUS 1D (Šimůnek et al. 2009).

The HYDRUS 1D simulation period for this study was set for 1277 days from January 2008 to June 2011. This period was selected mainly due to the availability of recycled water data. The simulated TDS and Na^+ concentration in the soil water in the root zone is shown in Figure 9.4 for the above period. As shown in this Figure, there appears to be significant fluctuations in the TDS and Na^+ concentration of the soil water over the study period. Root zone TDS and Na^+ concentration decreased during rainfall events, which can be due to the flushing of accumulated salt by the rain water towards the lower layers of the soil. Similar observations were reported by Ramos et al. (2011). However, there is generally an increasing trend in both TDS and Na^+ concentrations. Although the simulation predicts an increasing pattern of soil water TDS concentration at root zone (Figure 9.4), yet the simulated TDS is not high enough to affect the growth of turf grass (Kikuyu) existing in Greygums oval. According to NRMMC-EPHC-AHMC (2006), salt tolerance limit of Kikuyu grass is 2.56 to 5.12 g/L, and according to Ayers and Westcot (1985) FAO recommended limit is 3.84 to 7.68 g/L. These salt tolerance limit of Kikuyu grass is well above the maximum simulated soil water TDS concentration of 1.37 g/L. However, the trends in the current data indicate that the salt accumulation may reach or even exceed minimum salt tolerance limits in the long run. This justifies the relevance of the salt accumulation modelling for the selected study area.

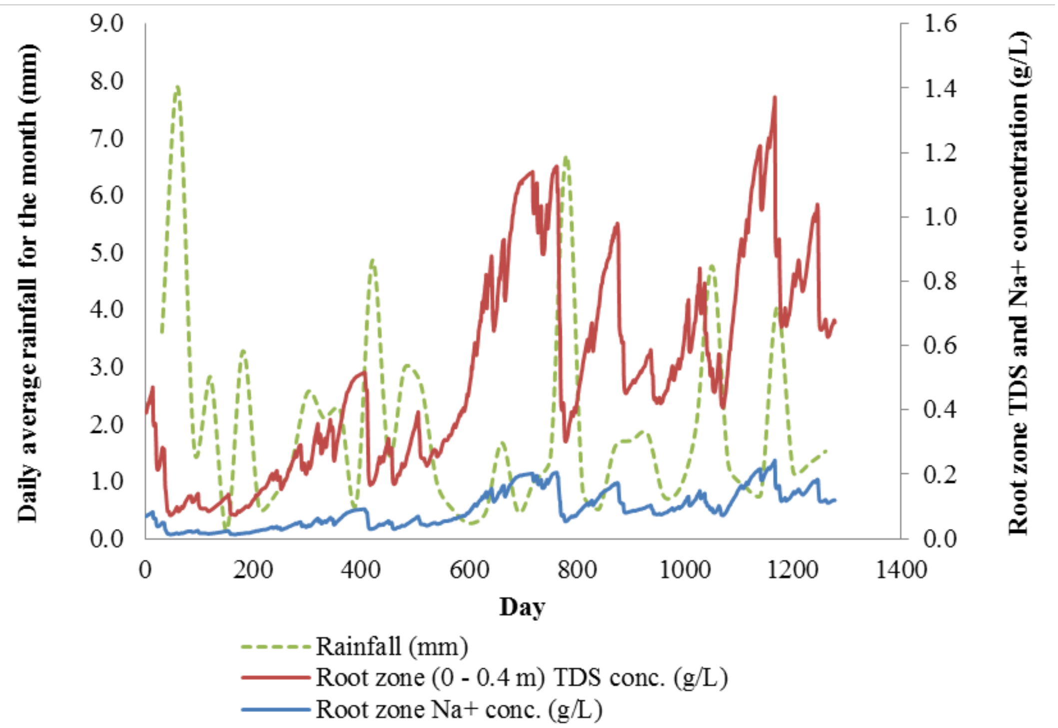


Figure 9.4 Variation of root zone salinity in relation to TDS and Na+ concentration.

As it was not possible to run HYDRUS 1D within Hugin-Expert®, a simple linear relationship was established between the salt concentration in recycled water and the salt accumulated in the soil over the study period. To get a simplified relationship between these two nodes (salt concentration in recycled water and salinity in soil), HYDRUS 1D was run several (sixteen) times by varying the TDS concentrations in the recycled water. The TDS concentrations considered for modelling were 0.27, 0.32, 0.38, 0.43, 0.49, 0.54, 0.59, 0.65, 0.70, 0.76, 0.81, 0.86, 0.92, 0.97, 1.03 and 1.08 g/L. These values were selected based on the typical characteristics of Australian recycled water (Table 2.2). The corresponding mean TDS concentrations in the soil water after each simulation were found to be 0.29, 0.33, 0.38, 0.42, 0.46, 0.51, 0.55, 0.59, 0.64, 0.68, 0.73, 0.77, 0.81, 0.86, 0.90 and 0.94 g/L respectively. The output of each run followed similar pattern as shown in Figure 9.4. The average values for the salt concentration in the soil water were calculated using the obtained pattern. The average salt accumulation in the root zone was then plotted against the salt content in the recycled water for all the runs.

Similar simulations were run for Na^+ concentrations of recycled water. The recycled water Na^+ concentrations used were 0.048, 0.058, 0.067, 0.077, 0.086, 0.096, 0.105, 0.115, 0.125, 0.134, 0.144, 0.153, 0.163, 0.173, 0.182 and 0.192 g/L. These concentrations were derived from the TDS concentrations chosen above. The corresponding mean Na^+ concentration in soil after each simulation was found as 0.051, 0.059, 0.067, 0.074, 0.082, 0.090, 0.098, 0.106, 0.113, 0.121, 0.129, 0.137, 0.144, 0.152, 0.160 and 0.168 g/L respectively.

The correlated equation between salt concentration in recycled water (*x*) and accumulated salt concentration in soil root zone (*y*) in relation to TDS and Na^+ concentration are:

$$y_{TDS} = 0.8097\, x_{TDS} + 0.0695 \tag{9.2}$$

$$y_{Na^+} = 0.8097 x_{Na^+} + 0.0123 \tag{9.3}$$

The developed correlated equation is suitable for the recycled water TDS and Na^+ concentration range of 0.27-1.1 g/L and 0.05-0.19 g/L respectively. The correlation coefficients for both the equations were closed to 1.0. It should be noted that the salt concentration in soil does not vary linearly with recycled water salt concentration; rather the relationship is explained using the partial differential equation which in this case is one dimensional advective-dispersive transport equation and is implemented in HYDRUS 1D model. Therefore, Equations (9.2) and (9.3) are only applicable to the current case study with the given input parameters such as, soil characteristics, irrigation scheduling, rainfall amount and meteorological conditions.

The correlation Equations (9.2) and (9.3) were used in Hugin-Expert® to populate the CPT between salt concentration in recycled water and salinity in soil nodes. The salinity in soil node was discretised using the output of Monte Carlo simulations. The discretised state values for this node are 0-0.32, 0.32-0.48, 0.48-0.64, 0.64-0.96 g/L for TDS concentration, and 0-0.056, 0.056-0.1, 0.1-0.14, 0.14-0.17 g/L for Na^+ concentration.

9.5 BBN model outputs

The model developed is applied using Hugin-Expert® system. Prior probability distribution for all the nodes were obtained using Hugin and the same is presented in Figure 9.5. As mentioned in Chapter 8, each box in the figure represents a variable containing three columns, where the first and second columns represent the discretised probability distribution graphically and numerically, respectively. Probability distribution of different states is shown in the third column. As observed in Figure 9.5 that the mean and variance for the parent nodes closely match with that of raw data given in Table 9.1. This indicates that the relationships between parent and child nodes and discretised probability distributions for each of the nodes are acceptable.

The BBN model was run in two modes, namely, likelihood and sensitivity analyses. The results from each of these runs are presented and discussed in the following sections.

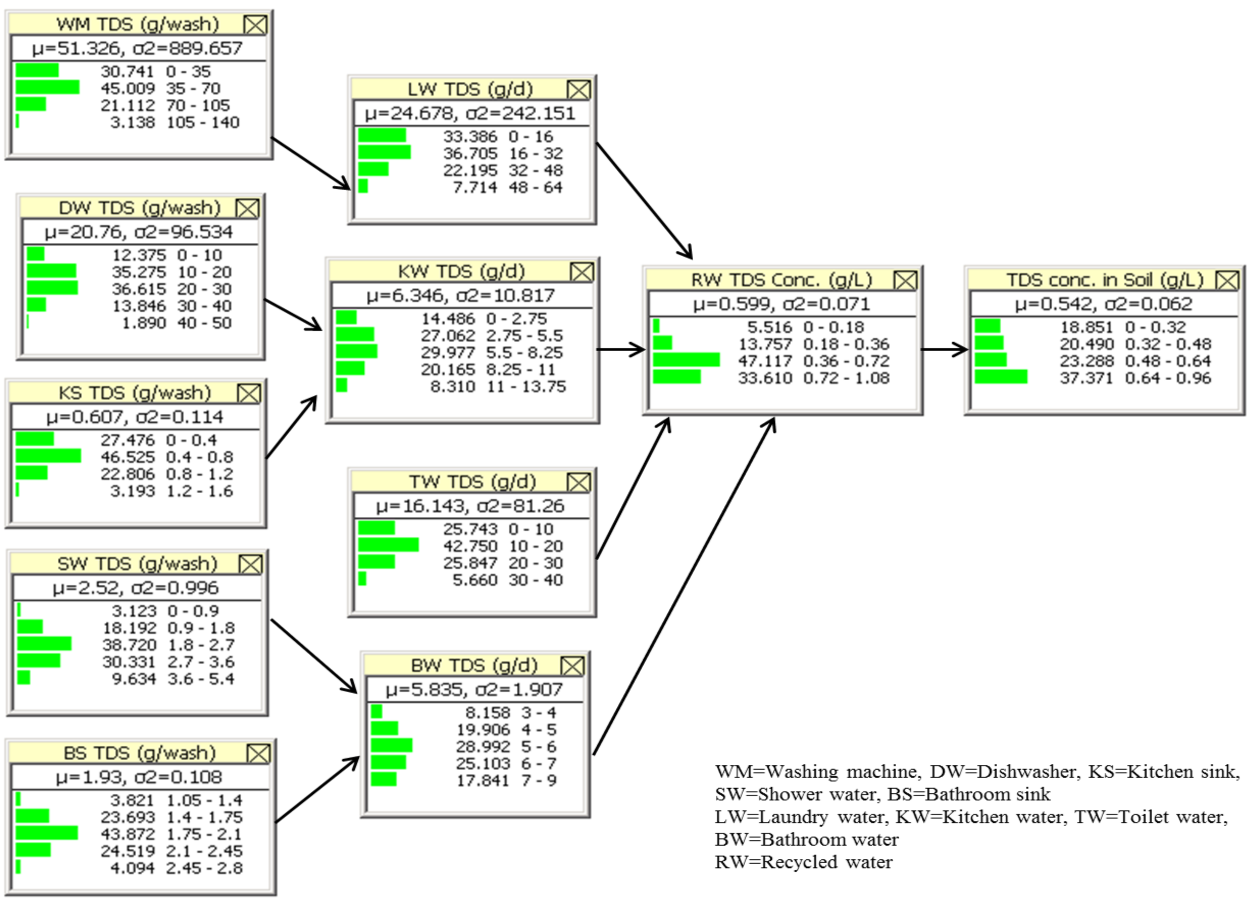


Figure 9.5 Probability distribution of different nodes based on prior beliefs.

9.5.1 Likelihood analysis

As discussed in Section 8.5, likelihood analyses were carried out using Bayes' theorem (Equation 3.19); a known probability distribution in child node was entered which changed the distribution in parent nodes. For this specific BBN model (Figure 9.2), probability distribution of the salt load at the parent nodes (source) was determined for a given or desired probability distribution in the root zone TDS and Na^+ concentrations (that is, to determine the value of $P\left(Parent\ nodes_{Salt\ load} \middle| Soil_{Salt\ concentration}\right)$). In the first instance a backward propagation analysis (discussed in Section 8.5) was carried-out using the discretised probability distribution of root zone TDS concentration (which is considered as evidence) assuming that all the TDS concentration lies in the range of 0 to 0.32 g/L (which is the first state value considered – Section 9.4.3). The results of this analysis are presented in Figure 9.6, which shows the posterior probability distribution of TDS loads for all the nodes.

Comparing Figures 9.5 and 9.6, it can be inferred that the parent nodes which will be impacted greatly are the washing machine and toilet water. All other parent nodes appear to show only a marginal change in their mean and variance. As shown in Figure 9.7, the probability distribution in the TDS load for washing machine and toilet water significantly shift to the left indicating significant decreases both in mean and variance. The mean values of TDS loads for the washing machine and toilet water need to be reduced by about 17 to 18% to achieve the TDS concentration in the soil in the range of 0 to 0.32 g/L. This indicates that to achieve reductions in the root zone soil TDS, significant reduction in the TDS loads from washing machine and toilet water needs to be achieved. This information can be used to identify the appropriate laundry detergent that must be used by the householders. For example, in this case to maintain the salt level in the soil in the range of 0 to 0.32 g/L, the average salt load for the washing machines should be reduced to 42.34 g/wash. This corresponds to the use of "no brand" washing powders (Diaper et al. 2008). This demonstrates that the proposed decision support system can be used to identify types of washing powders which, when used, could reduce the risk of high salinity in the soil.

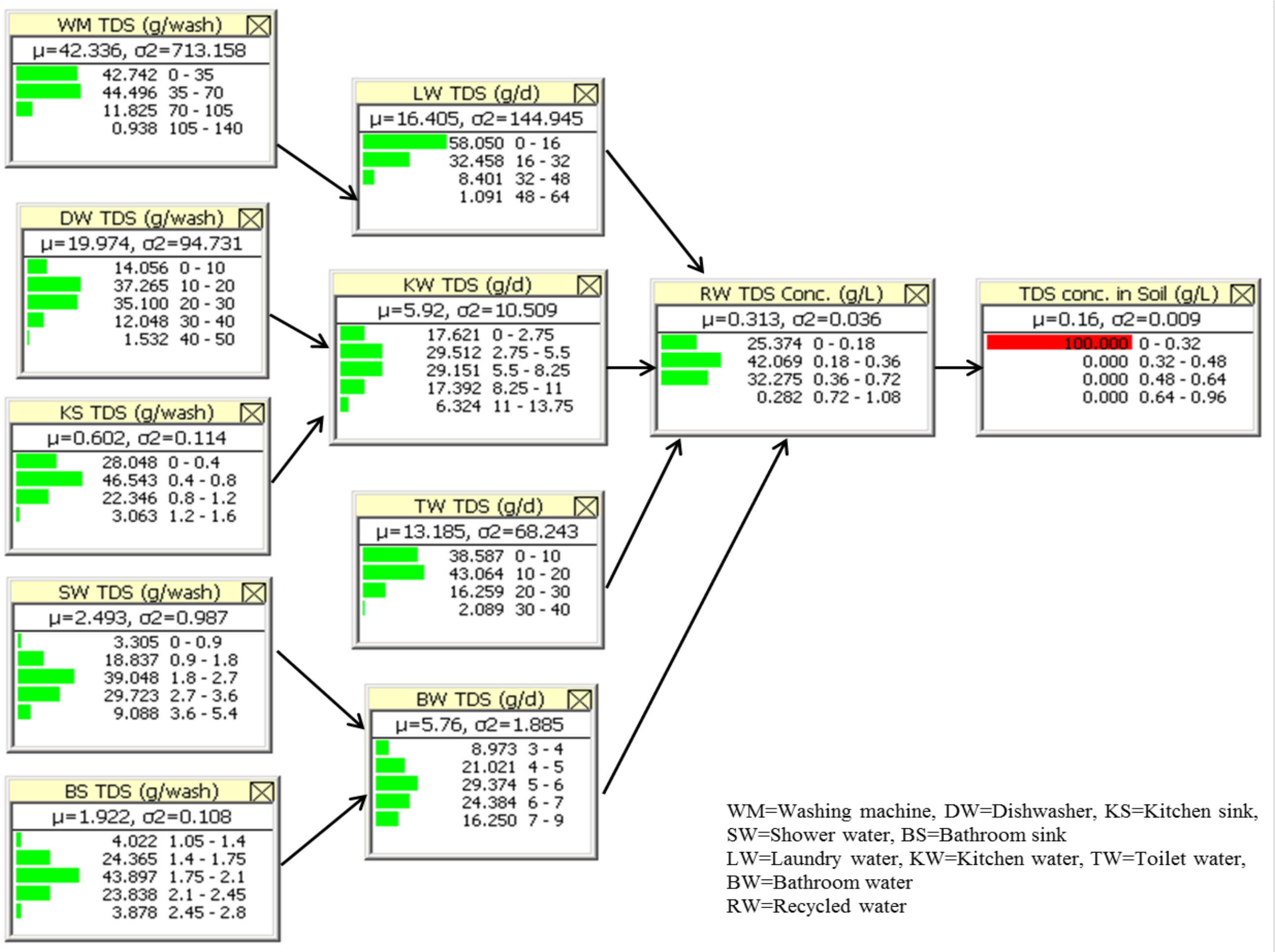


Figure 9.6 Probability distribution of different node after entering evidence in TDS concentration in soil node.

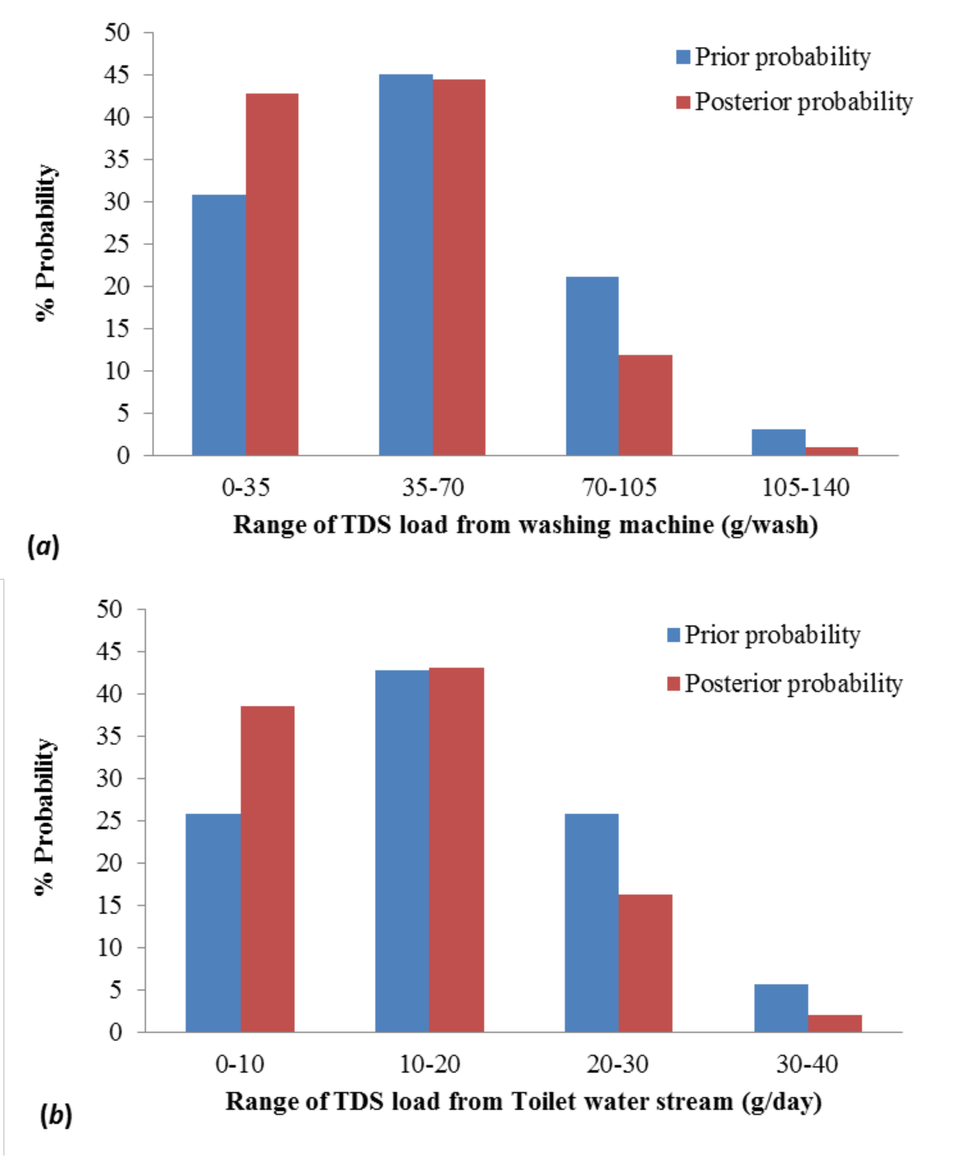


Figure 9.7 Comparison between prior and posterior (after back propagation) probability in (a) TDS load from washing machine and (b) TDS load from toilet water stream.

Similarly, backward propagation of the constructed BBN model was run for three additional scenarios considering all the root zone TDS concentrations to lie in the range of 0.32 – 0.48 g/L, 0.48-0.64 g/L and 0.64-0.96 g/L. The results from these backward propagation runs are summarised in Figure 9.8. These results again reinforce the significance of washing machine and toilet water TDS loads in determining the TDS concentration in the root zone. Source control of TDS loads from washing machine and toilet water will help to reduce the TDS accumulation in root zone. Interestingly, Makki et al. (2013) found that the shower water is the dominant sources of grey water, considering only the volume of generation. However, in this study, as shown in Figure 9.8, shower water has come out as less significant source when TDS load contribution towards salinity accumulation in irrigated soil is considered.

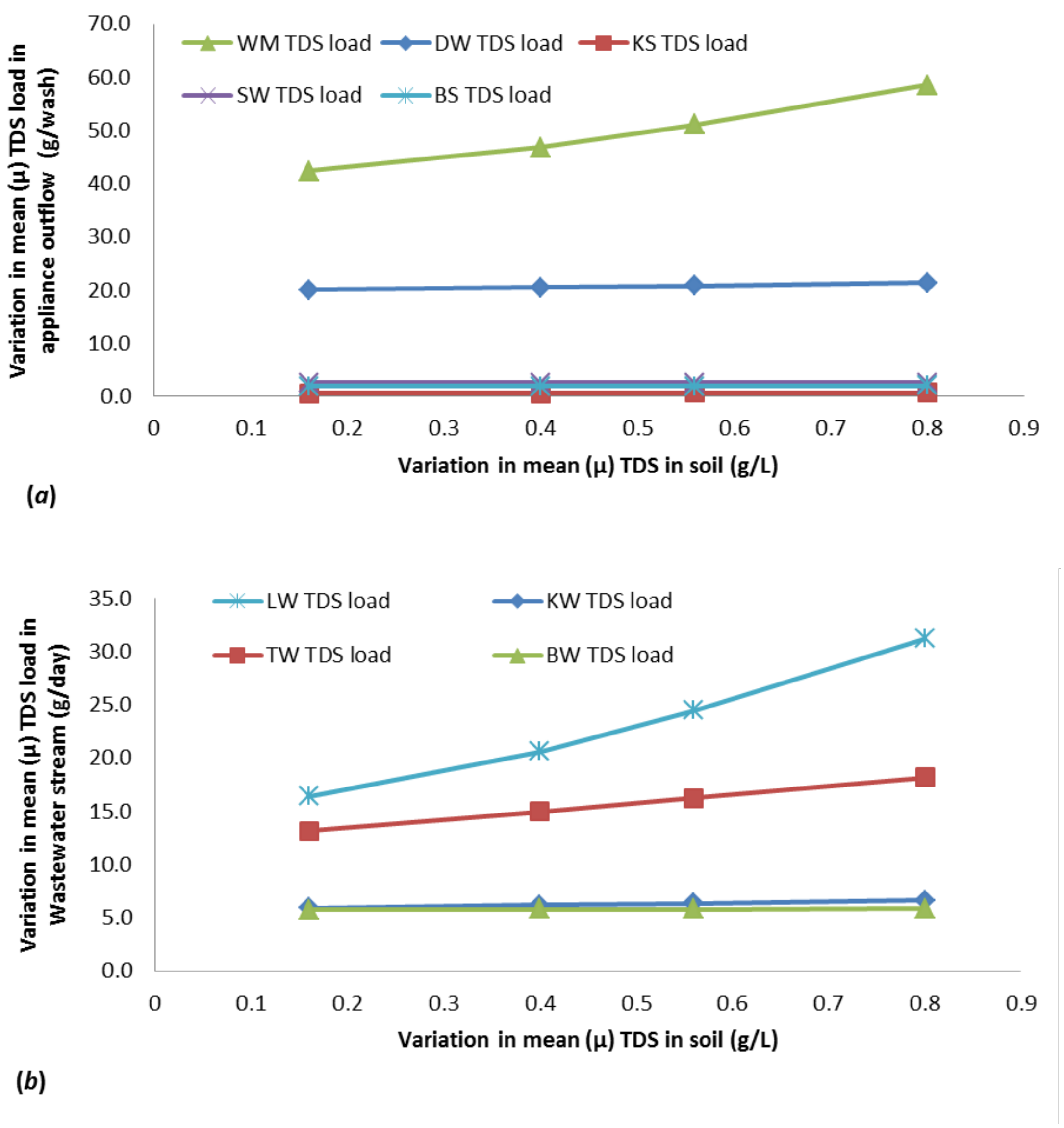
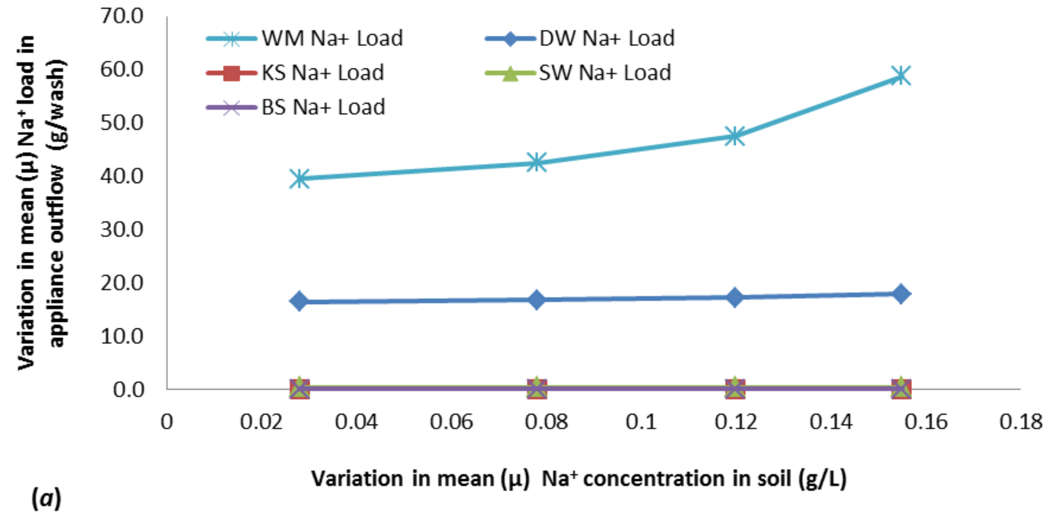


Figure 9.8 Impact of root zone TDS concentration on (a) appliance TDS load and (b) wastewater TDS load.

Similar backward propagation analyses were carried out for Na^+ concentrations in the root zone and the results are presented in Figure 9.9. Interestingly, in the case of Na^+ concentration only the washing machine appears to have a major influence on the root zone concentration. However, this is expected, as wastewater generated by washing machines usually contains high sodium levels.



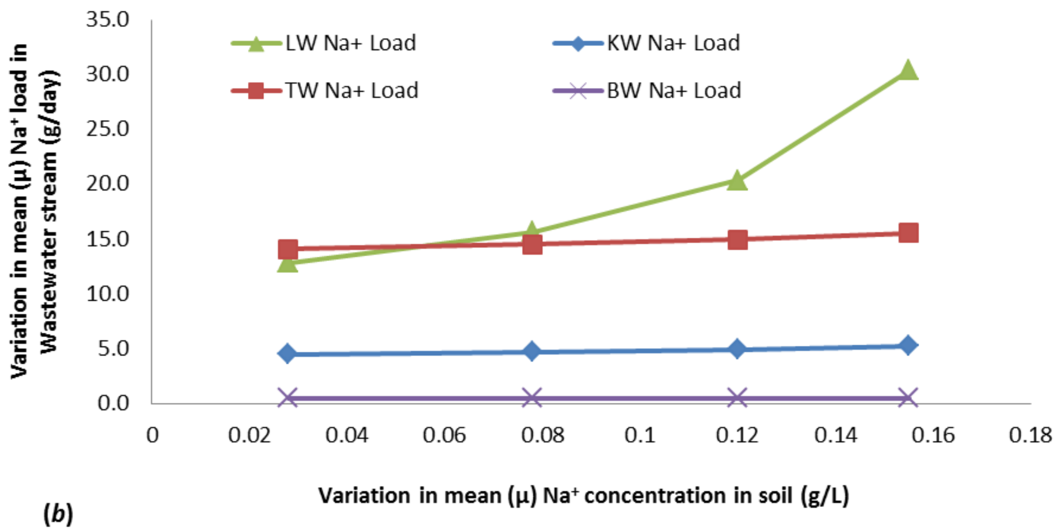


Figure 9.9 Impact of root zone Na^+ concentration on (a) appliance Na^+ load and (b) wastewater Na^+ load.

The above discussions imply that the proposed Bayesian framework can be used to determine the various source control measures that could be developed and implemented to reduce the salt concentrations in the soil. For example, it is possible to analyse the effect of use of different washing powders used by the householders on the long-term accumulation of salt in the soil. In other words, the forward propagation analysis could be used to determine the risk of soil salinisation due to a particular habit of householders in using certain types of detergents and washing powders. Hence the proposed tool can be a very good decision making tool for analysing various householders' habits and other management options for controlling the risk of soil salinisation.

9.5.2 Sensitivity Analysis

To determine the influence of parent nodes (domestic appliance load) on the final child node (salt concentration in the soil), scenario analyses were performed. This will help to further explore the significant sources that would influence the accumulation of salt in the soil. To perform scenario analysis, the distribution of parent nodes was adjusted to reflect ±50% of the prior mean. Figure 9.10 shows the variation in TDS concentrations in the soil under different distributions for the parent nodes.

Similar to the observations made in the Section 9.5.1, it is clear from the scenario analysis that the TDS concentration in the soil is mostly sensitive to washing machine and toilet water loads. The 50% increase in prior mean of these two nodes (washing machine and toilet water) resulted in 9.25 and 9.34% increase of posterior mean of TDS concentration in soil, respectively. For the 50% decrease in prior mean of these two nodes resulted in 8.66 and 9.34% decrease of posterior mean. Dishwasher TDS load also has slight effect on the TDS concentration in the soil, however not as significant as washing machine and toilet water loads. The posterior mean of TDS concentration in soil increased by 2.60% and decreased by 2.49% for increasing and decreasing the dishwasher TDS load prior mean by 50%, respectively. Other three parent nodes i.e., kitchen sink, shower water and bathroom sink had minor impact on the TDS concentration in soil (Figure 9.10). During the scenario analysis, the variance of the TDS concentration in the soil reduced for all of the appliance loads. For washing machine and toilet water, variance reduced by 8 and 10.3%, respectively. Variance of other appliance loads such as dishwasher, kitchen sink, shower water and bathroom sink reduced by 2.1, 0.3, 0.6 and 0.8%, respectively. The variance reduction means that the uncertainty associated with the variable will be reduced (Stiber et al. 1999).

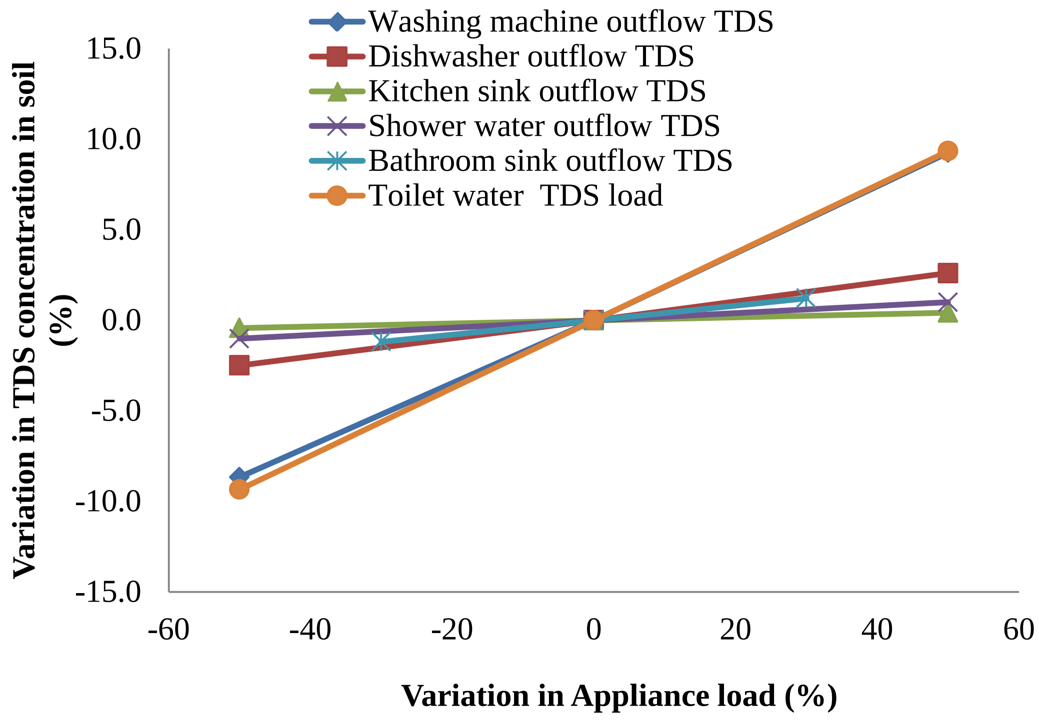


Figure 9.10 Variation of root zone TDS concentration in soil under different parent node distributions.

The results described above show the impact of controlling TDS load of individual source (one source at a time) on the TDS concentration of soil. Analysis was carried out to find the impact of controlling multiple significant sources (washing machine and toilet water stream) at the same time, on the TDS concentration in soil water. It was found that by reducing the prior mean of TDS load of these two nodes (at the same time) by 50%, reduces the TDS concentration in soil by about 19%. This implies that controlling multiple sources at the same time significantly reduces salt accumulation in the soil.

The BBN model results showed that it can identify the sources of salinity in domestic wastewater. The observations obtained in this study are supported by the experimental results of Diaper et al. (2008); yet, the model could perform better with some modifications. The framework is constructed for the sporting oval in New South Wales, Australia. But some of the user pattern data were from the survey carried out in the neighbouring state of Victoria. User pattern can vary depending on the socio-economic level of the community or region (Willis et al. 2013). For the sporting oval (Greygums oval) considered, the source management and control could be improved by using survey data from the catchment area, from where the recycled water is supplied for irrigation. However, as such data, are not readily available, the user pattern data from Victoria was used for this study.

Further, the model can be extended to determine an appropriate management or treatment option that can be used to minimise the salt accumulation in the root zone soil. To achieve this goal, some management options including residents' education on the use of specific detergents and monetary incentives for reducing consumption of water (Beal et al. 2013; Bartiaux 2008; Desmedt et al. 2009) might be helpful. Government's effort is also need to be significant to ensure that the residents get feedback on their household consumption pattern of water and on how it is related to the environmental pollution within sustainable level (Geyer-Allely and Zacarias-Farah 2003). Appropriate selection of detergents used in the washing machines can significantly reduce salt loads in laundry water streams and thereby substantially reduce the salt accumulation in the soil. For instance, it was observed that using environmental friendly detergents reduce the TDS load on the laundry stream by 4 to 7 times and Na^+ load by 2 times than popular brand detergents. Moreover, using environmental friendly liquid detergents reduced the TDS load by 1.6 and Na^+ load by 3.6 times than using environmental friendly powder (Diaper et al. 2008). These scenarios can be effectively tested using the proposed BBN model.

This model can be a valuable tool for the water authorities and the end users of the recycled water, through which they can determine a cost effective management and control option that is suitable for their specific and sustainable irrigation program.

The methodology presented in this study somewhat resemble Life Cycle Assessment (LCA) methods presented by Mahgoub et al. (2010) and Lemos et al. (2013) to identify environmental impacts associated with the entire urban water system. As such, the proposed method incorporating Bayesian Belief Network could be extended to perform LCA. Incorporation of BBN in LCA will help in the inclusion of uncertainty with respect to various parameters, which could be a significant improvement to the current deterministic approaches as suggested by Othman et al. (2013).

9.6 Summary

Methodology presented in this chapter reports a new approach incorporating Bayesian belief network model, to analyse the influence of sources of salt loads on the soil salinisation due to application of recycled water for irrigation. The proposed model allows for back calculating the source contribution that is significant, while considering the uncertainty (probability) of the parent and child nodes. Probability distributions for different variables of the salt exposure pathway (from source to end point) were developed from relationships given in the literature and with the output of solute transport software model. The developed framework provides a methodology for analysing the complex relationships between the source of generation of salt and the point of its accumulation. This provides distribution of salt load of the contributing sources, with a range and corresponding probability for the desired salt concentration in the soil.

Through BBN analysis it was determined that accumulation of salt in the root zone was largely due to the salt load in the wastewater stream from washing machines and the salt load in the wastewater from toilets was the second most influential source. The study highlighted that any strategies that would help to reduce the salt in the wastewater stream from these two sources will be beneficial to manage soil salinity due to irrigation using recycled water. It needs to be evaluated which of the salt loads are easier to control via user education, but prior research suggests that it will be easier for washing machines. An example analysis using back propagation indicated that the use of “no brand” washing powder (Diaper et al. 2008) may reduce the average TDS concentration in the soil by about 70% (from $\mu=0.542$ g/L to $\mu=0.16$ g/L). Thus the BBN model can be used as a tool to determine the magnitude of source control and appropriate product selection (for example, detergent type) to minimise the salt accumulation in the soil root zone. The proposed BBN model was also able to identify the significant source that would influence the sodium levels in the soil. The back propagation BBN model can thus be used to assess the effectiveness of various control and/or management options that can be implemented at source to minimise the sodium accumulation in the soil. Thereby, minimising or eliminating the risk of sodic soil. The results of this study indicate that the usefulness of the proposed BBN based assessment framework that can be used to develop recycled water irrigation schemes which are sustainable over the long run.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The thesis focuses on the management of salt accumulation in open fields due to recycled water irrigation. The open fields include paddocks situated in Hawkesbury campus of University of Western Sydney, and a sporting oval, namely, Greygums oval situated in Cranebrook, New South Wales, Australia. The thesis identifies elements associated with the process of salt accumulation due to recycled water irrigation and proposes an integrated management option to control root zone salinity in a probabilistic manner. The following conclusions can be drawn from this study:

10.1.1 Sensor based irrigation system

For the implementation of a sensor based irrigation system, site specific calibration of sensor was realised from the literature review for precise measurement of soil water EC. In this study, site specific calibration equation is proposed to calculate soil moisture form the sensor measured permittivity. In addition, regressed relationships are established among soil water EC, bulk EC and volumetric water content, which can be used to convert sensor measured bulk EC to soil water EC for given volumetric water content.

10.1.2 Continuous column experiments in the laboratory

Past studies suggest that conducting continuous column studies in the laboratory is useful to understand salt accumulation process. However, continuous column studies to understand impact of soil type, irrigation water salinity and rainfall on the salt accumulation in transient condition needs more research. Results from this study show that due to recycled water irrigation, loamy sand and loam soil showed similar pattern in terms of salt mass loading, however, average leachate concentration was found higher in loamy soil compared to loamy sand soil. In-situ measured EC_{SW} at the depth of 0.2 m from the surface was found to be 20% higher in loamy sand soil compared to loam soil, in the absence of simulated rainfall. In all of the continuous column studies, more salt accumulated in the upper part of the column (0-0.2 m) than the lower part (0.2-0.3 m). This is because only applied irrigation water could not leach the salt from upper part to downward. When simulated rainfall was applied (once in a week) in a loamy sand column along with recycled water (twice in a week), the average EC_{SW} showed a decreasing pattern. Results from another column study with silty loam soil showed that under similar experimental condition, average SAR due to recycled water (EC = 0.8 dS/m) irrigation was 3.6 times more than the tap water (EC = 0.2 dS/m) irrigation and 1.4 times less than the synthetic saline water (EC = 2.0 dS/m) irrigation. In the same column study, it was observed that ionic composition of saturated paste extract in terms of soluble cations increased with the increase of salinity in the irrigation water. The ratio of soluble cations (Na^+: Mg^{2+}: Ca^{2+}: K^+) in the soil sample changed than its initial ratio at the beginning of the study; in the recycled water irrigated columns Na^+ increased and K^+ decreased. The change in the ration occurred because of exchanging cations between soil and the water added for irrigation.

10.1.3 Modelling the salt accumulation under field conditions

Paddocks in HWRS have been irrigated with recycled water since long, however, salt accumulation due to recycled water irrigation was never been modelled. Especially, no scenario of soil salinisation is available under extreme (such as drought) or uncertain future climate condition. The salt transport modelling carried out in this study shows that in drought condition, yearly average EC_{SW} exceeded the maximum salinity tolerance threshold of 5.0 dS/m for rye pasture due to recycled water irrigation. The EC_{SW} was 1, 59, 79, 87 and 90% for the years from 1 to 5, respectively. In 5 years' time, root zone EC_{SW} exceeded the maximum salinity tolerance threshold by around 2 times in all of the four seasons. In another modelling study, with future climate condition between years 2021 and 2040, EC_{SW} was 24% higher in loamy soil paddock compared to loamy sand paddock. Amount of leachate in the loamy sand paddock was 27% more than the amount leached from loamy paddock, which may pose a salinity risk to the ground water if there is a perched aquifer in the field at a depth < 1 m. Salt accumulation modelling was also carried out for Greygums oval (one of the sports fields near Penrith, NSW, Australia) which predicts an increasing pattern of root zone salinity in terms of TDS and Na^+ concentration. However, the root zone salinity was found to be well below the level at which the growth of turf grass in the oval gets affected.

10.1.4 BBN framework to control salinity in irrigation water

Risk based approach such as Bayesian belief network has been extensively used by different researchers to study the risk from recycled water from microbial point of view. However, no study was conducted to assess the risk from recycled water in terms of soil salinisation. In this study, an integrated management framework implemented under Bayesian belief network identified the degree of treatment (in terms of removal of salt), the recycled water needed to keep the soil salinity within tolerance threshold for a loamy sand paddock irrigated with recycled water. Results from BBN framework analyses show that for root zone EC_{SW} of 2.25 dS/m, it is 92% probable that the Na^+ concentration of the root zone soil water would be in the range of 5 – 15 mmol(c)/L; for EC_{SW} of 16.5 dS/m, there is 86% probability that the Na^+ concentration of root zone soil water would be in the range of 30 – 35 mmol(c)/L. Furthermore, over the study period of 2021 to 2040, the probability that the recycled water EC of 0.1 to 0.8 dS/m range would cause average root zone EC_{SW} of 2.25 dS/m is 59.7%; however, high root zone $EC_{SW,}$ such as 16.5 dS/m would be caused by recycled water EC from 1 - 1.6 dS/m range with a probability of 62.3%. It was found that the reduction of the posterior mean of recycled water EC by 13% (from μ=0.92 to μ=0.8 dS/m), brings the average root zone EC_{SW} down from 6.5 dS/m to 4 dS/m, which is within the salinity threshold limit for rye pasture.

10.1.5 BBN framework to control sources of salt

The BBN framework also identified the most significant sources of salinity contributing to wastewater and proposed control strategy of those sources to minimise the salt accumulation in the soil for a sandy loam oval irrigated with recycled water. Results show that accumulation of salt in the root zone was largely due to the salt load in the wastewater stream from washing machines and the salt load in the wastewater from toilets was the second most influential source. It was found that by reducing TDS load from washing machine alone by 50% (from μ=51.3 to μ=25.7 g/d), reduces the TDS concentration in soil by about 9% (from 0.54 to 0.49 g/L) and this can be increased to 19% reduction by reducing the TDS loads from both washing machine and toilet water by 50%, simultaneously. This implies that controlling multiple sources at the same time significantly reduces salt accumulation in the soil. It was observed that by using environmental friendly detergents reduce the TDS load in the laundry stream by 4 to 7 times and Na^+ load by 2 times than popular brand detergents.

Results of this study indicate the usefulness of the proposed BBN based assessment framework as a decision making tool that can be used to develop recycled water irrigation schemes which are sustainable over the long run.

10.2 Recommendations

Following recommendations are suggested for further study:

1. For real-time monitoring system, site specific calibration equations were proposed for volumetric water content in the range of 0.2 to 0.4, which should be improved by considering low volumetric water content (i.e. 0.1 and 0.15).
2. Continuous column study may be conducted in exposed environment considering vegetation in the column to better replicate sensor based irrigation system. This would help to further understand the root zone salt accumulation including solute uptake by plant roots.
3. Further study should be conducted to understand how the selective adsorption of cations onto the soil particles occur and what are the parameters which drive the adsorption. Also the impact of chemical oxygen demand (COD) on the accumulation of organic matter, which may impact the cation retention behavior, should be studied.
4. Enrichment of nutrients in soil due to recycled water irrigation should be studied along with the salt analysis. Information on the availability of nutrients including K, N and P which are significant to plant growth will be helpful to reduce the use of fertilisers. In that case, conventional fertilisers would only be applied either as a complementary source of nutrients in case the recycled water

irrigation could not cope with all the crop needs, or as a source of material for balancing the ratio between nutrients.

5. Prediction of salt accumulation in this study was conducted based on equilibrium condition, which should be improved based on physical and chemical non-equilibrium condition. Modelling of individual cations (namely, Na^+, Mg^{2+}, Ca^{2+} and K^+) and SAR would provide vital information to predict risk of sodicity due to recycled water irrigation. The UNSATCHEM module of HYDRUS 1D may be used for this purpose.
6. It would be interesting to see how anions (e.g. chloride, bicarbonate, sulphate and phosphate), and soil organic matter (SOM) in soils are impacted due to prolonged recycled water irrigation. This is particularly important for bicarbonate, sulphate and phosphates that can form insoluble salt compounds with divalent cations in the soil solution. The intricacies of soil pH in controlling salt accumulation via formation of calcite, dolomite and gypsum can be studied.
7. The proposed assessment framework was based on static bayesian belief network for a fixed period of study period where change of nodes over time was not considered. The framework proposed in this thesis should be extended to include dynamic Bayesian belief network. Dynamic BBN is used to model time series data including the temporal analysis of cause-effect relationships among variables in the network.
8. Further calibration and validation work is needed to test the practical application of the proposed assessment framework. Also, additional sources of salt generation such as, commercial and industrial sources must be considered in the development of future BBN models.

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APPENDIX A: PHYSICO-CHEMICAL PARAMETERS OF SOIL SAMPLES COLLECTED FROM DIFFERENT PADDOCKS

Table A1a Data Sheet for textural classification of soil from D21 paddock

Sample ID	Time (min)	Hydrometer Reading (g/l) Rt	Average Hydrometer reading at 5 min. Rt5	Average Hydrometer reading at 90 min. Rt90	Blank Reading at 5 min (g/l) Ro	Blank Reading at 90 min (g/l) Ro	Blank Temp at 5 min T Deg Cel	Blank Temp at 90 min T Deg Cel	Temperature Correction at 5 min T5 oC=[T-19.5]*0.3	Temperature Correction at 90 min T90 oC=[T-19.5]*0.3	Corrected Hydrometer Reading at 5 min Ct5=(Rt5-Ro) + T5 oC	Corrected Hydrometer Reading at 90 min Ct90=(Rt90-Ro) + T90 oC	Summation Percentage P1 at 5 min = (Ct5/Wt of soil)*100	Summation Percentage P2 at 90 min = (Ct90/Wt of soil)*100
D21-1	5	7.5	6.75	3.75	2	2	23.5	23.5	1.2	1.2	5.95	2.95	11.9	5.9
	90	4.5												
D21-2	5	6												
	90	3												

Rt5 = Represents the silt and clay fraction suspended in the sample
Rt90 = Represents the clay fraction suspended in the sample

Sand = 88.1 % 100- P1 = % Sand

Silt = 6 % P1-P2 = % Silt

Clay = 5.9 % P2 = % Clay;

Soil Textural Classification: Loamy Sand

Table A1b Data Sheet for textural classification of soil from C5 paddock

Sample ID	Time (min)	Hydrometer Reading (g/l) Rt	Average Hydrometer reading at 5 min. Rt5	Average Hydrometer reading at 90 min. Rt90	Blank Reading at 5 min (g/l) Ro	Blank Reading at 90 min (g/l) Ro	Blank Temp at 5 min T Deg Cel	Blank Temp at 90 min T Deg Cel	Temperature Correction at 5 min T5 oC=[T-19.5]*0.3	Temperature Correction at 90 min T90 oC=[T-19.5]*0.3	Corrected Hydrometer Reading at 5 min Ct5=(Rt5-Ro) + T5 oC	Corrected Hydrometer Reading at 90 min Ct90=(Rt90-Ro) + T90 oC	Summation Percentage P1 at 5 min = (Ct5/Wt of soil)*100	Summation Percentage P2 at 90 min = (Ct90/Wt of soil)*100
C5-1	5	16	17	8	2	2	23.5	23.5	1.2	1.2	16.2	7.2	32.4	14.4
	90	8												
C5-2	5	18												
	90	8												

Rt5 = Represents the silt and clay fraction suspended in the sample
Rt90 = Represents the clay fraction suspended in the sample

Sand = 67.6 %   100- P1 = % Sand
Silt = 18.0 %   P1-P2 = % Silt
Clay = 4.4 %   P2 = % Clay
Soil Textural Classification: Loam

Table A1c Data Sheet for textural classification of soil from D33 paddock

Sample ID	Time (min)	Hydrometer Reading (g/l) Rt	Average Hydrometer reading at 5 min. Rt5	Average Hydrometer reading at 90 min. Rt90	Blank Reading at 5 min (g/l) Ro	Blank Reading at 90 min (g/l) Ro	Blank Temp at 5 min T Deg Cel	Blank Temp at 90 min T Deg Cel	Temperature Correction at 5 min T5 oC=[T-19.5]*0.3	Temperature Correction at 90 min T90 oC=[T-19.5]*0.3	Corrected Hydrometer Reading at 5 min Ct5=(Rt5-Ro) + T5 oC	Corrected Hydrometer Reading at 90 min Ct90=(Rt90-Ro) + T90 oC	Summation Percentage P1 at 5 min = (Ct5/Wt of soil)*100	Summation Percentage P2 at 90 min = (Ct90/Wt of soil)*100
D33-1	5	27	28	13.25	2	2	23.5	23.5	1.2	1.2	27.2	12.45	54.4	24.9
	90	12.5												
D33-2	5	29												
	90	14												

Rt5 = Represents the silt and clay fraction suspended in the sample
Rt90 = Represents the clay fraction suspended in the sample

Sand = 45.6 % 100- P1 = % Sand
Silt = 29.5 % P1-P2 = % Silt
Clay = 24.9 % P2 = % Clay

Soil Textural Classification: Silty loamy

Table A1d Data Sheet for textural classification of soil from Yarramundi paddock

Sample ID	Time (min)	Hydrometer Reading (g/l) Rt	Average Hydrometer reading at 5 min. Rt5	Average Hydrometer reading at 90 min. Rt90	Blank Reading at 5 min (g/l) Ro	Blank Reading at 90 min (g/l) Ro	Blank Temp at 5 min T Deg Cel	Blank Temp at 90 min T Deg Cel	Temperature Correction at 5 min T5 oC=[T-19.5]*0.3	Temperature Correction at 90 min T90 oC=[T-19.5]*0.3	Corrected Hydrometer Reading at 5 min Ct5=(Rt5-Ro) + T5 oC	Corrected Hydrometer Reading at 90 min Ct90=(Rt90-Ro) + T90 oC	Summation Percentage P1 at 5 min = (Ct5/Wt of soil)*100	Summation Percentage P2 at 90 min = (Ct90/Wt of soil)*100
Yar-1	5	8	7.5	3	2	2	23.5	23.5	1.2	1.2	6.7	2.2	13.4	4.4
	90	4												
Yar-2	5	7												
	90	2												

Rt5 = Represents the silt and clay fraction suspended in the sample
Rt90 = Represents the clay fraction suspended in the sample

Sand = 86.6 % 100- P1 = % Sand
Silt = 9.0 % P1-P2 = % Silt
Clay = 4.4 % P2 = % Clay
Soil Textural Classification: Loamy Sand

Table A2 Specification of Ring used to collect soil sample for the analysis of bulk density and volumetric water content at field condition

Dia (cm)	Height (cm)	Area (cm^2)	volume (cm^3)	Average volume (cm^3)
7.28	5.04	41.62	209.79	209.79
7.3	5.04	41.85	210.94	
7.26	5.04	41.40	208.64	

Table A3 Calculation of moisture content at field condition of different paddocks

ID	Wt of container, W1 (gm)	Wt of Crucible + wet soil, W2 (gm)	Wt of Crucible + dry soil, W3 (gm)	Wt of moisture, W4 =(W2-W1)-(W3-W1) (gm)	Air dry moisture content (g/g)	Average (g/g)	Air dry moisture content (%)	Average (%)
D21-1	12.30	347.62	324.93	22.69	0.07	0.062	7.26	6.15
D21-2	12.10	346.01	329.81	16.20	0.05		5.10	
D21-3	12.20	346.50	327.30	19.20	0.06		6.09	
D33-1	6.52	376.43	344.15	32.28	0.10	0.092	9.56	9.18
D33-2	12.38	388.16	357.90	30.26	0.09		8.76	
D33-3	12.40	380.50	349.40	31.10	0.09		9.23	
C5-1	12.32	364.99	326.95	38.04	0.12	0.121	12.09	12.14
C5-2	12.27	349.38	313.19	36.19	0.12		12.03	
C5-3	12.25	358.30	320.40	37.90	0.12		12.30	
Yar-1	6.58	381.29	360.59	20.70	0.06	0.058	5.85	5.84
Yar-2	6.43	375.90	355.90	20.00	0.06		5.72	
Yar-3	6.45	379.60	358.60	21.00	0.06		5.96	

Table A4 Calculation of bulk density at field condition of different paddocks

Site	Air dry soil (g)	Volume of ring (cm^3)	Bulk density (g/cm^3)	Average bulk density (g/cm^3)
D21-1	312.63	209.79	1.490	
D21-2	317.71	209.79	1.514	1.50
D21-3	315.10	209.79	1.502	
D33-1	337.63	209.79	1.609	
D33-2	345.52	209.79	1.647	1.62
D33-3	337.00	209.79	1.606	
C5-1	314.63	209.79	1.500	
C5-2	300.92	209.79	1.434	1.47
C5-3	308.15	209.79	1.469	
Yar-1	354.01	209.79	1.687	
Yar-2	349.47	209.79	1.666	1.68
Yar-3	352.15	209.79	1.679	

Table A5 Determination of $pH_{1:5}$ and $EC_{1:5}$ for soil from different paddocks

Sample ID	pH 1:5	Avg. pH 1:5	EC 1:5	Avg. EC 1:5 (uS/cm)
Yarra-1	5.4		26	
Yarra-2	5.33	5.35	28	27
Yarra-3	5.31		28	
D21-1	5.52		40	
D21-2	5.65	5.59	39	39
D21-3	5.59		39	
D33-1	6.07		63	
D33-2	6.00	6.01	63	63
D33-3	5.95		62	
C5-1	5.33		50	
C5-2	5.57	5.49	50	50
C5-3	5.58		50	

Table A6 Determination of pH_{SE} and EC_e for soil from different paddocks

Sample ID	pH_{SE}	Avg. pH_{SE}	EC_e (uS/cm)	Avg. EC_e (uS/cm)
Yarra-1	6.85	6.95	268	281
Yarra-2	7.06		276	
Yarra-3	6.85		290	
Yarra-4	7.03		291	
D21-1	5.52	5.92	557	547
D21-2	5.65		537	
D21-3	6.24		556	
D21-4	6.27		538	
D33-1	7.40	7.16	902	824
D33-2	7.00		862	
D33-3	7.24		822	
D33-4	6.99		712	
C5-1	7.04	7.01	347	340
C5-2	6.98		335	
C5-3	7.03		341	
C5-4	6.97		336	

Table A7a Data Sheet for soil water characteristic curve of soil from D21 paddock

Suction (bar)	ID	Wt of crucible, W1 (g)	Wt of Crucible + wet soil, W2 (g)	Wt of Crucible + dry soil, W3 (g)	Wt of moisture, W4 =(W2-W1)-(W3-W1) (g)	Gravimetric moisture content (g/g)	Volumetric water content (cm^3/ cm^3)
0.1	D21-1	31.583	64.445	55.312	9.133	0.385	0.38
0.1	D21-2	47.316	85.728	77.347	8.381	0.279	0.35
0.1	D21-3	31.818	67.801	59.409	8.392	0.304	0.35
0.33	D21-1	31.577	63.363	58.814	4.549	0.167	0.19
0.33	D21-2	47.303	77.324	74.018	3.306	0.124	0.14
0.33	D21-3	31.806	63.765	59.8	3.965	0.142	0.17
1	D21-1	31.584	59.196	57.982	1.214	0.046	0.05
1	D21-2	47.303	74.722	73.542	1.18	0.045	0.05
1	D21-3	31.823	60.935	59.669	1.266	0.045	0.05
3	D21-1	42.251	68.449	67.584	0.865	0.034	0.04
3	D21-2	36.068	63.415	62.492	0.923	0.035	0.04
3	D21-3	30.169	61.025	59.957	1.068	0.036	0.04
5	D21-1	31.582	60.888	60.032	0.856	0.030	0.04
5	D21-2	47.312	73.337	72.625	0.712	0.028	0.03
5	D21-3	31.816	58.465	57.715	0.75	0.029	0.03
10	D21-1	31.582	60.336	59.521	0.815	0.029	0.03
10	D21-2	47.312	77.001	76.156	0.845	0.029	0.04
10	D21-3	31.813	60.443	59.645	0.798	0.029	0.03
15	D21-1	31.583	59.907	59.185	0.722	0.026	0.03
15	D21-2	47.314	75.251	74.525	0.726	0.027	0.03
15	D21-3	31.815	61.123	60.338	0.785	0.028	0.03

Table A7b Data Sheet for soil water characteristic curve of soil from C5 paddock

Suction (bar)	ID	Wt of crucible, W1 (g)	Wt of Crucible + wet soil, W2 (g)	Wt of Crucible + dry soil, W3 (g)	Wt of moisture, W4 =(W2-W1)-(W3-W1) (g)	Gravimetric moisture content (g/g)	Volumetric water content (cm^3/ cm^3)
0.1	C5-1	30.45	66.05	56.177	9.873	0.384	0.42
0.1	C5-2	30.449	64.657	54.575	10.082	0.418	0.42
0.1	C5-3	31.703	68.042	57.955	10.087	0.384	0.42
0.33	C5-1	30.446	60.086	52.284	7.802	0.357	0.33
0.33	C5-2	30.439	58.677	52.822	5.855	0.262	0.25
0.33	C5-3	31.699	64.799	57.871	6.928	0.265	0.29
1	C5-1	31.701	55.516	53.174	2.342	0.109	0.10
1	C5-2	30.449	54.542	52.278	2.264	0.104	0.10
1	C5-3	31.706	57.606	55.168	2.438	0.104	0.10
3	C5-1	24.81	49.072	47.286	1.786	0.079	0.08
3	C5-2	17.595	41.249	39.494	1.755	0.080	0.07
3	C5-3	17.801	45.733	43.700	2.033	0.078	0.09
5	C5-1	30.448	56.02	54.503	1.517	0.063	0.06
5	C5-2	30.447	51.604	50.352	1.252	0.063	0.05
5	C5-3	31.703	55.574	54.174	1.400	0.062	0.06
10	C5-1	30.449	51.646	50.594	1.052	0.052	0.04
10	C5-2	30.44	54.981	53.724	1.257	0.054	0.05
10	C5-3	31.701	54.183	53.029	1.154	0.054	0.05
15	C5-1	30.451	55.161	53.994	1.167	0.050	0.05
15	C5-2	30.449	55.476	54.300	1.176	0.049	0.05
15	C5-3	31.702	58.257	57.009	1.248	0.049	0.05

Table A7c Data Sheet for soil water characteristic curve of soil from D33 paddock

Suction (bar)	ID	Wt of crucible, W1 (g)	Wt of Crucible + wet soil, W2 (g)	Wt of Crucible + dry soil, W3 (g)	Wt of moisture, W4 =(W2-W1)-(W3-W1) (g)	Gravimetric moisture content (g/g)	Volumetric water content (cm^3/ cm^3)
0.1	D33-1	29.947	67.15	58.415	8.735	0.307	0.37
0.1	D33-2	31.098	70.577	61.909	8.668	0.281	0.36
0.1	D33-3	31.31	69.478	59.552	9.926	0.351	0.42
0.33	D33-1	29.935	61.151	55.32	5.831	0.230	0.25
0.33	D33-2	31.08	62.038	56.428	5.61	0.221	0.24
0.33	D33-3	31.302	62.944	57.012	5.932	0.231	0.25
1	D33-1	29.945	58.666	55.45	3.216	0.126	0.14
1	D33-2	31.092	59.706	56.582	3.124	0.123	0.13
1	D33-3	31.308	55.334	52.754	2.58	0.120	0.11
3	D33-1	18.771	48.803	46.282	2.521	0.092	0.11
3	D33-2	19.535	48.862	46.368	2.494	0.093	0.10
3	D33-3	21.21	46.82	44.675	2.145	0.091	0.09
5	D33-1	29.944	59.311	57.170	2.141	0.079	0.09
5	D33-2	31.095	58.932	56.896	2.036	0.079	0.09
5	D33-3	31.306	60.484	58.376	2.108	0.078	0.09
10	D33-1	29.936	56.05	54.358	1.692	0.069	0.07
10	D33-2	31.09	56.797	55.137	1.66	0.069	0.07
10	D33-3	31.308	58.535	56.793	1.742	0.068	0.07
15	D33-1	29.942	54.697	53.248	1.449	0.062	0.06
15	D33-2	31.097	56.914	55.385	1.529	0.063	0.06
15	D33-3	31.301	59.946	58.224	1.722	0.064	0.07

Table A7d Data Sheet for soil water characteristic curve of soil from Yarramundi paddock

Suction (bar)	ID	Wt of crucible, W1 (g)	Wt of Crucible + wet soil, W2 (g)	Wt of Crucible + dry soil, W3 (g)	Wt of moisture, W4 =(W2-W1)-(W3-W1) (g)	Gravimetric moisture content (g/g)	Volumetric water content (cm^3/ cm^3)
0.1	Yarra-1	39.019	79.401	71.303	8.098	0.251	0.34
0.1	Yarra-2	38.505	72.995	64.632	8.363	0.320	0.35
0.1	Yarra-3	28.506	64.324	56.059	8.265	0.300	0.35
0.33	Yarra-1	38.996	71.554	67.74	3.814	0.133	0.16
0.33	Yarra-2	38.478	71.193	67.632	3.561	0.122	0.15
0.33	Yarra-3	28.491	61.472	57.915	3.557	0.121	0.15
1	Yarra-1	39.015	67.349	66.026	1.323	0.049	0.06
1	Yarra-2	38.501	66.015	64.792	1.223	0.047	0.05
1	Yarra-3	28.506	53.38	52.245	1.135	0.048	0.05
3	Yarra-1	31.277	57.407	56.429	0.978	0.039	0.04
3	Yarra-2	28.726	55.884	54.818	1.066	0.041	0.04
3	Yarra-3	36.843	67.775	66.475	1.300	0.044	0.05
5	Yarra-1	39.017	71.323	70.241	1.082	0.035	0.05
5	Yarra-2	38.503	66.96	66.062	0.898	0.033	0.04
5	Yarra-3	28.505	56.025	55.172	0.853	0.032	0.04
10	Yarra-1	39.015	66.653	65.846	0.807	0.030	0.03
10	Yarra-2	38.497	64.076	63.373	0.703	0.028	0.03
10	Yarra-3	28.502	51.538	50.943	0.595	0.027	0.03
15	Yarra-1	39.018	65.979	65.278	0.701	0.027	0.03
15	Yarra-2	38.503	68.008	67.287	0.721	0.025	0.03
15	Yarra-3	28.502	55.979	55.316	0.663	0.025	0.03

Table A8a Determination of VG parameter using RETC in soil from D21 paddock

VG parameter	Trial 1	Trial 2	Trial 3	Average value used in HYDRUS
θ_r	0.03399	0.03364	0.03095	0.033
θ_s	0.4021	0.42858	0.38288	0.405
A	0.00451	0.00711	0.00509	0.006
N	3.00054	2.5889	2.72464	2.771

Table A8b Determination of VG parameter using RETC in soil from C5 paddock

VG parameter	Trial 1	Trial 2	Trial 3	Average value used in HYDRUS
θ_r	0.0539	0.04751	0.05648	0.053
θ_s	0.42638	0.46793	0.4379	0.444
A	0.00521	0.00521	0.00361	0.005
N	2.2125	2.2125	2.51641	2.314

Table A8c Determination of VG parameter using RETC in soil from D33 paddock

VG parameter	Trial 1	Trial 2	Trial 3	Average value used in HYDRUS
θ_r	0.03965	0.0532	0.07506	0.056
θ_s	0.50351	0.45073	0.46255	0.472
α	0.01329	0.00913	0.0052	0.009
n	1.54739	1.68439	2.3654	1.866

Table A8d Determination of VG parameter using RETC in soil from Yarramundi paddock

VG parameter	Trial 1	Trial 2	Trial 3	Average value used in HYDRUS
θ_r	0.03386	0.03328	0.03516	0.034
θ_s	0.41824	0.41006	0.41614	0.415
α	0.00722	0.00637	0.00663	0.007
n	2.30162	2.60778	2.56959	2.493

Table A9a Data sheet for the determination of EC_{SW} from EC_{bulk} for D21 paddock soil

Trial	EC_w (dS/m)	Weight of dry soil (g)	VWC (m^3/m^3)	EC_{SW} (dS/m)	ϵ	EC_{bulk} (dS/m)	ρ_b (g/cm^3)
D21-1a	2.0	520.33	0.34	2.39	19.79	0.46	1.59
D21-1b	2.0	526.03	0.34	2.35	20.23	0.46	1.48
D21-2a	2.0	521.99	0.28	2.39	14.67	0.31	1.61
D21-2b	2.0	524.50	0.29	2.40	20.04	0.37	1.61
D21-3a	2.0	526.38	0.19	2.46	9.20	0.11	1.41
D21-3b	2.0	525.96	0.20	2.45	10.13	0.15	1.45
D21-4a	1.0	524.07	0.32	*2.40	26.22	0.27	1.60
D21-4b	1.0	528.73	0.32	1.45	23.74	0.26	1.52
D21-5a	1.0	527.36	0.27	1.80	17.47	0.19	1.63
D21-5b	1.0	527.87	0.26	*1.44	20.06	0.21	1.58
D21-6a	1.0	527.34	0.21	1.47	9.89	0.07	1.52
D21-6b	1.0	525.08	0.21	1.56	10.07	0.08	1.49
D21-7a	0.5	528.41	0.32	1.12	26.12	0.16	1.60
D21-7b	0.5	532.38	0.32	0.87	27.58	0.17	1.54
D21-8a	0.5	525.86	0.28	0.90	24.49	0.14	1.61
D21-8b	0.5	527.20	0.28	0.90	28.07	0.14	1.56
D21-9a	0.5	525.17	0.20	0.92	10.13	0.05	1.43
D21-9b	0.5	523.11	0.19	*1.03	10.58	0.07	1.44

* Not used in the calculation
EC_w = Electrical conductivity of application water
VWC = Volumetric water content
EC_{SW} = Electrical conductivity of soil water
ϵ = mean permittivity measured by GS3 sensor
EC_{bulk} = Bulk electrical conductivity of soil measured by GS3 sensor
ρ_b = Bulk density of soil in the column

Table A9b Data sheet for the determination of EC_{SW} from EC_{bulk} for Yarramundi paddock soil

Trial	EC_w (dS/m)	Weight of dry soil (g)	VWC (m^3/m^3)	EC_{SW} (dS/m)	ϵ	EC_{bulk} (dS/m)	ρ_b (g/cm^3)
Yarra-1a	2.0	521.67	0.35	2.25	20.07	0.44	1.46
Yarra-1b	2.0	624.73	0.35	2.24	19.32	0.44	1.44
Yarra-2a	2.0	513.92	0.32	2.27	19.28	0.37	1.63
Yarra-2b	2.0	528.12	0.30	2.27	17.35	0.35	1.57
Yarra-3a	2.0	538.24	0.21	2.32	10.31	0.18	1.57
Yarra-3b	2.0	526.29	0.22	2.28	10.45	0.18	1.56
Yarra-4a	1.0	511.09	0.35	1.27	23.35	0.27	1.51
Yarra-4b	1.0	511.32	0.35	1.60	23.48	0.28	1.55
Yarra-5a	1.0	509.92	0.30	1.30	20.22	0.22	1.67
Yarra-5b	1.0	515.23	0.30	1.29	20.26	0.23	1.62
Yarra-6a	1.0	509.26	0.23	1.36	10.09	0.12	1.65
Yarra-6b	1.0	517.48	0.22	1.34	10.53	0.12	1.55
Yarra-7a	0.5	510.27	0.36	0.77	25.53	0.18	1.57
Yarra-7b	0.5	524.18	0.36	0.95	24.46	0.17	1.53
Yarra-8a	0.5	512.64	0.30	0.82	20.97	0.14	1.69
Yarra-8b	0.5	519.50	0.27	0.80	22.50	0.15	1.56
Yarra-9a	0.5	510.93	0.21	0.86	10.82	0.09	1.51
Yarra-9b	0.5	503.67	0.22	0.84	11.36	0.09	1.55

EC_w = Electrical conductivity of application water
VWC = Volumetric water content
EC_{SW} = Electrical conductivity of soil water
ϵ = mean permittivity measured by GS3 sensor
EC_{bulk} = Bulk electrical conductivity of soil measured by GS3 sensor
ρ_b = Bulk density of soil in the column

Table A9c Data sheet for the determination of EC_{SW} from EC_{bulk} for D33 paddock soil

Trial	EC_w (dS/m)	Weight of dry soil (g)	VWC (m^3/m^3)	EC_{SW} (dS/m)	ϵ	EC_{bulk} (dS/m)	ρ_b (g/cm^3)
D33-1a	2.0	516.49	0.43	*1.70	26.57	0.66	1.40
D33-1b	2.0	514.41	0.40	2.45	25.82	0.69	1.36
D33-2a	2.0	511.17	0.39	2.53	25.41	0.60	1.48
D33-2b	2.0	521.86	0.38	2.56	23.04	0.60	1.47
D33-3a	2.0	506.18	0.36	2.23	21.30	0.54	1.49
D33-3b	2.0	509.02	0.34	*2.69	20.20	0.54	1.50
D33-4a	1.0	509.49	0.49	*2.03	26.02	0.47	1.53
D33-4b	1.0	516.41	0.41	1.55	28.16	0.47	1.36
D33-5a	1.0	508.70	0.39	1.57	26.50	0.46	1.44
D33-5b	1.0	515.35	0.38	1.60	25.08	0.43	1.42
D33-6a	1.0	510.26	0.35	1.29	23.63	0.39	1.50
D33-6b	1.0	514.80	0.35	1.69	21.33	0.37	1.48
D33-7a	0.5	510.57	0.43	1.32	31.98	0.39	1.34
D33-7b	0.5	515.25	0.43	1.05	28.55	0.37	1.46
D33-8a	0.5	513.93	0.37	1.19	28.32	0.33	1.51
D33-8b	0.5	519.10	0.38	1.13	27.73	0.36	1.45
D33-9a	0.5	509.89	0.37	1.14	23.76	0.31	1.59
D33-9b	0.5	516.21	0.37	1.21	24.51	0.36	1.54

* Not used in the calculation
EC_w = Electrical conductivity of application water
VWC = Volumetric water content
EC_{SW} = Electrical conductivity of soil water
ϵ = mean permittivity measured by GS3 sensor
EC_{bulk} = Bulk electrical conductivity of soil measured by GS3 sensor
ρ_b = Bulk density of soil in the column

Table A9d Data sheet for the determination of EC_{SW} from EC_{bulk} for C5 paddock soil

Trial	EC_w (dS/m)	Weight of dry soil (g)	VWC (m^3/m^3)	EC_{SW} (dS/m)	ϵ	EC_{bulk} (dS/m)	ρ_b (g/cm^3)
C5-1a	2.0	469.36	0.33	1.68	22.70	0.56	1.33
C5-1b	2.0	400.00	0.32	*1.30	21.36	0.59	1.28
C5-2a	2.0	471.23	0.33	1.97	21.17	0.61	1.12
C5-2b	2.0	450.00	0.37	*2.27	23.25	0.66	1.29
C5-3a	2.0	450.00	0.25	1.32	11.28	0.44	1.26
C5-3b	2.0	450.00	0.25	1.84	12.19	0.49	1.27
C5-4a	1.0	450.01	0.37	0.69	23.57	0.43	1.27
C5-4b	1.0	450.01	0.37	0.96	23.20	0.43	1.23
C5-5a	1.0	450.01	0.31	0.95	21.14	0.38	1.22
C5-5b	1.0	450.00	0.35	1.34	23.15	0.42	1.40
C5-6a	1.0	450.01	0.24	0.89	11.33	0.19	1.21
C5-6b	1.0	450.00	0.24	0.79	11.05	0.19	1.23
C5-7a	0.5	450.01	0.37	0.79	25.97	0.35	1.26
C5-7b	0.5	450.00	0.38	0.59	25.39	0.36	1.27
C5-8a	0.5	450.00	0.32	*0.38	21.97	0.30	1.30
C5-8b	0.5	450.01	0.35	1.04	24.38	0.31	1.39
C5-9a	0.5	450.01	0.26	0.55	13.42	0.19	1.32
C5-9b	0.5	450.00	0.25	0.59	13.30	0.23	1.27

* Not used in the calculation
EC_w = Electrical conductivity of application water
VWC = Volumetric water content
EC_{SW} = Electrical conductivity of soil water
ϵ = mean permittivity measured by GS3 sensor
EC_{bulk} = Bulk electrical conductivity of soil measured by GS3 sensor
ρ_b = Bulk density of soil in the column

APPENDIX B: ADDITIONAL DATA RELATED TO CHAPTERS 5 AND 8

Table B1a Column operation data related to column 1 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
15-Jul-13	1	4000	0.81	366.00	2.518
19-Jul-13	5	1000	0.81	930.00	1.003
23-Jul-13	9	200	0.81	178.00	0.848
5-Aug-13	22	400	0.81	45.00	NM
13-Aug-13	30	300	0.81	130.00	NM
14-Aug-13	31	200	0.81	0.00	0.000
16-Aug-13	33	300	0.81	140.00	0.864
21-Aug-13	38	200	0.81	0.00	0.000
23-Aug-13	40	200	0.81	0.00	0.000
26-Aug-13	43	100	0.81	0.00	0.000
30-Aug-13	47	200	0.81	0.00	0.000
2-Sep-13	50	200	0.81	160.00	0.885
4-Sep-13	52	100	0.81	0.00	0.000
6-Sep-13	54	200	0.81	100.00	0.838
9-Sep-13	57	100	0.81	0.00	0.000
11-Sep-13	59	100	0.81	0.00	0.000
13-Sep-13	61	200	0.81	77.00	0.947
15-Sep-13	63	100	0.81	52.00	0.887
17-Sep-13	65	100	0.81	30.00	0.932
20-Sep-13	68	200	0.81	0.00	0.000
23-Sep-13	71	200	0.81	77.00	0.995
25-Sep-13	73	100	0.81	0.00	0.000
27-Sep-13	75	200	0.81	75.00	0.976
1-Oct-13	79	200	0.81	0.00	0.000
4-Oct-13	82	200	0.81	0.00	0.000
7-Oct-13	85	200	0.81	107.50	1.060
9-Oct-13	87	100	0.81	20.00	1.081
11-Oct-13	89	200	0.81	70.00	NM
14-Oct-13	92	200	0.81	NM	0.963
16-Oct-13	94	100	0.81	0.00	0.000
18-Oct-13	96	200	0.81	0.00	0.000
21-Oct-13	99	200	0.81	85.00	1.096
23-Oct-13	101	100	0.81	42.00	1.052
25-Oct-13	103	200	0.81	30.00	1.144
28-Oct-13	106	200	0.81	115.00	1.111
30-Oct-13	108	100	0.81	0.00	0.000
1-Nov-13	110	200	0.81	100.00	1.156

Table B1a (Contd.) Column operation data related to column 1 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
4-Nov-13	113	200	0.81	0.00	0.000
6-Nov-13	115	100	0.81	0.00	0.000
8-Nov-13	117	200	0.81	75.00	1.415
13-Nov-13	122	200	0.81	0.00	0.000
15-Nov-13	124	200	0.81	135.00	1.354
19-Nov-13	128	200	0.81	85.00	1.261
22-Nov-13	131	200	0.81	102.00	1.208
25-Nov-13	134	200	0.81	105.00	1.222
27-Nov-13	136	100	0.81	35.00	1.326
29-Nov-13	138	200	0.81	50.00	1.308
2-Dec-13	141	100	0.81	36.67	1.357
4-Dec-13	143	100	0.81	36.67	1.357
6-Dec-13	145	100	0.81	36.67	1.357
9-Dec-13	148	100	0.81	0.00	0.000
11-Dec-13	150	100	0.81	0.00	0.000
13-Dec-13	152	200	0.81	0.00	0.000
16-Dec-13	155	200	0.00	125.00	1.378
18-Dec-13	157	100	0.81	50.00	1.358
20-Dec-13	159	200	0.81	132.00	1.301
23-Dec-13	162	200	0.00	110.00	1.282
25-Dec-13	164	100	0.81	55.00	1.300
27-Dec-13	166	150	0.81	100.00	1.265
30-Dec-13	169	200	0.00	100.00	1.302
3-Jan-14	173	200	0.81	100.00	1.329
6-Jan-14	176	200	0.00	90.00	1.316
8-Jan-14	178	100	0.81	0.00	0.000
10-Jan-14	180	200	0.81	120.00	1.370
13-Jan-14	183	200	0.00	125.00	1.303
15-Jan-14	185	100	0.81	55.00	1.264
17-Jan-14	187	200	0.81	106.00	1.281
20-Jan-14	190	200	0.00	110.00	1.292
22-Jan-14	192	100	0.81	65.00	1.305
24-Jan-14	194	150	0.81	90.00	1.299
28-Jan-14	198	200	0.00	35.00	1.496
31-Jan-14	201	200	0.81	100.00	1.361
3-Feb-14	204	200	0.00	108.00	1.238

Table B1a (Contd.) Column operation data related to column 1 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
5-Feb-14	206	100	0.81	0.00	0.000
7-Feb-14	208	200	0.81	124.00	1.242
10-Feb-14	211	200	0.00	110.00	1.133
12-Feb-14	213	100	0.81	60.00	1.071
14-Feb-14	215	200	0.81	132.00	1.027
17-Feb-14	218	100	0.00	52.00	1.001
21-Feb-14	222	200	0.81	54.00	1.100
24-Feb-14	225	200	0.00	60.00	1.072
26-Feb-14	227	150	0.81	50.00	1.061
28-Feb-14	229	150	0.81	93.00	0.983
3-Mar-14	232	200	0.00	115.00	0.929
7-Mar-14	236	200	0.81	102.00	0.923
10-Mar-14	239	150	0.00	82.00	0.904
12-Mar-14	241	100	0.81	45.00	0.920
14-Mar-14	243	200	0.81	115.00	0.880
17-Mar-14	246	200	0.00	90.00	0.865
19-Mar-14	248	100	0.81	40.00	0.889
21-Mar-14	250	150	0.81	122.00	0.843
24-Mar-14	253	200	0.00	120.00	0.836
28-Mar-14	257	200	0.81	100.00	0.825
4-Apr-14	264	200	0.81	100.00	0.825

NM=Mot measured

Table B1b Column operation data related to column 2 of D21 paddock soil

Date	Day	Water added (mL)	Influent EC (dS/m)	Combined Drained amount (ml)	Drained EC (dS/m)
15-Jul-13	1	4000	0.81	319.00	2.696
19-Jul-13	5	1000	0.81	930.00	1.014
23-Jul-13	9	200	0.81	91.00	0.971
5-Aug-13	22	400	0.81	50.00	NM
13-Aug-13	30	300	0.81	95.00	NM
14-Aug-13	31	200	0.81	0.00	0.000
16-Aug-13	33	300	0.81	140.00	0.849
21-Aug-13	38	200	0.81	0.00	0.000
23-Aug-13	40	200	0.81	37.20	1.087
26-Aug-13	43	100	0.81	0.00	0.000
30-Aug-13	47	200	0.81	0.00	0.000
2-Sep-13	50	200	0.81	90.00	1.045
4-Sep-13	52	100	0.81	0.00	0.000
6-Sep-13	54	200	0.81	85.00	0.945
9-Sep-13	57	100	0.81	0.00	0.000
11-Sep-13	59	100	0.81	0.00	0.000
13-Sep-13	61	200	0.81	15.00	1.135
15-Sep-13	63	100	0.81	45.00	0.993
17-Sep-13	65	100	0.81	25.00	1.051
20-Sep-13	68	200	0.81	0.00	0.000
23-Sep-13	71	200	0.81	65.00	1.034
25-Sep-13	73	100	0.81	0.00	0.000
27-Sep-13	75	200	0.81	43.00	1.048
1-Oct-13	79	200	0.81	0.00	0.000
4-Oct-13	82	200	0.81	0.00	0.000
7-Oct-13	85	200	0.81	50.00	1.217
9-Oct-13	87	100	0.81	0.00	0.000
11-Oct-13	89	200	0.81	0.00	0.000
14-Oct-13	92	200	0.81	65.00	1.001
16-Oct-13	94	100	0.81	0.00	0.000
18-Oct-13	96	200	0.81	0.00	0.000
21-Oct-13	99	200	0.81	142.00	1.080
23-Oct-13	101	100	0.81	17.00	1.036
25-Oct-13	103	200	0.81	35.00	1.080
28-Oct-13	106	200	0.81	100.00	0.980
30-Oct-13	108	100	0.81	0.00	0.000
1-Nov-13	110	200	0.81	85.00	1.020

Table B1b (Contd.) Column operation data related to column 2 of D21 paddock soil

Date	Day	Water added (mL)	Influent EC (dS/m)	Combined Drained amount (ml)	Drained EC (dS/m)
4-Nov-13	113	200	0.81	0.00	0.000
6-Nov-13	115	100	0.81	0.00	0.000
8-Nov-13	117	200	0.81	30.00	1.334
13-Nov-13	122	200	0.81	0.00	0.000
15-Nov-13	124	200	0.81	80.00	1.323
19-Nov-13	128	200	0.81	60.00	1.175
22-Nov-13	131	200	0.81	95.00	1.141
25-Nov-13	134	200	0.81	105.00	1.155
27-Nov-13	136	100	0.81	0.00	0.000
29-Nov-13	138	200	0.81	50.00	1.373
2-Dec-13	141	100	0.81	33.33	1.375
4-Dec-13	143	100	0.81	33.33	1.375
6-Dec-13	145	100	0.81	33.33	1.375
9-Dec-13	148	100	0.81	0.00	0.000
11-Dec-13	150	100	0.81	0.00	0.000
13-Dec-13	152	200	0.81	0.00	0.000
16-Dec-13	155	200	0.00	110.00	1.612
18-Dec-13	157	100	0.81	35.00	1.562
20-Dec-13	159	200	0.81	115.00	1.529
23-Dec-13	162	200	0.00	115.00	1.550
25-Dec-13	164	100	0.81	56.00	1.587
27-Dec-13	166	150	0.81	90.00	1.604
30-Dec-13	169	200	0.00	100.00	1.664
3-Jan-14	173	200	0.81	82.00	1.805
6-Jan-14	176	200	0.00	90.00	1.781
8-Jan-14	178	100	0.81	0.00	0.000
10-Jan-14	180	200	0.81	100.00	1.863
13-Jan-14	183	200	0.00	115.00	1.714
15-Jan-14	185	100	0.81	50.00	1.783
17-Jan-14	187	200	0.81	105.00	1.775
20-Jan-14	190	200	0.00	100.00	1.808
22-Jan-14	192	100	0.81	45.00	1.854
24-Jan-14	194	150	0.81	80.00	1.768
28-Jan-14	198	200	0.00	45.00	2.011
31-Jan-14	201	200	0.81	70.00	1.971
3-Feb-14	204	200	0.00	101.00	1.829

Table B1b (Contd.) Column operation data related to column 2 of D21 paddock soil

Date	Day	Water added (mL)	Influent EC (dS/m)	Combined Drained amount (ml)	Drained EC (dS/m)
5-Feb-14	206	100	0.81	0.00	0.000
7-Feb-14	208	200	0.81	89.00	1.873
10-Feb-14	211	200	0.00	102.00	1.731
12-Feb-14	213	100	0.81	52.00	1.643
14-Feb-14	215	200	0.81	135.00	1.549
17-Feb-14	218	100	0.00	50.00	1.545
21-Feb-14	222	200	0.81	45.00	1.767
24-Feb-14	225	200	0.00	50.00	1.772
26-Feb-14	227	150	0.81	30.00	1.701
28-Feb-14	229	150	0.81	85.00	1.566
3-Mar-14	232	200	0.00	120.00	1.390
7-Mar-14	236	200	0.81	85.00	1.365
10-Mar-14	239	150	0.00	80.00	1.307
12-Mar-14	241	100	0.81	35.00	1.308
14-Mar-14	243	200	0.81	110.00	1.229
17-Mar-14	246	200	0.00	85.00	1.188
19-Mar-14	248	100	0.81	25.00	1.204
21-Mar-14	250	150	0.81	120.00	1.160
24-Mar-14	253	200	0.00	118.00	1.091
28-Mar-14	257	200	0.81	90.00	1.100
4-Apr-14	264	200	0.81	90.00	1.100

Table B1c Column operation data related to column 3 of D21 paddock soil

Date	Day	Water added (mL)	Influent EC (dS/m)	Combined Drained amount (ml)	Drained EC (dS/m)
15-Jul-13	1	4000	0.81	274.00	1.974
19-Jul-13	5	1000	0.81	807.00	1.026
23-Jul-13	9	200	0.81	42.50	0.876
5-Aug-13	22	400	0.81	0.00	0.000
13-Aug-13	30	300	0.81	0.00	0.000
14-Aug-13	31	200	0.81	0.00	0.000
16-Aug-13	33	300	0.81	74.00	1.383
21-Aug-13	38	200	0.81	0.00	0.000
23-Aug-13	40	200	0.81	105.00	0.964
26-Aug-13	43	100	0.81	0.00	0.000
30-Aug-13	47	200	0.81	0.00	0.000
2-Sep-13	50	200	0.81	0.00	0.000
4-Sep-13	52	100	0.81	0.00	0.000
6-Sep-13	54	200	0.81	22.00	1.720
9-Sep-13	57	100	0.81	0.00	0.000
11-Sep-13	59	100	0.81	0.00	0.000
13-Sep-13	61	200	0.81	25.00	1.692
15-Sep-13	63	100	0.81	0.00	0.000
17-Sep-13	65	100	0.81	0.00	0.000
20-Sep-13	68	200	0.81	17.50	1.659
23-Sep-13	71	200	0.81	0.00	0.000
25-Sep-13	73	100	0.81	0.00	0.000
27-Sep-13	75	200	0.81	20.00	1.663
1-Oct-13	79	200	0.81	0.00	0.000
4-Oct-13	82	200	0.81	19.50	1.813
7-Oct-13	85	200	0.81	0.00	0.000
9-Oct-13	87	100	0.81	0.00	0.000
11-Oct-13	89	200	0.81	22.50	1.680
14-Oct-13	92	200	0.81	0.00	0.000
16-Oct-13	94	100	0.81	0.00	0.000
18-Oct-13	96	200	0.81	25.00	1.815
21-Oct-13	99	200	0.81	0.00	0.000
23-Oct-13	101	100	0.81	0.00	0.000
25-Oct-13	103	200	0.81	25.00	1.937
28-Oct-13	106	200	0.81	0.00	0.000
30-Oct-13	108	100	0.81	0.00	0.000
1-Nov-13	110	200	0.81	0.00	0.000

Table B1c (Contd.) Column operation data related to column 3 of D21 paddock soil

Date	Day	Water added (mL)	Influent EC (dS/m)	Combined Drained amount (ml)	Drained EC (dS/m)
4-Nov-13	113	200	0.81	27.00	3.650
6-Nov-13	115	100	0.81	0.00	0.000
8-Nov-13	117	200	0.81	0.00	0.000
13-Nov-13	122	200	0.81	0.00	0.000
15-Nov-13	124	200	0.81	0.00	0.000
19-Nov-13	128	200	0.81	43.00	2.700
22-Nov-13	131	200	0.81	40.00	2.038
25-Nov-13	134	200	0.81	75.00	1.988
27-Nov-13	136	100	0.81	0.00	0.000
29-Nov-13	138	200	0.81	17.00	2.270
2-Dec-13	141	100	0.81	13.33	2.300
4-Dec-13	143	100	0.81	13.33	2.300
6-Dec-13	145	100	0.81	13.33	2.300
9-Dec-13	148	100	0.81	0.00	0.000
11-Dec-13	150	100	0.81	0.00	0.000
13-Dec-13	152	200	0.81	0.00	0.000
16-Dec-13	155	200	0.00	64.00	2.530
18-Dec-13	157	100	0.81	7.50	2.680
20-Dec-13	159	200	0.81	50.00	2.520
23-Dec-13	162	200	0.00	85.00	2.450
25-Dec-13	164	100	0.81	43.00	2.390
27-Dec-13	166	150	0.81	55.00	2.400
30-Dec-13	169	200	0.00	77.00	2.530
3-Jan-14	173	200	0.81	10.00	3.310
6-Jan-14	176	200	0.00	65.00	2.950
8-Jan-14	178	100	0.81	0.00	0.000
10-Jan-14	180	200	0.81	27.00	3.400
13-Jan-14	183	200	0.00	100.00	3.190
15-Jan-14	185	100	0.81	27.00	3.370
17-Jan-14	187	200	0.81	42.00	3.390
20-Jan-14	190	200	0.00	100.00	3.390
22-Jan-14	192	100	0.81	32.50	3.520
24-Jan-14	194	150	0.81	45.00	3.630
28-Jan-14	198	200	0.00	10.00	4.520
31-Jan-14	201	200	0.81	20.00	4.310
3-Feb-14	204	200	0.00	80.00	4.610

Table B1c (Contd.) Column operation data related to column 3 of D21 paddock soil

Date	Day	Water added (mL)	Influent EC (dS/m)	Combined Drained amount (ml)	Drained EC (dS/m)
5-Feb-14	206	100	0.81	0.00	0.000
7-Feb-14	208	200	0.81	25.00	4.840
10-Feb-14	211	200	0.00	86.00	4.300
12-Feb-14	213	100	0.81	45.00	4.160
14-Feb-14	215	200	0.81	88.00	3.900
17-Feb-14	218	100	0.00	40.00	3.980
21-Feb-14	222	200	0.81	0.00	0.000
24-Feb-14	225	200	0.00	30.00	4.650
26-Feb-14	227	150	0.81	17.00	4.450
28-Feb-14	229	150	0.81	48.00	4.410
3-Mar-14	232	200	0.00	105.00	4.030
7-Mar-14	236	200	0.81	20.00	4.280
10-Mar-14	239	150	0.00	75.00	3.950
12-Mar-14	241	100	0.81	20.00	4.110
14-Mar-14	243	200	0.81	70.00	3.730
17-Mar-14	246	200	0.00	70.00	3.630
19-Mar-14	248	100	0.81	0.00	0.000
21-Mar-14	250	150	0.81	70.00	3.630
24-Mar-14	253	200	0.00	98.00	3.270
28-Mar-14	257	200	0.81	42.00	3.230
4-Apr-14	264	200	0.81	42.00	3.230

Table B2 Parameters measured by sensors at 0.35 and 0.1 m of column 3 of D21 paddock soil

Date	Day	Average Permittivity at 0.35 m	Average Permittivity at 0.1 m	Average ECbulk (µS/cm) at 0.35 m	Average ECbulk (µS/cm) at 0.1 m
15/07/2013	1	17.64	10.16	176.89	71.70
16/07/2013	2	17.19	9.21	188.84	58.36
17/07/2013	3	16.14	8.62	195.87	54.17
18/07/2013	4	15.80	8.13	198.24	50.59
19/07/2013	5	15.92	10.88	193.23	95.22
20/07/2013	6	16.06	12.53	190.97	105.31
21/07/2013	7	16.08	12.34	192.28	93.75
22/07/2013	8	16.02	11.93	187.66	83.67
23/07/2013	9	16.00	11.51	179.80	82.44
24/07/2013	10	16.04	11.53	180.01	86.15
25/07/2013	11	15.95	11.21	175.33	82.53
26/07/2013	12	15.93	10.45	164.05	77.33
27/07/2013	13	15.73	9.73	141.87	73.52
28/07/2013	14	15.47	9.37	127.35	71.79
29/07/2013	15	15.14	8.87	118.23	69.46
30/07/2013	16	14.46	8.32	107.40	66.61
31/07/2013	17	13.90	7.96	99.86	63.87
1/08/2013	18	13.64	7.49	94.41	61.55
2/08/2013	19	13.56	7.04	89.78	58.92
3/08/2013	20	13.83	6.88	85.76	57.19
4/08/2013	21	13.67	6.80	84.68	56.08
5/08/2013	22	13.48	7.34	89.26	63.38
6/08/2013	23	13.39	7.83	96.55	73.57
7/08/2013	24	13.72	7.60	96.28	71.40
8/08/2013	25	13.67	7.30	94.68	68.98
9/08/2013	26	12.98	6.99	92.48	66.17
10/08/2013	27	12.35	6.75	89.68	63.33
11/08/2013	28	12.21	6.65	87.90	61.80
12/08/2013	29	12.02	6.52	87.27	59.98
13/08/2013	30	12.05	6.76	91.90	64.97
14/08/2013	31	12.05	7.15	101.41	80.88
15/08/2013	32	11.93	7.20	105.66	90.45
16/08/2013	33	12.11	7.27	107.99	99.62
17/08/2013	34	12.04	7.35	117.02	127.99
18/08/2013	35	12.07	7.27	117.73	121.45
19/08/2013	36	12.23	7.20	116.54	112.42
20/08/2013	37	12.11	7.04	111.71	99.79
21/08/2013	38	12.11	7.02	111.25	100.63

Table B2 (Contd.) Parameters measured by sensors at 0.35 and 0.1 m of column 3 of D21 paddock soil

Date	Day	Average Permittivity at 0.35 m	Average Permittivity at 0.1 m	Average ECbulk (µS/cm) at 0.35 m	Average ECbulk (µS/cm) at 0.1 m
22/08/2013	39	11.99	7.00	112.32	103.84
23/08/2013	40	12.02	7.04	112.55	107.88
24/08/2013	41	12.06	7.19	117.73	122.06
25/08/2013	42	12.10	7.14	115.72	117.21
26/08/2013	43	12.07	7.06	114.93	113.74
27/08/2013	44	12.71	6.91	124.94	106.49
28/08/2013	45	13.68	6.68	129.01	88.04
29/08/2013	46	13.57	6.61	120.54	81.69
30/08/2013	47	13.54	6.61	117.73	83.79
31/08/2013	48	13.55	6.67	123.62	92.25
1/09/2013	49	13.57	6.63	119.70	89.32
2/09/2013	50	13.51	6.62	120.16	94.81
3/09/2013	51	13.55	6.64	126.57	110.79
4/09/2013	52	13.55	6.61	124.01	106.76
5/09/2013	53	13.60	6.60	125.52	110.48
6/09/2013	54	13.95	6.65	122.04	110.88
7/09/2013	55	13.89	6.67	127.80	125.44
8/09/2013	56	14.04	6.65	125.78	123.02
9/09/2013	57	13.92	6.64	125.07	121.27
10/09/2013	58	13.82	6.63	127.07	118.99
11/09/2013	59	13.74	6.59	122.51	115.34
12/09/2013	60	13.74	6.59	122.99	113.28
13/09/2013	61	13.64	6.57	119.43	114.63
14/09/2013	62	13.53	6.61	125.48	114.70
15/09/2013	63	13.49	6.61	125.27	111.55
16/09/2013	64	13.40	6.67	129.34	106.75
17/09/2013	65	13.44	6.63	127.73	108.41
18/09/2013	66	13.42	6.64	129.40	105.06
19/09/2013	67	13.63	6.56	122.99	111.73
20/09/2013	68	13.53	6.55	120.09	112.01
21/09/2013	69	13.33	6.61	127.62	107.41
22/09/2013	70	13.29	6.57	126.22	106.59
23/09/2013	71	13.26	6.62	128.45	107.08
24/09/2013	72	13.17	6.66	132.79	104.39
25/09/2013	73	13.15	6.61	130.96	107.45
26/09/2013	74	13.19	6.65	131.14	106.35
27/09/2013	75	12.91	6.61	130.75	108.41
28/09/2013	76	12.64	6.58	135.22	100.81

Table B2 (Contd.) Parameters measured by sensors at 0.35 and 0.1 m of column 3 of D21 paddock soil

Date	Day	Average Permittivity at 0.35 m	Average Permittivity at 0.1 m	Average ECbulk (µS/cm) at 0.35 m	Average ECbulk (µS/cm) at 0.1 m
29/09/2013	77	12.62	6.52	133.51	104.81
30/09/2013	78	12.57	6.45	129.29	110.82
1/10/2013	79	12.51	6.46	130.07	110.99
2/10/2013	80	12.50	6.51	132.97	105.63
3/10/2013	81	12.51	6.40	126.09	112.52
4/10/2013	82	12.35	6.36	125.86	111.51
5/10/2013	83	12.29	6.31	129.73	106.48
6/10/2013	84	12.24	6.25	128.32	108.80
7/10/2013	85	12.17	6.32	131.43	109.76
8/10/2013	86	12.19	6.37	135.98	106.52
9/10/2013	87	12.12	6.31	133.66	108.82
10/10/2013	88	12.10	6.28	133.93	109.00
11/10/2013	89	11.98	6.30	132.17	116.16
12/10/2013	90	11.91	6.51	141.03	111.24
13/10/2013	91	11.85	6.45	140.08	110.42
14/10/2013	92	11.69	6.41	141.15	110.35
15/10/2013	93	11.41	6.20	145.73	106.45
16/10/2013	94	11.50	6.15	143.52	109.34
17/10/2013	95	11.56	6.10	141.10	112.48
18/10/2013	96	11.58	6.07	137.18	118.80
19/10/2013	97	11.53	6.11	144.33	110.09
20/10/2013	98	11.52	6.06	143.27	109.59
21/10/2013	99	11.39	6.09	145.19	111.28
22/10/2013	100	11.22	6.15	154.24	107.76
23/10/2013	101	11.25	6.14	153.30	111.38
24/10/2013	102	11.28	6.13	154.99	110.56
25/10/2013	103	11.41	6.07	150.52	118.50
26/10/2013	104	11.32	6.13	159.78	113.25
27/10/2013	105	11.38	6.08	158.83	114.34
28/10/2013	106	11.32	6.11	160.78	114.60
29/10/2013	107	11.10	6.17	170.18	104.89
30/10/2013	108	11.22	6.14	167.21	114.45
31/10/2013	109	11.37	6.10	170.59	112.73
1/11/2013	110	11.32	6.13	168.25	121.58
2/11/2013	111	11.01	6.24	178.86	113.96
3/11/2013	112	11.02	6.19	179.89	114.61
4/11/2013	113	10.96	6.33	185.87	114.86
5/11/2013	114	10.99	6.31	190.08	116.17

Table B2 (Contd.) Parameters measured by sensors at 0.35 and 0.1 m of column 3 of D21 paddock soil

Date	Day	Average Permittivity at 0.35 m	Average Permittivity at 0.1 m	Average ECbulk (µS/cm) at 0.35 m	Average ECbulk (µS/cm) at 0.1 m
6/11/2013	115	11.08	6.26	186.00	128.98
7/11/2013	116	11.10	6.25	189.87	128.05
8/11/2013	117	11.06	6.24	190.28	135.18
9/11/2013	118	11.02	6.22	200.23	132.67
10/11/2013	119	11.08	6.22	199.81	135.87
11/11/2013	120	11.14	6.23	196.68	142.21
12/11/2013	121	11.12	6.20	192.80	147.10
13/11/2013	122	10.98	6.22	192.72	152.11
14/11/2013	123	10.96	6.33	203.25	159.55
15/11/2013	124	11.05	6.31	201.65	156.34
16/11/2013	125	11.03	6.40	214.40	163.74
17/11/2013	126	11.08	6.40	215.28	163.04
18/11/2013	127	11.11	6.38	212.76	162.00
19/11/2013	128	11.09	6.39	215.69	167.09
20/11/2013	129	10.95	6.38	230.03	168.63
21/11/2013	130	10.95	6.30	227.33	169.21
22/11/2013	131	10.97	6.32	229.61	173.37
23/11/2013	132	10.90	6.35	244.00	175.41
24/11/2013	133	10.88	6.32	244.89	172.85
25/11/2013	134	10.88	6.57	246.82	194.73
26/11/2013	135	10.76	7.01	260.44	243.41
27/11/2013	136	10.79	6.82	256.67	214.80
28/11/2013	137	10.88	6.79	262.34	225.24
29/11/2013	138	10.88	6.76	262.41	222.19
30/11/2013	139	10.81	6.76	279.22	235.27
1/12/2013	140	10.81	6.72	278.83	232.72
2/12/2013	141	10.78	6.72	281.90	229.42
3/12/2013	142	10.74	6.67	282.80	225.44
4/12/2013	143	10.76	6.65	282.61	225.80
5/12/2013	144	10.76	6.64	284.28	223.67
6/12/2013	145	10.83	6.63	278.56	223.84
7/12/2013	146	10.82	6.61	282.88	222.09
8/12/2013	147	10.79	6.55	280.01	221.86
9/12/2013	148	10.73	6.52	277.92	220.06
10/12/2013	149	10.71	6.55	282.54	217.34
11/12/2013	150	10.69	6.48	276.09	215.81
12/12/2013	151	10.67	6.49	278.80	212.76
13/12/2013	152	10.64	6.54	282.84	208.65

Table B2 (Contd.) Parameters measured by sensors at 0.35 and 0.1 m of column 3 of D21 paddock soil

Date	Day	Average Permittivity at 0.35 m	Average Permittivity at 0.1 m	Average ECbulk (µS/cm) at 0.35 m	Average ECbulk (µS/cm) at 0.1 m
14/12/2013	153	10.65	6.59	294.87	196.59
15/12/2013	154	10.67	6.57	293.63	196.95
16/12/2013	155	10.67	6.68	299.30	184.29
17/12/2013	156	10.62	6.71	309.08	161.50
18/12/2013	157	10.61	6.66	307.39	167.89
19/12/2013	158	10.59	6.67	311.73	162.29
20/12/2013	159	10.59	6.67	312.83	162.12
21/12/2013	160	10.48	6.63	324.55	141.48
22/12/2013	161	10.44	6.57	323.51	146.75
23/12/2013	162	10.49	6.64	323.58	148.90
24/12/2013	163	10.52	6.72	334.78	126.17
25/12/2013	164	10.52	6.73	335.89	126.48
26/12/2013	165	10.49	6.74	341.70	118.90
27/12/2013	166	10.54	6.81	343.52	111.47
28/12/2013	167	10.60	6.81	347.09	100.60
29/12/2013	168	10.54	6.73	346.00	105.63
30/12/2013	169	10.60	6.84	347.80	106.00
31/12/2013	170	10.61	6.92	354.88	90.77
1/01/2014	171	10.53	6.77	350.63	96.66
2/01/2014	172	10.51	6.72	347.83	104.20
3/01/2014	173	10.52	6.80	350.28	104.74
4/01/2014	174	10.49	6.87	361.21	91.22
5/01/2014	175	10.43	6.79	360.07	94.05
6/01/2014	176	10.47	6.86	359.15	96.42
7/01/2014	177	10.49	6.97	366.10	83.48
8/01/2014	178	10.49	6.90	362.49	88.33
9/01/2014	179	10.56	6.95	366.10	86.05
10/01/2014	180	10.52	6.92	363.10	90.32
11/01/2014	181	10.50	7.04	373.68	76.69
12/01/2014	182	10.42	6.93	373.17	78.70
13/01/2014	183	10.48	7.06	374.86	77.25
14/01/2014	184	10.52	7.09	378.61	71.14
15/01/2014	185	10.41	7.07	377.98	72.42
16/01/2014	186	10.35	7.03	377.05	72.72
17/01/2014	187	10.38	7.08	375.78	74.94
18/01/2014	188	10.54	7.25	385.55	71.07
19/01/2014	189	10.43	7.12	383.39	71.76
20/01/2014	190	10.47	7.21	381.28	72.89

Table B2 (Contd.) Parameters measured by sensors at 0.35 and 0.1 m of column 3 of D21 paddock soil

Date	Day	Average Permittivity at 0.35 m	Average Permittivity at 0.1 m	Average ECbulk (µS/cm) at 0.35 m	Average ECbulk (µS/cm) at 0.1 m
21/01/2014	191	10.58	7.30	385.37	69.74
22/01/2014	192	10.58	7.29	382.40	70.80
23/01/2014	193	10.63	7.30	381.64	70.58
24/01/2014	194	10.64	7.29	379.59	69.84
25/01/2014	195	10.66	7.25	379.66	67.55
26/01/2014	196	10.64	7.19	375.95	68.50
27/01/2014	197	10.63	7.15	371.10	70.64
28/01/2014	198	10.62	7.17	368.90	73.85
29/01/2014	199	10.69	7.25	372.00	70.98
30/01/2014	200	10.64	7.15	366.49	72.65
31/01/2014	201	10.66	7.22	366.72	73.27
1/02/2014	202	10.62	7.18	367.54	70.45
2/02/2014	203	10.56	7.11	364.44	71.58
3/02/2014	204	10.64	7.22	361.33	71.76
4/02/2014	205	10.80	7.33	359.36	66.17
5/02/2014	206	10.81	7.28	354.75	66.89
6/02/2014	207	10.86	7.29	353.72	67.15
7/02/2014	208	10.81	7.26	349.25	69.65
8/02/2014	209	10.85	7.32	349.36	65.69
9/02/2014	210	10.78	7.22	345.41	66.78
10/02/2014	211	10.82	7.29	341.38	68.26
11/02/2014	212	10.94	7.35	335.88	66.82
12/02/2014	213	10.92	7.31	330.28	68.03
13/02/2014	214	10.98	7.32	325.16	68.05
14/02/2014	215	10.91	7.30	319.08	67.27
15/02/2014	216	10.85	7.28	311.45	62.66
16/02/2014	217	10.81	7.22	306.23	63.69
17/02/2014	218	10.86	7.25	301.05	64.69
18/02/2014	219	10.85	7.24	301.77	64.53
19/02/2014	220	10.90	7.20	292.28	65.99
20/02/2014	221	10.80	7.12	286.87	66.98
21/02/2014	222	10.98	7.26	287.30	69.43
22/02/2014	223	11.18	7.31	286.17	70.87
23/02/2014	224	11.15	7.26	283.53	70.94
24/02/2014	225	11.17	7.30	281.09	72.23
25/02/2014	226	11.29	7.33	276.15	72.52
26/02/2014	227	11.26	7.29	272.64	72.67
27/02/2014	228	11.36	7.34	270.58	73.28

Table B2 (Contd.) Parameters measured by sensors at 0.35 and 0.1 m of column 3 of D21 paddock soil

Date	Day	Average Permittivity at 0.35 m	Average Permittivity at 0.1 m	Average ECbulk (µS/cm) at 0.35 m	Average ECbulk (µS/cm) at 0.1 m
28/02/2014	229	11.40	7.37	267.04	73.30
1/03/2014	230	11.55	7.43	262.70	70.65
2/03/2014	231	11.53	7.39	259.58	70.65
3/03/2014	232	11.54	7.44	256.64	71.07
4/03/2014	233	11.70	7.44	249.55	68.97
5/03/2014	234	11.62	7.33	245.00	68.95
6/03/2014	235	11.51	7.24	242.30	69.71
7/03/2014	236	11.46	7.28	241.78	71.59
8/03/2014	237	11.54	7.32	240.34	71.78
9/03/2014	238	11.47	7.24	237.68	71.56
10/03/2014	239	11.49	7.30	235.26	71.77
11/03/2014	240	11.60	7.30	229.90	68.84
12/03/2014	241	11.57	7.26	227.12	69.65
13/03/2014	242	11.63	7.28	225.18	69.51
14/03/2014	243	11.59	7.29	221.56	69.53
15/03/2014	244	11.65	7.32	218.29	64.79
16/03/2014	245	11.60	7.24	215.78	65.27
17/03/2014	246	11.61	7.30	213.93	66.78
18/03/2014	247	11.72	7.30	209.66	65.20
19/03/2014	248	11.65	7.21	206.89	66.64
20/03/2014	249	11.70	7.22	206.86	68.42
21/03/2014	250	11.75	7.27	204.60	69.47
22/03/2014	251	12.03	7.40	203.27	67.66
23/03/2014	252	11.98	7.32	201.54	67.65
24/03/2014	253	12.06	7.44	199.45	67.94
25/03/2014	254	12.30	7.56	196.22	64.41
26/03/2014	255	12.21	7.42	193.67	65.16
27/03/2014	256	12.16	7.36	191.91	65.88
28/03/2014	257	12.18	7.45	191.56	67.78
29/03/2014	258	12.27	7.52	192.73	66.72
30/03/2014	259	12.23	7.46	191.54	66.56
31/03/2014	260	12.20	7.41	190.15	66.82
1/04/2014	261	12.14	7.33	188.02	68.02
2/04/2014	262	12.10	7.27	187.43	70.04
3/04/2014	263	12.04	7.22	186.22	72.03
4/04/2014	264	12.02	7.28	185.25	73.35

APPENDIX C: ADDITIONAL DATA RELATED TO CHAPTER 6

Table C1a Column operation data related to column 1 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
19-Aug-13	1	2000	0.806	0.00	0.000
21-Aug-13	3	1000	0.806	660.00	2.892
23-Aug-13	5	100	0.806	0.00	0.000
26-Aug-13	8	200	0.806	530.00	1.469
29-Aug-13	11	500	0.806	310.00	1.029
02-Sep-13	15	200	0.806	0.00	0.000
04-Sep-13	17	100	0.806	0.00	0.000
06-Sep-13	19	200	0.806	27.00	1.221
09-Sep-13	22	200	0.806	80.00	1.024
11-Sep-13	24	200	0.806	55.00	1.053
12-Sep-13	25	200	0.806	50.00	1.047
15-Sep-13	28	100	0.806	37.00	1.016
17-Sep-13	30	100	0.806	43.00	1.060
20-Sep-13	33	200	0.806	0.00	0.000
23-Sep-13	36	200	0.806	105.00	1.074
25-Sep-13	38	100	0.806	0.00	0.000
27-Sep-13	40	200	0.806	0.00	0.000
01-Oct-13	44	200	0.806	0.00	0.000
04-Oct-13	47	200	0.806	0.00	0.000
07-Oct-13	50	200	0.806	10.00	1.795
09-Oct-13	52	200	0.806	35.00	1.405
11-Oct-13	54	200	0.806	40.00	1.296
14-Oct-13	57	200	0.806	57.50	1.243
16-Oct-13	59	100	0.806	0.00	0.000
18-Oct-13	61	200	0.806	0.00	0.000
21-Oct-13	64	200	0.806	17.00	1.738
23-Oct-13	66	100	0.806	0.00	0.000
25-Oct-13	68	200	0.806	20.00	1.661
28-Oct-13	71	200	0.806	90.00	1.358
30-Oct-13	73	100	0.806	0.00	0.000
01-Nov-13	75	200	0.806	25.00	1.444
04-Nov-13	78	100	0.806	0.00	0.000
06-Nov-13	80	100	0.806	0.00	0.000
08-Nov-13	82	200	0.806	0.00	0.000
13-Nov-13	87	200	0.806	0.00	0.000
15-Nov-13	89	200	0.806	43.00	1.828
19-Nov-13	93	200	0.806	0.00	0.000
22-Nov-13	96	100	0.806	0.00	0.000
25-Nov-13	99	200	0.806	101.00	1.791
27-Nov-13	101	100	0.806	0.00	0.000

Table C1a (Contd.) Column operation data related to column 1 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
29-Nov-13	103	200	0.806	0.00	0.000
02-Dec-13	106	100	0.806	0.00	0.000
04-Dec-13	108	100	0.806	0.00	0.000
06-Dec-13	110	100	0.806	100.00	1.829
09-Dec-13	113	100	0.806	0.00	0.000
11-Dec-13	115	100	0.806	0.00	0.000
13-Dec-13	117	200	0.806	22.50	2.383
16-Dec-13	120	200	0.806	98.00	2.148
18-Dec-13	122	100	0.806	0.00	0.000
20-Dec-13	124	200	0.806	100.00	2.040
23-Dec-13	127	200	0.806	83.00	1.980
25-Dec-13	129	100	0.806	37.00	1.953
27-Dec-13	131	150	0.806	98.00	1.986
30-Dec-13	134	200	0.806	83.00	2.056
03-Jan-14	138	200	0.806	63.00	2.136
06-Jan-14	141	200	0.806	80.00	2.146
08-Jan-14	143	100	0.806	0.00	0.000
10-Jan-14	145	200	0.806	80.00	2.189
13-Jan-14	148	200	0.806	117.00	2.044
15-Jan-14	150	100	0.806	0.00	0.000
17-Jan-14	152	200	0.806	102.00	2.115
20-Jan-14	155	200	0.806	105.00	2.015
22-Jan-14	157	100	0.806	30.00	2.079
24-Jan-14	159	200	0.806	120.00	1.954
28-Jan-14	163	200	0.806	45.00	2.060
31-Jan-14	166	200	0.806	45.00	2.038
03-Feb-14	169	150	0.806	55.00	1.994
05-Feb-14	171	100	0.806	0.00	0.000
07-Feb-14	173	150	0.806	20.00	2.134
10-Feb-14	176	150	0.806	54.00	2.040
12-Feb-14	178	100	0.806	27.00	1.954
14-Feb-14	180	150	0.806	70.00	1.857
17-Feb-14	183	100	0.806	40.00	1.785
21-Feb-14	187	150	0.806	0.00	0.000
24-Feb-14	190	150	0.806	27.50	2.097
26-Feb-14	192	100	0.806	17.50	1.958
28-Feb-14	194	150	0.806	70.00	1.842
03-Mar-14	197	150	0.806	90.00	1.697
07-Mar-14	201	150	0.806	0.00	0.000

Table C1a (Contd.) Column operation data related to column 1 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
10-Mar-14	204	150	0.806	64.00	1.765
12-Mar-14	206	100	0.806	92.00	1.681
14-Mar-14	208	150	0.806	0.00	0.000
17-Mar-14	211	150	0.806	40.00	1.641
19-Mar-14	213	100	0.806	0.00	0.000
21-Mar-14	215	150	0.806	70.00	2.661
24-Mar-14	218	150	0.806	80.00	1.574
28-Mar-14	222	150	0.806	25.00	1.658
04-Apr-14	229	150	0.806	0.00	0.000
11-Apr-14	236	150	0.806	0.00	0.000
22-Apr-14	247	150	0.806	0.00	0.000
28-Apr-14	253	150	0.806	0.00	0.000
30-Apr-14	255	150	0.806	0.00	0.000
02-May-14	257	150	0.806	0.00	0.000
09-May-14	264	150	0.806	0.00	0.000
15-May-14	270	150	0.806	0.00	0.000
22-May-14	277	150	0.806	0.00	0.000
23-May-14	278	150	0.806	50.00	3.996
27-May-14	282	150	0.806	0.00	0.000
30-May-14	285	150	0.806	0.00	0.000
02-Jun-14	288	150	0.806	27.50	2.142
04-Jun-14	290	150	0.806	0.00	0.000
06-Jun-14	292	150	0.806	86.00	3.314
11-Jun-14	297	150	0.806	0.00	0.000
13-Jun-14	299	150	0.806	17.50	3.500
16-Jun-14	302	150	0.806	63.00	3.307
18-Jun-14	304	150	0.806	25.00	3.212
20-Jun-14	306	150	0.806	32.00	3.318
23-Jun-14	309	150	0.806	71.00	3.249
25-Jun-14	311	150	0.806	0.00	0.000
30-Jun-14	316	150	0.806	15.00	3.751
02-Jul-14	318	150	0.806	0.00	0.000
04-Jul-14	320	150	0.806	0.00	0.000
11-Jul-14	327	150	0.806	0.00	0.000
16-Jul-14	332	150	0.806	0.00	0.000
18-Jul-14	334	150	0.806	0.00	0.000
28-Jul-14	344	150	0.806	0.00	0.000
30-Jul-14	346	150	0.806	0.00	0.000
01-Aug-14	348	150	0.806	0.00	0.000

Table C1a (Contd.) Column operation data related to column 1 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
05-Aug-14	352	150	0.843	0.00	0.000
08-Aug-14	355	150	0.843	0.00	0.000
11-Aug-14	358	150	0.843	0.00	0.000
13-Aug-14	360	150	0.843	0.00	0.000
15-Aug-14	362	150	0.843	0.00	0.000
18-Aug-14	365	150	0.843	0.00	0.000
20-Aug-14	367	150	0.843	0.00	0.000
22-Aug-14	369	150	0.843	0.00	0.000
25-Aug-14	372	150	0.843	0.00	0.000
27-Aug-14	374	150	0.843	0.00	0.000
29-Aug-14	376	150	0.843	0.00	0.000
02-Sep-14	380	150	0.843	0.00	0.000
04-Sep-14	382	150	0.843	0.00	0.000
05-Sep-14	383	150	0.843	0.00	0.000
09-Sep-14	387	150	0.843	0.00	0.000
12-Sep-14	390	150	0.843	0.00	0.000
19-Sep-14	397	150	0.843	0.00	0.000
22-Sep-14	400	150	0.843	0.00	0.000

Table C1b Column operation data related to column 2 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
19-Aug-13	1	2000	0.806	0.00	0.000
21-Aug-13	3	1000	0.806	0.00	0.000
23-Aug-13	5	100	0.806	0.00	0.000
26-Aug-13	8	200	0.806	590.00	1.411
29-Aug-13	11	500	0.806	350.00	1.090
02-Sep-13	15	200	0.806	0.00	0.000
04-Sep-13	17	100	0.806	0.00	0.000
06-Sep-13	19	200	0.806	83.00	1.040
09-Sep-13	22	200	0.806	93.00	1.012
11-Sep-13	24	200	0.806	42.00	1.295
12-Sep-13	25	200	0.806	55.00	1.060
15-Sep-13	28	100	0.806	55.00	1.052
17-Sep-13	30	100	0.806	43.00	1.102
20-Sep-13	33	200	0.806	0.00	0.000
23-Sep-13	36	200	0.806	82.00	1.101
25-Sep-13	38	100	0.806	0.00	0.000
27-Sep-13	40	200	0.806	0.00	0.000
01-Oct-13	44	200	0.806	0.00	0.000
04-Oct-13	47	200	0.806	0.00	0.000
07-Oct-13	50	200	0.806	75.00	1.388
09-Oct-13	52	200	0.806	52.00	1.195
11-Oct-13	54	200	0.806	43.00	1.181
14-Oct-13	57	200	0.806	65.00	1.167
16-Oct-13	59	100	0.806	0.00	0.000
18-Oct-13	61	200	0.806	0.00	0.000
21-Oct-13	64	200	0.806	67.00	1.282
23-Oct-13	66	100	0.806	0.00	0.000
25-Oct-13	68	200	0.806	42.00	1.292
28-Oct-13	71	200	0.806	95.00	1.195
30-Oct-13	73	100	0.806	0.00	0.000
01-Nov-13	75	200	0.806	48.00	1.260
04-Nov-13	78	100	0.806	0.00	0.000
06-Nov-13	80	100	0.806	0.00	0.000
08-Nov-13	82	200	0.806	0.00	0.000
13-Nov-13	87	200	0.806	0.00	0.000
15-Nov-13	89	200	0.806	100.00	1.556
19-Nov-13	93	200	0.806	107.50	1.396
22-Nov-13	96	100	0.806	0.00	0.000
25-Nov-13	99	200	0.806	112.00	1.528
27-Nov-13	101	100	0.806	0.00	0.000

Table C1b (Contd.) Column operation data related to column 2 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
29-Nov-13	103	200	0.806	0.00	0.000
02-Dec-13	106	100	0.806	0.00	0.000
04-Dec-13	108	100	0.806	0.00	0.000
06-Dec-13	110	100	0.806	135.00	1.682
09-Dec-13	113	100	0.806	0.00	0.000
11-Dec-13	115	100	0.806	0.00	0.000
13-Dec-13	117	200	0.806	50.00	2.237
16-Dec-13	120	200	0.806	116.00	1.939
18-Dec-13	122	100	0.806	0.00	0.000
20-Dec-13	124	200	0.806	135.00	1.906
23-Dec-13	127	200	0.806	105.00	1.890
25-Dec-13	129	100	0.806	50.00	1.862
27-Dec-13	131	150	0.806	115.00	1.890
30-Dec-13	134	200	0.806	105.00	1.909
03-Jan-14	138	200	0.806	70.00	1.974
06-Jan-14	141	200	0.806	90.00	1.951
08-Jan-14	143	100	0.806	0.00	0.000
10-Jan-14	145	200	0.806	90.00	1.934
13-Jan-14	148	200	0.806	110.00	1.807
15-Jan-14	150	100	0.806	0.00	0.000
17-Jan-14	152	200	0.806	110.00	1.808
20-Jan-14	155	200	0.806	100.00	1.765
22-Jan-14	157	100	0.806	40.00	1.642
24-Jan-14	159	200	0.806	140.00	1.608
28-Jan-14	163	200	0.806	50.00	1.638
31-Jan-14	166	200	0.806	65.00	1.595
03-Feb-14	169	150	0.806	47.50	1.554
05-Feb-14	171	100	0.806	0.00	0.000
07-Feb-14	173	150	0.806	45.00	1.784
10-Feb-14	176	150	0.806	40.00	1.666
12-Feb-14	178	100	0.806	35.00	1.498
14-Feb-14	180	150	0.806	92.00	1.417
17-Feb-14	183	100	0.806	48.00	1.398
21-Feb-14	187	150	0.806	0.00	0.000
24-Feb-14	190	150	0.806	37.00	1.599
26-Feb-14	192	100	0.806	25.00	1.495
28-Feb-14	194	150	0.806	75.00	1.452
03-Mar-14	197	150	0.806	90.00	1.366
07-Mar-14	201	150	0.806	0.00	0.000

Table C1b (Contd.) Column operation data related to column 2 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
10-Mar-14	204	150	0.806	84.00	1.384
12-Mar-14	206	100	0.806	0.00	0.000
14-Mar-14	208	150	0.806	76.00	1.389
17-Mar-14	211	150	0.806	50.00	1.366
19-Mar-14	213	100	0.806	0.00	0.000
21-Mar-14	215	150	0.806	75.00	0.000
24-Mar-14	218	150	0.806	75.00	1.390
28-Mar-14	222	150	0.806	50.00	1.374
04-Apr-14	229	150	0.806	0.00	0.000
11-Apr-14	236	150	0.806	0.00	0.000
22-Apr-14	247	150	0.806	0.00	0.000
28-Apr-14	253	150	0.806	0.00	0.000
30-Apr-14	255	150	0.806	0.00	0.000
02-May-14	257	150	0.806	0.00	0.000
09-May-14	264	150	0.806	0.00	0.000
15-May-14	270	150	0.806	0.00	0.000
22-May-14	277	150	0.806	0.00	0.000
23-May-14	278	150	0.806	70.00	2.473
27-May-14	282	150	0.806	0.00	0.000
30-May-14	285	150	0.806	0.00	0.000
02-Jun-14	288	150	0.806	50.00	2.205
04-Jun-14	290	150	0.806	0.00	0.000
06-Jun-14	292	150	0.806	102.00	2.133
11-Jun-14	297	150	0.806	0.00	0.000
13-Jun-14	299	150	0.806	21.00	2.475
16-Jun-14	302	150	0.806	70.00	2.275
18-Jun-14	304	150	0.806	27.50	2.327
20-Jun-14	306	150	0.806	45.00	2.359
23-Jun-14	309	150	0.806	69.00	2.250
25-Jun-14	311	150	0.806	0.00	0.000
30-Jun-14	316	150	0.806	22.50	2.669
02-Jul-14	318	150	0.806	0.00	0.000
04-Jul-14	320	150	0.806	0.00	0.000
11-Jul-14	327	150	0.806	0.00	0.000
16-Jul-14	332	150	0.806	0.00	0.000
18-Jul-14	334	150	0.806	0.00	0.000
28-Jul-14	344	150	0.806	0.00	0.000
30-Jul-14	346	150	0.806	0.00	0.000
01-Aug-14	348	150	0.806	0.00	0.000

Table C1b (Contd.) Column operation data related to column 2 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
05-Aug-14	352	150	0.843	0.00	0.000
08-Aug-14	355	150	0.843	0.00	0.000
11-Aug-14	358	150	0.843	0.00	0.000
13-Aug-14	360	150	0.843	0.00	0.000
15-Aug-14	362	150	0.843	0.00	0.000
18-Aug-14	365	150	0.843	0.00	0.000
20-Aug-14	367	150	0.843	0.00	0.000
22-Aug-14	369	150	0.843	0.00	0.000
25-Aug-14	372	150	0.843	0.00	0.000
27-Aug-14	374	150	0.843	0.00	0.000
29-Aug-14	376	150	0.843	0.00	0.000
02-Sep-14	380	150	0.843	0.00	0.000
04-Sep-14	382	150	0.843	0.00	0.000
05-Sep-14	383	150	0.843	0.00	0.000
09-Sep-14	387	150	0.843	0.00	0.000
12-Sep-14	390	150	0.843	0.00	0.000
19-Sep-14	397	150	0.843	0.00	0.000
22-Sep-14	400	150	0.843	0.00	0.000

Table C1c Column operation data related to column 3 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
19-Aug-13	1	2000	0.806	0.00	0.00
21-Aug-13	3	1000	0.806	0.00	0.00
23-Aug-13	5	100	0.806	0.00	0.00
26-Aug-13	8	200	0.806	175.00	0.18
29-Aug-13	11	500	0.806	310.00	0.31
02-Sep-13	15	200	0.806	0.00	0.00
04-Sep-13	17	100	0.806	0.00	0.00
06-Sep-13	19	200	0.806	0.00	0.00
09-Sep-13	22	200	0.806	115.00	0.12
11-Sep-13	24	200	0.806	49.00	0.05
12-Sep-13	25	200	0.806	20.00	0.02
15-Sep-13	28	100	0.806	35.00	0.04
17-Sep-13	30	100	0.806	20.00	0.02
20-Sep-13	33	200	0.806	0.00	0.00
23-Sep-13	36	200	0.806	65.00	0.07
25-Sep-13	38	100	0.806	0.00	0.00
27-Sep-13	40	200	0.806	0.00	0.00
01-Oct-13	44	200	0.806	0.00	0.00
04-Oct-13	47	200	0.806	0.00	0.00
07-Oct-13	50	200	0.806	0.00	0.00
09-Oct-13	52	200	0.806	0.00	0.00
11-Oct-13	54	200	0.806	0.00	0.00
14-Oct-13	57	200	0.806	50.00	0.05
16-Oct-13	59	100	0.806	0.00	0.00
18-Oct-13	61	200	0.806	0.00	0.00
21-Oct-13	64	200	0.806	22.00	0.02
23-Oct-13	66	100	0.806	0.00	0.00
25-Oct-13	68	200	0.806	0.00	0.00
28-Oct-13	71	200	0.806	95.00	0.10
30-Oct-13	73	100	0.806	0.00	0.00
01-Nov-13	75	200	0.806	20.00	0.02
04-Nov-13	78	100	0.806	0.00	0.00
06-Nov-13	80	100	0.806	0.00	0.00
08-Nov-13	82	200	0.806	0.00	0.00
13-Nov-13	87	200	0.806	0.00	0.00
15-Nov-13	89	200	0.806	15.00	0.02
19-Nov-13	93	200	0.806	85.00	0.09
22-Nov-13	96	100	0.806	0.00	0.00

Table C1c (Contd.) Column operation data related to column 3 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
25-Nov-13	99	200	0.806	70.00	0.07
27-Nov-13	101	100	0.806	0.00	0.00
29-Nov-13	103	200	0.806	0.00	0.00
02-Dec-13	106	100	0.806	0.00	0.00
04-Dec-13	108	100	0.806	0.00	0.00
06-Dec-13	110	100	0.806	80.00	0.08
09-Dec-13	113	100	0.806	0.00	0.00
11-Dec-13	115	100	0.806	0.00	0.00
13-Dec-13	117	200	0.806	0.00	0.00
16-Dec-13	120	200	0.806	0.00	0.00
18-Dec-13	122	100	0.806	55.00	0.06
20-Dec-13	124	200	0.806	90.00	0.09
23-Dec-13	127	200	0.806	100.00	0.10
25-Dec-13	129	100	0.806	42.00	0.04
27-Dec-13	131	150	0.806	67.00	0.07
30-Dec-13	134	200	0.806	100.00	0.10
03-Jan-14	138	200	0.806	27.50	0.03
06-Jan-14	141	200	0.806	75.00	0.08
08-Jan-14	143	100	0.806	0.00	0.00
10-Jan-14	145	200	0.806	55.00	0.06
13-Jan-14	148	200	0.806	110.00	0.11
15-Jan-14	150	100	0.806	0.00	0.00
17-Jan-14	152	200	0.806	78.00	0.08
20-Jan-14	155	200	0.806	105.00	0.11
22-Jan-14	157	100	0.806	37.00	0.04
24-Jan-14	159	200	0.806	110.00	0.11
28-Jan-14	163	200	0.806	45.00	0.05
31-Jan-14	166	200	0.806	25.00	0.03
03-Feb-14	169	150	0.806	50.00	0.05
05-Feb-14	171	100	0.806	0.00	0.00
07-Feb-14	173	150	0.806	20.00	0.02
10-Feb-14	176	150	0.806	50.00	0.05
12-Feb-14	178	100	0.806	35.00	0.04
14-Feb-14	180	150	0.806	60.00	0.06
17-Feb-14	183	100	0.806	40.00	0.04
21-Feb-14	187	150	0.806	0.00	0.00
24-Feb-14	190	150	0.806	20.00	0.02
26-Feb-14	192	100	0.806	15.00	0.02
28-Feb-14	194	150	0.806	50.00	0.05

Table C1c (Contd.) Column operation data related to column 3 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
03-Mar-14	197	150	0.806	90.00	0.09
07-Mar-14	201	150	0.806	0.00	0.00
10-Mar-14	204	150	0.806	63.00	0.06
12-Mar-14	206	100	0.806	0.00	0.00
14-Mar-14	208	150	0.806	56.00	0.06
17-Mar-14	211	150	0.806	41.00	0.04
19-Mar-14	213	100	0.806	0.00	0.00
21-Mar-14	215	150	0.806	37.50	0.04
24-Mar-14	218	150	0.806	65.00	0.07
28-Mar-14	222	150	0.806	20.00	0.02
04-Apr-14	229	150	0.806	0.00	0.00
11-Apr-14	236	150	0.806	0.00	0.00
22-Apr-14	247	150	0.806	0.00	0.00
28-Apr-14	253	150	0.806	0.00	0.00
30-Apr-14	255	150	0.806	0.00	0.00
02-May-14	257	150	0.806	0.00	0.00
09-May-14	264	150	0.806	0.00	0.00
15-May-14	270	150	0.806	0.00	0.00
22-May-14	277	150	0.806	0.00	0.00
23-May-14	278	150	0.806	0.00	0.00
27-May-14	282	150	0.806	0.00	0.00
30-May-14	285	150	0.806	0.00	0.00
02-Jun-14	288	150	0.806	0.00	0.00
04-Jun-14	290	150	0.806	0.00	0.00
06-Jun-14	292	150	0.806	13.00	0.01
11-Jun-14	297	150	0.806	0.00	0.00
13-Jun-14	299	150	0.806	0.00	0.00
16-Jun-14	302	150	0.806	20.00	0.02
18-Jun-14	304	150	0.806	7.50	0.01
20-Jun-14	306	150	0.806	17.50	0.02
23-Jun-14	309	150	0.806	45.00	0.05
25-Jun-14	311	150	0.806	0.00	0.00
30-Jun-14	316	150	0.806	0.00	0.00
02-Jul-14	318	150	0.806	17.00	0.02
04-Jul-14	320	150	0.806	0.00	0.00
11-Jul-14	327	150	0.806	15.00	0.02
16-Jul-14	332	150	0.806	0.00	0.00
18-Jul-14	334	150	0.806	0.00	0.00
28-Jul-14	344	150	0.806	14.00	0.01

Table C1c (Contd.) Column operation data related to column 3 of D21 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
30-Jul-14	346	150	0.806	0.00	0.00
01-Aug-14	348	150	0.806	0.00	0.00
05-Aug-14	352	150	0.843	0.00	0.00
08-Aug-14	355	150	0.843	0.00	0.00
11-Aug-14	358	150	0.843	0.00	0.00
13-Aug-14	360	150	0.843	0.00	0.00
15-Aug-14	362	150	0.843	0.00	0.00
18-Aug-14	365	150	0.843	0.00	0.00
20-Aug-14	367	150	0.843	0.00	0.00
22-Aug-14	369	150	0.843	0.00	0.00
25-Aug-14	372	150	0.843	0.00	0.00
27-Aug-14	374	150	0.843	0.00	0.00
29-Aug-14	376	150	0.843	0.00	0.00
02-Sep-14	380	150	0.843	0.00	0.00
04-Sep-14	382	150	0.843	0.00	0.00
05-Sep-14	383	150	0.843	0.00	0.00
09-Sep-14	387	150	0.843	0.00	0.00
12-Sep-14	390	150	0.843	0.00	0.00
19-Sep-14	397	150	0.843	0.00	0.00
22-Sep-14	400	150	0.843	0.00	0.00

Table C2a Column operation data related to column 1 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
19-Aug-13	1	2000	0.806	0.00	0.00
21-Aug-13	3	1000	0.806	410.00	0.41
23-Aug-13	5	100	0.806	0.00	0.00
26-Aug-13	8	200	0.806	240.00	0.24
29-Aug-13	11	500	0.806	320.00	0.32
02-Sep-13	15	200	0.806	0.00	0.00
04-Sep-13	17	100	0.806	0.00	0.00
06-Sep-13	19	200	0.806	60.00	0.06
09-Sep-13	22	200	0.806	85.00	0.09
11-Sep-13	24	200	0.806	50.00	0.05
12-Sep-13	25	200	0.806	35.00	0.04
15-Sep-13	28	100	0.806	33.00	0.03
17-Sep-13	30	100	0.806	0.00	0.00
20-Sep-13	33	200	0.806	0.00	0.00
23-Sep-13	36	200	0.806	70.00	0.07
25-Sep-13	38	100	0.806	0.00	0.00
27-Sep-13	40	200	0.806	0.00	0.00
01-Oct-13	44	200	0.806	0.00	0.00
04-Oct-13	47	200	0.806	0.00	0.00
07-Oct-13	50	200	0.806	25.00	0.03
09-Oct-13	52	200	0.806	50.00	0.05
11-Oct-13	54	200	0.806	25.00	0.03
14-Oct-13	57	200	0.806	60.00	0.06
16-Oct-13	59	100	0.806	0.00	0.00
18-Oct-13	61	200	0.806	0.00	0.00
21-Oct-13	64	200	0.806	25.00	0.03
23-Oct-13	66	100	0.806	0.00	0.00
25-Oct-13	68	200	0.806	15.00	0.02
28-Oct-13	71	200	0.806	77.00	0.08
30-Oct-13	73	100	0.806	0.00	0.00
01-Nov-13	75	200	0.806	42.00	0.04
04-Nov-13	78	100	0.806	0.00	0.00
06-Nov-13	80	100	0.806	0.00	0.00
08-Nov-13	82	200	0.806	0.00	0.00
13-Nov-13	87	200	0.806	0.00	0.00
15-Nov-13	89	200	0.806	65.00	0.07
19-Nov-13	93	200	0.806	0.00	0.00
22-Nov-13	96	100	0.806	0.00	0.00

Table C2a (Contd.) Column operation data related to column 1 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
25-Nov-13	99	200	0.806	83.00	0.08
27-Nov-13	101	100	0.806	0.00	0.00
29-Nov-13	103	200	0.806	0.00	0.00
02-Dec-13	106	100	0.806	0.00	0.00
04-Dec-13	108	100	0.806	0.00	0.00
06-Dec-13	110	100	0.806	93.00	0.09
09-Dec-13	113	100	0.806	0.00	0.00
11-Dec-13	115	100	0.806	0.00	0.00
13-Dec-13	117	200	0.806	7.50	0.01
16-Dec-13	120	200	0.806	90.00	0.09
18-Dec-13	122	100	0.806	0.00	0.00
20-Dec-13	124	200	0.806	90.00	0.09
23-Dec-13	127	200	0.806	80.00	0.08
25-Dec-13	129	100	0.806	40.00	0.04
27-Dec-13	131	150	0.806	95.00	0.10
30-Dec-13	134	200	0.806	80.00	0.08
03-Jan-14	138	200	0.806	45.00	0.05
06-Jan-14	141	200	0.806	63.00	0.06
08-Jan-14	143	100	0.806	0.00	0.00
10-Jan-14	145	200	0.806	66.00	0.07
13-Jan-14	148	200	0.806	100.00	0.10
15-Jan-14	150	100	0.806	0.00	0.00
17-Jan-14	152	200	0.806	85.00	0.09
20-Jan-14	155	200	0.806	100.00	0.10
22-Jan-14	157	100	0.806	32.50	0.03
24-Jan-14	159	200	0.806	115.00	0.12
28-Jan-14	163	200	0.806	50.00	0.05
31-Jan-14	166	200	0.806	50.00	0.05
03-Feb-14	169	150	0.806	30.00	0.03
05-Feb-14	171	100	0.806	0.00	0.00
07-Feb-14	173	150	0.806	22.50	0.02
10-Feb-14	176	150	0.806	45.00	0.05
12-Feb-14	178	100	0.806	25.00	0.03
14-Feb-14	180	150	0.806	75.00	0.08
17-Feb-14	183	100	0.806	40.00	0.04
21-Feb-14	187	150	0.806	0.00	0.00
24-Feb-14	190	150	0.806	30.00	0.03
26-Feb-14	192	100	0.806	7.50	0.01
28-Feb-14	194	150	0.806	78.00	0.08

Table C2a (Contd.)   Column operation data related to column 1 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
03-Mar-14	197	150	0.806	80.00	0.08
07-Mar-14	201	150	0.806	0.00	0.00
10-Mar-14	204	150	0.806	77.00	0.08
12-Mar-14	206	100	0.806	70.00	0.07
14-Mar-14	208	150	0.806	0.00	0.00
17-Mar-14	211	150	0.806	37.50	0.04
19-Mar-14	213	100	0.806	0.00	0.00
21-Mar-14	215	150	0.806	56.00	0.06
24-Mar-14	218	150	0.806	70.00	0.07
28-Mar-14	222	150	0.806	30.00	0.03
04-Apr-14	229	150	0.806	0.00	0.00
11-Apr-14	236	150	0.806	0.00	0.00
22-Apr-14	247	150	0.806	0.00	0.00
28-Apr-14	253	150	0.806	0.00	0.00
30-Apr-14	255	150	0.806	0.00	0.00
02-May-14	257	150	0.806	0.00	0.00
09-May-14	264	150	0.806	0.00	0.00
15-May-14	270	150	0.806	0.00	0.00
22-May-14	277	150	0.806	0.00	0.00
23-May-14	278	150	0.806	30.00	0.03
27-May-14	282	150	0.806	0.00	0.00
30-May-14	285	150	0.806	0.00	0.00
02-Jun-14	288	150	0.806	15.00	0.02
04-Jun-14	290	150	0.806	0.00	0.00
06-Jun-14	292	150	0.806	62.00	0.06
11-Jun-14	297	150	0.806	0.00	0.00
13-Jun-14	299	150	0.806	0.00	0.00
16-Jun-14	302	150	0.806	42.00	0.04
18-Jun-14	304	150	0.806	14.00	0.01
20-Jun-14	306	150	0.806	20.00	0.02
23-Jun-14	309	150	0.806	48.00	0.05
25-Jun-14	311	150	0.806	0.00	0.00
30-Jun-14	316	150	0.806	0.00	0.00
02-Jul-14	318	150	0.806	0.00	0.00
04-Jul-14	320	150	0.806	0.00	0.00
11-Jul-14	327	150	0.806	0.00	0.00
16-Jul-14	332	150	0.806	0.00	0.00
18-Jul-14	334	150	0.806	0.00	0.00
28-Jul-14	344	150	0.806	0.00	0.00

Table C2a (Contd.) Column operation data related to column 1 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
30-Jul-14	346	150	0.806	0.00	0.00
01-Aug-14	348	150	0.806	0.00	0.00
05-Aug-14	352	150	0.843	0.00	0.00
08-Aug-14	355	150	0.843	0.00	0.00
11-Aug-14	358	150	0.843	0.00	0.00
13-Aug-14	360	150	0.843	0.00	0.00
15-Aug-14	362	150	0.843	0.00	0.00
18-Aug-14	365	150	0.843	0.00	0.00
20-Aug-14	367	150	0.843	0.00	0.00
22-Aug-14	369	150	0.843	0.00	0.00
25-Aug-14	372	150	0.843	0.00	0.00
27-Aug-14	374	150	0.843	0.00	0.00
29-Aug-14	376	150	0.843	0.00	0.00
02-Sep-14	380	150	0.843	0.00	0.00
04-Sep-14	382	150	0.843	0.00	0.00
05-Sep-14	383	150	0.843	0.00	0.00
09-Sep-14	387	150	0.843	0.00	0.00
12-Sep-14	390	150	0.843	0.00	0.00
19-Sep-14	397	150	0.843	0.00	0.00
22-Sep-14	400	150	0.843	0.00	0.00

Table C2b Column operation data related to column 2 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
19-Aug-13	1	2000	0.806	0.00	0.00
21-Aug-13	3	1000	0.806	450.00	0.45
23-Aug-13	5	100	0.806	0.00	0.00
26-Aug-13	8	200	0.806	295.00	0.30
29-Aug-13	11	500	0.806	320.00	0.32
02-Sep-13	15	200	0.806	0.00	0.00
04-Sep-13	17	100	0.806	0.00	0.00
06-Sep-13	19	200	0.806	77.00	0.08
09-Sep-13	22	200	0.806	77.00	0.08
11-Sep-13	24	200	0.806	55.00	0.06
12-Sep-13	25	200	0.806	40.00	0.04
15-Sep-13	28	100	0.806	33.00	0.03
17-Sep-13	30	100	0.806	0.00	0.00
20-Sep-13	33	200	0.806	0.00	0.00
23-Sep-13	36	200	0.806	82.00	0.08
25-Sep-13	38	100	0.806	0.00	0.00
27-Sep-13	40	200	0.806	0.00	0.00
01-Oct-13	44	200	0.806	0.00	0.00
04-Oct-13	47	200	0.806	0.00	0.00
07-Oct-13	50	200	0.806	33.00	0.03
09-Oct-13	52	200	0.806	49.00	0.05
11-Oct-13	54	200	0.806	35.00	0.04
14-Oct-13	57	200	0.806	40.00	0.04
16-Oct-13	59	100	0.806	0.00	0.00
18-Oct-13	61	200	0.806	0.00	0.00
21-Oct-13	64	200	0.806	50.00	0.05
23-Oct-13	66	100	0.806	0.00	0.00
25-Oct-13	68	200	0.806	15.00	0.02
28-Oct-13	71	200	0.806	92.00	0.09
30-Oct-13	73	100	0.806	0.00	0.00
01-Nov-13	75	200	0.806	37.00	0.04
04-Nov-13	78	100	0.806	0.00	0.00
06-Nov-13	80	100	0.806	0.00	0.00
08-Nov-13	82	200	0.806	0.00	0.00
13-Nov-13	87	200	0.806	0.00	0.00
15-Nov-13	89	200	0.806	67.00	0.07
19-Nov-13	93	200	0.806	0.00	0.00
22-Nov-13	96	100	0.806	0.00	0.00

Table C2b (Contd.) Column operation data related to column 2 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
25-Nov-13	99	200	0.806	85.00	0.09
27-Nov-13	101	100	0.806	0.00	0.00
29-Nov-13	103	200	0.806	0.00	0.00
02-Dec-13	106	100	0.806	0.00	0.00
04-Dec-13	108	100	0.806	0.00	0.00
06-Dec-13	110	100	0.806	85.00	0.09
09-Dec-13	113	100	0.806	0.00	0.00
11-Dec-13	115	100	0.806	0.00	0.00
13-Dec-13	117	200	0.806	22.50	0.02
16-Dec-13	120	200	0.806	91.00	0.09
18-Dec-13	122	100	0.806	0.00	0.00
20-Dec-13	124	200	0.806	80.00	0.08
23-Dec-13	127	200	0.806	78.00	0.08
25-Dec-13	129	100	0.806	47.00	0.05
27-Dec-13	131	150	0.806	90.00	0.09
30-Dec-13	134	200	0.806	87.00	0.09
03-Jan-14	138	200	0.806	45.00	0.05
06-Jan-14	141	200	0.806	65.00	0.07
08-Jan-14	143	100	0.806	0.00	0.00
10-Jan-14	145	200	0.806	74.00	0.07
13-Jan-14	148	200	0.806	95.00	0.10
15-Jan-14	150	100	0.806	0.00	0.00
17-Jan-14	152	200	0.806	92.00	0.09
20-Jan-14	155	200	0.806	92.00	0.09
22-Jan-14	157	100	0.806	32.50	0.03
24-Jan-14	159	200	0.806	115.00	0.12
28-Jan-14	163	200	0.806	50.00	0.05
31-Jan-14	166	200	0.806	50.00	0.05
03-Feb-14	169	150	0.806	40.00	0.04
05-Feb-14	171	100	0.806	0.00	0.00
07-Feb-14	173	150	0.806	17.00	0.02
10-Feb-14	176	150	0.806	45.00	0.05
12-Feb-14	178	100	0.806	30.00	0.03
14-Feb-14	180	150	0.806	65.00	0.07
17-Feb-14	183	100	0.806	35.00	0.04
21-Feb-14	187	150	0.806	0.00	0.00
24-Feb-14	190	150	0.806	35.00	0.04
26-Feb-14	192	100	0.806	7.50	0.01
28-Feb-14	194	150	0.806	78.00	0.08

Table C2b (Contd.) Column operation data related to column 2 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
03-Mar-14	197	150	0.806	85.00	0.09
07-Mar-14	201	150	0.806	0.00	0.00
10-Mar-14	204	150	0.806	72.00	0.07
12-Mar-14	206	100	0.806	58.00	0.06
14-Mar-14	208	150	0.806	0.00	0.00
17-Mar-14	211	150	0.806	35.00	0.04
19-Mar-14	213	100	0.806	0.00	0.00
21-Mar-14	215	150	0.806	50.00	0.05
24-Mar-14	218	150	0.806	65.00	0.07
28-Mar-14	222	150	0.806	25.00	0.03
04-Apr-14	229	150	0.806	0.00	0.00
11-Apr-14	236	150	0.806	0.00	0.00
22-Apr-14	247	150	0.806	0.00	0.00
28-Apr-14	253	150	0.806	0.00	0.00
30-Apr-14	255	150	0.806	0.00	0.00
02-May-14	257	150	0.806	0.00	0.00
09-May-14	264	150	0.806	0.00	0.00
15-May-14	270	150	0.806	0.00	0.00
22-May-14	277	150	0.806	0.00	0.00
23-May-14	278	150	0.806	0.00	0.00
27-May-14	282	150	0.806	0.00	0.00
30-May-14	285	150	0.806	0.00	0.00
02-Jun-14	288	150	0.806	0.00	0.00
04-Jun-14	290	150	0.806	0.00	0.00
06-Jun-14	292	150	0.806	52.00	0.05
11-Jun-14	297	150	0.806	0.00	0.00
13-Jun-14	299	150	0.806	0.00	0.00
16-Jun-14	302	150	0.806	21.00	0.02
18-Jun-14	304	150	0.806	0.00	0.00
20-Jun-14	306	150	0.806	15.00	0.02
23-Jun-14	309	150	0.806	45.00	0.05
25-Jun-14	311	150	0.806	0.00	0.00
30-Jun-14	316	150	0.806	0.00	0.00
02-Jul-14	318	150	0.806	0.00	0.00
04-Jul-14	320	150	0.806	0.00	0.00
11-Jul-14	327	150	0.806	0.00	0.00
16-Jul-14	332	150	0.806	0.00	0.00
18-Jul-14	334	150	0.806	0.00	0.00
28-Jul-14	344	150	0.806	0.00	0.00

Table C2b (Contd.) Column operation data related to column 2 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
30-Jul-14	346	150	0.806	0.00	0.00
01-Aug-14	348	150	0.806	0.00	0.00
05-Aug-14	352	150	0.843	0.00	0.00
08-Aug-14	355	150	0.843	0.00	0.00
11-Aug-14	358	150	0.843	0.00	0.00
13-Aug-14	360	150	0.843	0.00	0.00
15-Aug-14	362	150	0.843	0.00	0.00
18-Aug-14	365	150	0.843	0.00	0.00
20-Aug-14	367	150	0.843	0.00	0.00
22-Aug-14	369	150	0.843	0.00	0.00
25-Aug-14	372	150	0.843	0.00	0.00
27-Aug-14	374	150	0.843	0.00	0.00
29-Aug-14	376	150	0.843	0.00	0.00
02-Sep-14	380	150	0.843	0.00	0.00
04-Sep-14	382	150	0.843	0.00	0.00
05-Sep-14	383	150	0.843	0.00	0.00
09-Sep-14	387	150	0.843	0.00	0.00
12-Sep-14	390	150	0.843	0.00	0.00
19-Sep-14	397	150	0.843	0.00	0.00
22-Sep-14	400	150	0.843	0.00	0.00

Table C2c Column operation data related to column 3 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
19-Aug-13	1	2000	0.806	0.00	0.000
21-Aug-13	3	1000	0.806	460.00	2.771
23-Aug-13	5	100	0.806	0.00	0.000
26-Aug-13	8	200	0.806	150.00	1.627
29-Aug-13	11	500	0.806	300.00	1.589
02-Sep-13	15	200	0.806	0.00	0.000
04-Sep-13	17	100	0.806	0.00	0.000
06-Sep-13	19	200	0.806	40.00	1.444
09-Sep-13	22	200	0.806	0.00	0.000
11-Sep-13	24	200	0.806	45.00	1.352
12-Sep-13	25	200	0.806	20.00	1.346
15-Sep-13	28	100	0.806	35.00	1.353
17-Sep-13	30	100	0.806	0.00	0.000
20-Sep-13	33	200	0.806	0.00	0.000
23-Sep-13	36	200	0.806	62.00	1.462
25-Sep-13	38	100	0.806	0.00	0.000
27-Sep-13	40	200	0.806	0.00	0.000
01-Oct-13	44	200	0.806	0.00	0.000
04-Oct-13	47	200	0.806	0.00	0.000
07-Oct-13	50	200	0.806	0.00	0.000
09-Oct-13	52	200	0.806	0.00	0.000
11-Oct-13	54	200	0.806	0.00	0.000
14-Oct-13	57	200	0.806	47.00	1.770
16-Oct-13	59	100	0.806	0.00	0.000
18-Oct-13	61	200	0.806	0.00	0.000
21-Oct-13	64	200	0.806	20.00	1.919
23-Oct-13	66	100	0.806	0.00	0.000
25-Oct-13	68	200	0.806	0.00	0.000
28-Oct-13	71	200	0.806	75.00	1.995
30-Oct-13	73	100	0.806	0.00	0.000
01-Nov-13	75	200	0.806	22.00	1.915
04-Nov-13	78	100	0.806	0.00	0.000
06-Nov-13	80	100	0.806	0.00	0.000
08-Nov-13	82	200	0.806	0.00	0.000
13-Nov-13	87	200	0.806	0.00	0.000
15-Nov-13	89	200	0.806	27.00	2.106
19-Nov-13	93	200	0.806	80.00	2.096
22-Nov-13	96	100	0.806	0.00	0.000

Table C2c (Contd.) Column operation data related to column 3 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
25-Nov-13	99	200	0.806	70.00	2.274
27-Nov-13	101	100	0.806	0.00	0.000
29-Nov-13	103	200	0.806	0.00	0.000
02-Dec-13	106	100	0.806	0.00	0.000
04-Dec-13	108	100	0.806	0.00	0.000
06-Dec-13	110	100	0.806	78.00	2.188
09-Dec-13	113	100	0.806	0.00	0.000
11-Dec-13	115	100	0.806	0.00	0.000
13-Dec-13	117	200	0.806	20.00	2.203
16-Dec-13	120	200	0.806	73.00	2.152
18-Dec-13	122	100	0.806	0.00	0.000
20-Dec-13	124	200	0.806	73.00	2.152
23-Dec-13	127	200	0.806	90.00	2.064
25-Dec-13	129	100	0.806	42.00	2.040
27-Dec-13	131	150	0.806	76.00	2.063
30-Dec-13	134	200	0.806	85.00	1.997
03-Jan-14	138	200	0.806	32.00	2.053
06-Jan-14	141	200	0.806	75.00	2.039
08-Jan-14	143	100	0.806	0.00	0.000
10-Jan-14	145	200	0.806	45.00	2.095
13-Jan-14	148	200	0.806	105.00	2.042
15-Jan-14	150	100	0.806	0.00	0.000
17-Jan-14	152	200	0.806	80.00	2.025
20-Jan-14	155	200	0.806	90.00	2.011
22-Jan-14	157	100	0.806	17.00	1.654
24-Jan-14	159	200	0.806	110.00	1.907
28-Jan-14	163	200	0.806	62.00	1.867
31-Jan-14	166	200	0.806	27.50	1.915
03-Feb-14	169	150	0.806	45.00	1.987
05-Feb-14	171	100	0.806	0.00	0.000
07-Feb-14	173	150	0.806	0.00	0.000
10-Feb-14	176	150	0.806	40.00	2.170
12-Feb-14	178	100	0.806	30.00	2.084
14-Feb-14	180	150	0.806	60.00	2.045
17-Feb-14	183	100	0.806	42.00	1.996
21-Feb-14	187	150	0.806	0.00	0.000
24-Feb-14	190	150	0.806	15.00	2.276
26-Feb-14	192	100	0.806	7.50	2.286
28-Feb-14	194	150	0.806	22.50	2.119

Table C2c (Contd.) Column operation data related to column 3 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
03-Mar-14	197	150	0.806	85.00	2.082
07-Mar-14	201	150	0.806	0.00	0.000
10-Mar-14	204	150	0.806	60.00	2.074
12-Mar-14	206	100	0.806	0.00	0.000
14-Mar-14	208	150	0.806	40.00	2.155
17-Mar-14	211	150	0.806	45.00	2.086
19-Mar-14	213	100	0.806	0.00	0.000
21-Mar-14	215	150	0.806	30.00	2.175
24-Mar-14	218	150	0.806	72.00	2.067
28-Mar-14	222	150	0.806	0.00	0.000
04-Apr-14	229	150	0.806	0.00	0.000
11-Apr-14	236	150	0.806	0.00	0.000
22-Apr-14	247	150	0.806	0.00	0.000
28-Apr-14	253	150	0.806	0.00	0.000
30-Apr-14	255	150	0.806	0.00	0.000
02-May-14	257	150	0.806	0.00	0.000
09-May-14	264	150	0.806	0.00	0.000
15-May-14	270	150	0.806	0.00	0.000
22-May-14	277	150	0.806	0.00	0.000
23-May-14	278	150	0.806	0.00	0.000
27-May-14	282	150	0.806	0.00	0.000
30-May-14	285	150	0.806	0.00	0.000
02-Jun-14	288	150	0.806	30.00	5.870
04-Jun-14	290	150	0.806	0.00	0.000
06-Jun-14	292	150	0.806	43.00	3.871
11-Jun-14	297	150	0.806	0.00	0.000
13-Jun-14	299	150	0.806	0.00	0.000
16-Jun-14	302	150	0.806	30.00	3.973
18-Jun-14	304	150	0.806	0.00	0.000
20-Jun-14	306	150	0.806	15.00	4.436
23-Jun-14	309	150	0.806	45.00	4.044
25-Jun-14	311	150	0.806	0.00	0.000
30-Jun-14	316	150	0.806	0.00	0.000
02-Jul-14	318	150	0.806	15.00	2.712
04-Jul-14	320	150	0.806	0.00	0.000
11-Jul-14	327	150	0.806	20.00	0.000
16-Jul-14	332	150	0.806	0.00	0.000
18-Jul-14	334	150	0.806	0.00	0.000
28-Jul-14	344	150	0.806	0.00	0.000

Table C2c (Contd.) Column operation data related to column 3 of C5 paddock soil

Date	Day	Water added (mL)	Irrigation water EC (dS/m)	Drained amount (ml)	Drained EC (dS/m)
30-Jul-14	346	150	0.806	0.00	0.000
01-Aug-14	348	150	0.806	0.00	0.000
05-Aug-14	352	150	0.843	0.00	0.000
08-Aug-14	355	150	0.843	0.00	0.000
11-Aug-14	358	150	0.843	0.00	0.000
13-Aug-14	360	150	0.843	0.00	0.000
15-Aug-14	362	150	0.843	0.00	0.000
18-Aug-14	365	150	0.843	0.00	0.000
20-Aug-14	367	150	0.843	0.00	0.000
22-Aug-14	369	150	0.843	0.00	0.000
25-Aug-14	372	150	0.843	0.00	0.000
27-Aug-14	374	150	0.843	0.00	0.000
29-Aug-14	376	150	0.843	0.00	0.000
02-Sep-14	380	150	0.843	0.00	0.000
04-Sep-14	382	150	0.843	0.00	0.000
05-Sep-14	383	150	0.843	0.00	0.000
09-Sep-14	387	150	0.843	0.00	0.000
12-Sep-14	390	150	0.843	0.00	0.000
19-Sep-14	397	150	0.843	0.00	0.000
22-Sep-14	400	150	0.843	0.00	0.000

Table C3 Parameters measured by sensors at 0.2 m depth in D21 and C5 columns

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
19-Aug-13	1	17.412	0.141	17.468	0.122
20-Aug-13	2	17.474	0.136	18.603	0.121
21-Aug-13	3	17.108	0.130	19.503	0.160
22-Aug-13	4	17.015	0.128	20.080	0.235
23-Aug-13	5	16.831	0.131	19.569	0.259
24-Aug-13	6	16.759	0.134	19.238	0.283
25-Aug-13	7	16.741	0.135	19.009	0.309
26-Aug-13	8	16.643	0.136	18.584	0.330
27-Aug-13	9	16.730	0.140	18.160	0.350
28-Aug-13	10	16.669	0.140	17.954	0.365
29-Aug-13	11	16.847	0.144	18.036	0.374
30-Aug-13	12	16.893	0.150	18.084	0.383
31-Aug-13	13	16.860	0.147	18.058	0.394
01-Sep-13	14	16.901	0.144	17.929	0.398
02-Sep-13	15	16.933	0.142	17.692	0.394
03-Sep-13	16	17.302	0.148	17.713	0.417
04-Sep-13	17	17.238	0.146	17.711	0.425
05-Sep-13	18	17.215	0.148	17.577	0.433
06-Sep-13	19	17.040	0.148	17.408	0.437
07-Sep-13	20	17.113	0.153	17.468	0.439
08-Sep-13	21	17.169	0.155	17.498	0.446
09-Sep-13	22	17.037	0.155	17.348	0.446
10-Sep-13	23	16.836	0.154	17.141	0.444
11-Sep-13	24	16.824	0.155	17.364	0.451
12-Sep-13	25	16.686	0.155	17.494	0.454
13-Sep-13	26	16.419	0.153	17.416	0.456
14-Sep-13	27	16.467	0.153	17.530	0.459
15-Sep-13	28	16.458	0.151	17.571	0.463
16-Sep-13	29	16.379	0.150	17.636	0.464
17-Sep-13	30	16.134	0.147	17.464	0.461
18-Sep-13	31	15.947	0.142	17.341	0.455
19-Sep-13	32	15.867	0.137	17.290	0.453
20-Sep-13	33	15.659	0.131	17.179	0.452
21-Sep-13	34	16.007	0.128	17.355	0.448
22-Sep-13	35	15.913	0.133	17.327	0.453

Table C3 (Contd.) **Parameters measured by sensors at 0.2 m depth in D21 and C5 columns**

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
23-Sep-13	36	15.706	0.132	17.217	0.448
24-Sep-13	37	15.708	0.132	17.115	0.447
25-Sep-13	38	15.543	0.131	17.045	0.442
26-Sep-13	39	15.394	0.130	16.971	0.442
27-Sep-13	40	15.299	0.128	16.931	0.440
28-Sep-13	41	15.408	0.130	16.957	0.434
29-Sep-13	42	15.272	0.132	16.903	0.430
30-Sep-13	43	14.936	0.130	16.727	0.429
01-Oct-13	44	14.778	0.125	16.626	0.414
02-Oct-13	45	15.030	0.128	16.827	0.416
03-Oct-13	46	14.466	0.129	16.519	0.419
04-Oct-13	47	14.752	0.121	16.737	0.380
05-Oct-13	48	15.011	0.128	17.068	0.382
06-Oct-13	49	14.661	0.129	16.941	0.401
07-Oct-13	50	14.746	0.125	16.955	0.378
08-Oct-13	51	15.111	0.130	17.134	0.385
09-Oct-13	52	14.982	0.133	17.145	0.407
10-Oct-13	53	14.984	0.132	17.113	0.408
11-Oct-13	54	14.915	0.133	17.157	0.409
12-Oct-13	55	14.879	0.134	17.165	0.408
13-Oct-13	56	14.632	0.135	17.090	0.409
14-Oct-13	57	14.754	0.134	17.221	0.410
15-Oct-13	58	14.758	0.136	17.214	0.413
16-Oct-13	59	14.621	0.136	17.212	0.414
17-Oct-13	60	14.438	0.135	17.079	0.407
18-Oct-13	61	14.287	0.131	16.923	0.392
19-Oct-13	62	14.835	0.131	17.282	0.379
20-Oct-13	63	14.788	0.137	17.252	0.401
21-Oct-13	64	14.729	0.136	17.166	0.398
22-Oct-13	65	14.586	0.138	17.149	0.395
23-Oct-13	66	14.612	0.141	17.169	0.399
24-Oct-13	67	14.770	0.141	17.297	0.398
25-Oct-13	68	14.816	0.141	17.270	0.401
26-Oct-13	69	14.967	0.142	17.393	0.394
27-Oct-13	70	14.839	0.148	17.367	0.404
28-Oct-13	71	14.655	0.146	17.322	0.400
29-Oct-13	72	14.401	0.148	17.361	0.398

**Table C3 (Contd.)	Parameters measured by sensors at 0.2 m depth in D21 and C5 columns**

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
30-Oct-13	73	14.462	0.151	17.407	0.399
31-Oct-13	74	14.394	0.151	17.294	0.397
01-Nov-13	75	14.408	0.152	17.251	0.398
02-Nov-13	76	14.338	0.156	17.253	0.395
03-Nov-13	77	14.236	0.163	17.205	0.400
04-Nov-13	78	14.382	0.162	17.310	0.400
05-Nov-13	79	14.343	0.165	17.350	0.401
06-Nov-13	80	14.220	0.162	17.194	0.400
07-Nov-13	81	14.158	0.161	17.224	0.391
08-Nov-13	82	13.985	0.161	17.082	0.393
09-Nov-13	83	14.080	0.164	17.152	0.387
10-Nov-13	84	14.329	0.172	17.284	0.400
11-Nov-13	85	14.382	0.174	17.395	0.400
12-Nov-13	86	14.158	0.170	17.233	0.394
13-Nov-13	87	14.025	0.165	17.080	0.380
14-Nov-13	88	14.396	0.168	17.463	0.375
15-Nov-13	89	14.362	0.180	17.434	0.390
16-Nov-13	90	14.452	0.189	17.565	0.391
17-Nov-13	91	14.529	0.188	17.682	0.388
18-Nov-13	92	14.528	0.186	17.701	0.385
19-Nov-13	93	14.437	0.189	17.604	0.384
20-Nov-13	94	14.252	0.198	17.473	0.384
21-Nov-13	95	14.125	0.193	17.417	0.383
22-Nov-13	96	14.029	0.191	17.408	0.382
23-Nov-13	97	14.025	0.197	17.351	0.386
24-Nov-13	98	13.998	0.195	17.335	0.384
25-Nov-13	99	14.018	0.196	17.405	0.382
26-Nov-13	100	14.102	0.207	17.523	0.381
27-Nov-13	101	14.062	0.204	17.535	0.380
28-Nov-13	102	14.011	0.205	17.614	0.379
29-Nov-13	103	13.969	0.204	17.636	0.380
30-Nov-13	104	14.119	0.217	17.726	0.381
01-Dec-13	105	14.116	0.216	17.744	0.382
02-Dec-13	106	14.039	0.217	17.697	0.382
03-Dec-13	107	13.945	0.215	17.627	0.381
04-Dec-13	108	13.828	0.213	17.573	0.381
05-Dec-13	109	13.787	0.212	17.548	0.380

Table C3 (Contd.) **Parameters measured by sensors at 0.2 m depth in D21 and C5 columns**

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
06-Dec-13	110	13.880	0.210	17.584	0.378
07-Dec-13	111	13.952	0.214	17.626	0.384
08-Dec-13	112	13.895	0.213	17.476	0.385
09-Dec-13	113	13.765	0.210	17.297	0.378
10-Dec-13	114	13.834	0.213	17.399	0.381
11-Dec-13	115	13.759	0.209	17.209	0.374
12-Dec-13	116	13.914	0.214	17.307	0.376
13-Dec-13	117	13.967	0.218	17.243	0.372
14-Dec-13	118	14.104	0.226	17.445	0.379
15-Dec-13	119	14.091	0.224	17.504	0.377
16-Dec-13	120	14.120	0.224	17.608	0.376
17-Dec-13	121	14.099	0.225	17.610	0.375
18-Dec-13	122	14.018	0.223	17.620	0.374
19-Dec-13	123	13.983	0.223	17.540	0.372
20-Dec-13	124	14.034	0.226	17.484	0.371
21-Dec-13	125	13.867	0.225	17.275	0.370
22-Dec-13	126	13.686	0.221	17.221	0.370
23-Dec-13	127	13.707	0.217	17.469	0.373
24-Dec-13	128	13.834	0.215	17.534	0.371
25-Dec-13	129	13.818	0.213	17.564	0.369
26-Dec-13	130	13.677	0.209	17.409	0.368
27-Dec-13	131	13.683	0.208	17.481	0.368
28-Dec-13	132	13.629	0.206	17.404	0.367
29-Dec-13	133	13.527	0.205	17.343	0.368
30-Dec-13	134	13.671	0.207	17.571	0.369
31-Dec-13	135	13.690	0.204	17.551	0.365
01-Jan-14	136	13.548	0.203	17.433	0.365
02-Jan-14	137	13.500	0.202	17.496	0.366
03-Jan-14	138	13.526	0.201	17.532	0.366
04-Jan-14	139	13.500	0.199	17.365	0.363
05-Jan-14	140	13.399	0.201	17.311	0.363
06-Jan-14	141	13.414	0.201	17.518	0.365
07-Jan-14	142	13.472	0.198	17.593	0.361
08-Jan-14	143	13.394	0.196	17.694	0.362
09-Jan-14	144	13.441	0.197	17.625	0.359
10-Jan-14	145	13.381	0.196	17.641	0.362
11-Jan-14	146	13.392	0.196	17.482	0.358

Table C3 (Contd.) Parameters measured by sensors at 0.2 m depth in D21 and C5 columns

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
12-Jan-14	147	13.192	0.192	17.335	0.358
13-Jan-14	148	13.348	0.194	17.553	0.359
14-Jan-14	149	13.388	0.191	17.571	0.356
15-Jan-14	150	13.374	0.190	17.595	0.355
16-Jan-14	151	13.333	0.189	17.596	0.355
17-Jan-14	152	13.350	0.190	17.615	0.358
18-Jan-14	153	13.341	0.188	17.288	0.356
19-Jan-14	154	13.102	0.185	17.120	0.357
20-Jan-14	155	13.488	0.187	17.386	0.358
21-Jan-14	156	13.692	0.185	17.423	0.354
22-Jan-14	157	13.691	0.185	17.498	0.354
23-Jan-14	158	13.762	0.184	17.556	0.352
24-Jan-14	159	13.843	0.183	17.552	0.351
25-Jan-14	160	14.025	0.183	17.451	0.349
26-Jan-14	161	14.075	0.184	17.522	0.349
27-Jan-14	162	13.989	0.182	17.572	0.349
28-Jan-14	163	13.917	0.182	17.599	0.349
29-Jan-14	164	14.153	0.183	17.588	0.349
30-Jan-14	165	14.125	0.183	17.573	0.352
31-Jan-14	166	14.253	0.183	17.587	0.352
01-Feb-14	167	14.160	0.181	17.380	0.352
02-Feb-14	168	14.065	0.181	17.296	0.351
03-Feb-14	169	14.207	0.182	17.512	0.351
04-Feb-14	170	14.285	0.180	17.530	0.349
05-Feb-14	171	14.346	0.180	17.634	0.349
06-Feb-14	172	14.423	0.180	17.590	0.347
07-Feb-14	173	14.415	0.181	17.610	0.347
08-Feb-14	174	14.351	0.179	17.336	0.348
09-Feb-14	175	14.183	0.177	17.221	0.347
10-Feb-14	176	14.237	0.177	17.374	0.347
11-Feb-14	177	14.291	0.174	17.414	0.347
12-Feb-14	178	14.234	0.174	17.400	0.346
13-Feb-14	179	14.328	0.174	17.415	0.346
14-Feb-14	180	14.314	0.174	17.439	0.344
15-Feb-14	181	14.261	0.171	17.529	0.345
16-Feb-14	182	14.275	0.172	17.431	0.343
17-Feb-14	183	14.430	0.174	17.566	0.344

Table C3 (Contd.) **Parameters measured by sensors at 0.2 m depth in D21 and C5 columns**

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
18-Feb-14	184	14.423	0.173	17.570	0.344
19-Feb-14	185	14.386	0.174	17.456	0.342
20-Feb-14	186	14.410	0.174	17.482	0.344
21-Feb-14	187	14.436	0.175	17.613	0.346
22-Feb-14	188	14.562	0.178	17.576	0.347
23-Feb-14	189	14.599	0.178	17.593	0.347
24-Feb-14	190	14.598	0.177	17.664	0.348
25-Feb-14	191	14.521	0.176	17.591	0.346
26-Feb-14	192	14.479	0.175	17.626	0.347
27-Feb-14	193	14.556	0.175	17.625	0.346
28-Feb-14	194	14.711	0.177	17.671	0.346
01-Mar-14	195	14.710	0.176	17.561	0.344
02-Mar-14	196	14.718	0.176	17.572	0.343
03-Mar-14	197	14.689	0.177	17.568	0.344
04-Mar-14	198	14.632	0.176	17.545	0.343
05-Mar-14	199	14.564	0.175	17.523	0.342
06-Mar-14	200	14.531	0.174	17.536	0.342
07-Mar-14	201	14.499	0.174	17.705	0.344
08-Mar-14	202	14.485	0.176	17.791	0.343
09-Mar-14	203	14.342	0.174	17.698	0.342
10-Mar-14	204	14.339	0.174	17.789	0.342
11-Mar-14	205	14.277	0.173	17.801	0.341
12-Mar-14	206	14.227	0.172	17.797	0.340
13-Mar-14	207	14.21	0.171	17.81	0.339
14-Mar-14	208	14.15	0.171	17.78	0.339
15-Mar-14	209	14.19	0.171	17.64	0.337
16-Mar-14	210	14.27	0.172	17.57	0.336
17-Mar-14	211	14.30	0.173	17.70	0.336
18-Mar-14	212	14.27	0.173	17.64	0.335
19-Mar-14	213	14.42	0.175	17.63	0.335
20-Mar-14	214	14.49	0.176	17.60	0.335
21-Mar-14	215	14.50	0.176	17.62	0.334
22-Mar-14	216	14.44	0.176	17.62	0.334
23-Mar-14	217	14.40	0.175	17.55	0.332
24-Mar-14	218	14.46	0.175	17.71	0.332
25-Mar-14	219	14.59	0.176	17.86	0.330
26-Mar-14	220	14.63	0.177	17.80	0.330

Table C3 (Contd.) Parameters measured by sensors at 0.2 m depth in D21 and C5 columns

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
27-Mar-14	221	14.64	0.177	17.81	0.329
28-Mar-14	222	14.60	0.175	17.88	0.330
29-Mar-14	223	14.61	0.176	17.78	0.329
30-Mar-14	224	14.54	0.175	17.72	0.328
31-Mar-14	225	14.48	0.175	17.75	0.327
01-Apr-14	226	14.45	0.173	17.80	0.327
02-Apr-14	227	14.32	0.170	17.79	0.327
03-Apr-14	228	14.02	0.164	17.60	0.323
04-Apr-14	229	14.02	0.164	17.51	0.322
05-Apr-14	230	14.49	0.173	17.79	0.329
06-Apr-14	231	14.49	0.172	17.85	0.328
07-Apr-14	232	14.47	0.171	17.93	0.327
08-Apr-14	233	14.25	0.166	17.79	0.324
09-Apr-14	234	14.08	0.162	17.43	0.315
10-Apr-14	235	13.83	0.158	17.12	0.304
11-Apr-14	236	13.69	0.155	17.11	0.295
12-Apr-14	237	14.47	0.168	17.89	0.317
13-Apr-14	238	14.63	0.170	17.99	0.317
14-Apr-14	239	14.32	0.165	17.77	0.310
15-Apr-14	240	13.79	0.156	17.26	0.291
16-Apr-14	241	13.29	0.146	16.91	0.263
17-Apr-14	242	12.95	0.138	16.73	0.239
18-Apr-14	243	12.69	0.132	16.64	0.220
19-Apr-14	244	12.53	0.129	16.61	0.208
20-Apr-14	245	12.38	0.126	16.56	0.198
21-Apr-14	246	12.24	0.123	16.50	0.191
22-Apr-14	247	12.31	0.127	16.53	0.194
23-Apr-14	248	12.70	0.136	16.70	0.206
24-Apr-14	249	12.30	0.129	16.47	0.197
25-Apr-14	250	12.02	0.124	16.32	0.192
26-Apr-14	251	11.97	0.121	16.28	0.190
27-Apr-14	252	11.93	0.120	16.21	0.190
28-Apr-14	253	11.97	0.123	16.19	0.197
29-Apr-14	254	12.30	0.134	16.39	0.213
30-Apr-14	255	12.35	0.138	16.38	0.218
01-May-14	256	12.68	0.147	16.54	0.230
02-May-14	257	12.62	0.146	16.49	0.232

Table C3 (Contd.) Parameters measured by sensors at 0.2 m depth in D21 and C5 columns

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
03-May-14	258	13.08	0.157	16.75	0.249
04-May-14	259	13.00	0.155	16.66	0.241
05-May-14	260	13.00	0.159	16.64	0.250
06-May-14	261	13.19	0.167	16.73	0.263
07-May-14	262	12.76	0.158	16.44	0.244
08-May-14	263	12.32	0.148	16.17	0.229
09-May-14	264	12.17	0.146	16.10	0.229
10-May-14	265	12.61	0.158	16.42	0.246
11-May-14	266	12.59	0.159	16.35	0.245
12-May-14	267	12.62	0.165	16.29	0.255
13-May-14	268	13.11	0.176	16.51	0.270
14-May-14	269	12.86	0.172	16.33	0.259
15-May-14	270	12.85	0.177	16.30	0.265
16-May-14	271	13.37	0.202	16.57	0.301
17-May-14	272	13.75	0.216	16.80	0.318
18-May-14	273	13.71	0.213	16.73	0.307
19-May-14	274	13.43	0.209	16.51	0.295
20-May-14	275	13.48	0.220	16.59	0.313
21-May-14	276	13.59	0.228	16.66	0.322
22-May-14	277	13.51	0.229	16.55	0.320
23-May-14	278	13.86	0.255	16.70	0.352
24-May-14	279	13.95	0.255	16.75	0.352
25-May-14	280	13.93	0.247	16.81	0.345
26-May-14	281	13.75	0.238	16.80	0.338
27-May-14	282	13.71	0.238	16.85	0.340
28-May-14	283	13.80	0.242	16.94	0.347
29-May-14	284	13.71	0.230	16.95	0.334
30-May-14	285	13.79	0.235	16.90	0.337
31-May-14	286	14.05	0.246	17.02	0.350
01-Jun-14	287	14.03	0.241	17.03	0.349
02-Jun-14	288	13.98	0.246	16.70	0.356
03-Jun-14	289	14.06	0.252	16.37	0.358
04-Jun-14	290	14.02	0.250	16.69	0.359
05-Jun-14	291	13.98	0.256	17.30	0.368
06-Jun-14	292	NR	NR	NR	NR
07-Jun-14	293	NR	NR	NR	NR
08-Jun-14	294	14.08	0.257	17.36	0.370

Table C3 (Contd.) Parameters measured by sensors at 0.2 m depth in D21 and C5 columns

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
09-Jun-14	295	14.08	0.259	17.33	0.372
10-Jun-14	296	13.82	0.247	17.07	0.353
11-Jun-14	297	13.88	0.255	17.12	0.361
12-Jun-14	298	13.97	0.261	17.27	0.376
13-Jun-14	299	13.94	0.263	17.23	0.381
14-Jun-14	300	14.11	0.272	17.25	0.388
15-Jun-14	301	14.22	0.273	17.31	0.389
16-Jun-14	302	14.08	0.279	17.25	0.395
17-Jun-14	303	14.02	0.281	17.21	0.395
18-Jun-14	304	13.99	0.281	17.20	0.400
19-Jun-14	305	13.97	0.280	17.17	0.403
20-Jun-14	306	13.84	0.278	17.20	0.408
21-Jun-14	307	13.93	0.280	17.27	0.412
22-Jun-14	308	14.04	0.286	17.31	0.413
23-Jun-14	309	13.84	0.287	17.21	0.417
24-Jun-14	310	13.72	0.286	17.14	0.418
25-Jun-14	311	13.64	0.295	16.97	0.420
26-Jun-14	312	13.83	0.293	16.97	0.419
27-Jun-14	313	13.57	0.279	16.71	0.399
28-Jun-14	314	13.47	0.268	16.44	0.372
29-Jun-14	315	13.44	0.264	16.34	0.359
30-Jun-14	316	13.39	0.272	16.37	0.363
01-Jul-14	317	13.61	0.284	16.59	0.376
02-Jul-14	318	13.63	0.289	16.63	0.381
03-Jul-14	319	13.64	0.289	16.67	0.382
04-Jul-14	320	13.71	0.291	16.66	0.387
05-Jul-14	321	13.88	0.291	16.81	0.392
06-Jul-14	322	13.88	0.285	16.72	0.381
07-Jul-14	323	13.50	0.278	16.35	0.362
08-Jul-14	324	13.17	0.267	15.91	0.335
09-Jul-14	325	12.88	0.258	15.34	0.311
10-Jul-14	326	12.47	0.247	14.84	0.290
11-Jul-14	327	12.41	0.248	14.87	0.295
12-Jul-14	328	12.73	0.259	15.13	0.306
13-Jul-14	329	12.69	0.256	15.07	0.299
14-Jul-14	330	12.33	0.247	14.75	0.287
15-Jul-14	331	11.90	0.232	14.36	0.270

Table C3 (Contd.) **Parameters measured by sensors at 0.2 m depth in D21 and C5 columns**

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
16-Jul-14	332	11.70	0.228	14.28	0.269
17-Jul-14	333	11.76	0.239	14.62	0.282
18-Jul-14	334	11.77	0.244	14.62	0.287
19-Jul-14	335	12.01	0.251	14.85	0.291
20-Jul-14	336	11.96	0.246	14.79	0.285
21-Jul-14	337	11.64	0.237	14.44	0.276
22-Jul-14	338	11.27	0.220	13.91	0.259
23-Jul-14	339	11.02	0.207	13.44	0.245
24-Jul-14	340	10.73	0.193	12.93	0.231
25-Jul-14	341	10.50	0.181	12.42	0.218
26-Jul-14	342	10.37	0.171	12.06	0.207
27-Jul-14	343	10.32	0.165	11.90	0.201
28-Jul-14	344	10.46	0.175	12.05	0.211
29-Jul-14	345	10.57	0.184	12.28	0.219
30-Jul-14	346	10.45	0.183	12.36	0.220
31-Jul-14	347	10.48	0.189	12.62	0.226
01-Aug-14	348	10.46	0.187	12.52	0.224
02-Aug-14	349	10.59	0.193	12.71	0.228
03-Aug-14	350	10.51	0.186	12.47	0.220
04-Aug-14	351	10.34	0.178	12.08	0.211
05-Aug-14	352	10.26	0.174	11.89	0.207
06-Aug-14	353	10.43	0.188	12.31	0.221
07-Aug-14	354	10.25	0.175	11.83	0.207
08-Aug-14	355	10.26	0.177	11.78	0.207
09-Aug-14	356	10.45	0.189	12.19	0.218
10-Aug-14	357	10.43	0.184	12.06	0.214
11-Aug-14	358	10.35	0.190	12.19	0.221
12-Aug-14	359	10.36	0.194	12.32	0.226
13-Aug-14	360	10.31	0.197	12.33	0.227
14-Aug-14	361	10.35	0.205	12.61	0.236
15-Aug-14	362	10.37	0.209	12.65	0.238
16-Aug-14	363	10.58	0.219	13.04	0.247
17-Aug-14	364	10.55	0.217	12.95	0.245
18-Aug-14	365	10.64	0.229	13.14	0.256
19-Aug-14	366	10.81	0.242	13.49	0.268
20-Aug-14	367	10.95	0.250	13.63	0.276
21-Aug-14	368	11.09	0.257	13.82	0.284

Table C3 (Contd.) Parameters measured by sensors at 0.2 m depth in D21 and C5 columns

Date	Day	D21 soil column		C5 soil column	
		Average Permittivity	Average ECbulk (dS/cm)	Average Permittivity	Average ECbulk (dS/cm)
22-Aug-14	369	11.10	0.259	13.83	0.286
23-Aug-14	370	11.18	0.270	14.00	0.297
24-Aug-14	371	10.95	0.257	13.72	0.287
25-Aug-14	372	10.75	0.244	13.42	0.277
26-Aug-14	373	10.56	0.230	13.07	0.266
27-Aug-14	374	10.61	0.236	13.16	0.269
28-Aug-14	375	10.83	0.246	13.51	0.277
29-Aug-14	376	10.77	0.243	13.39	0.274
30-Aug-14	377	NR	NR	NR	NR
31-Aug-14	378	NR	NR	NR	NR
01-Sep-14	379	10.59	0.236	13.10	0.268
02-Sep-14	380	10.69	0.235	13.08	0.272
03-Sep-14	381	10.86	0.240	13.26	0.279
04-Sep-14	382	10.59	0.222	12.80	0.263
05-Sep-14	383	10.44	0.213	12.49	0.255
06-Sep-14	384	10.75	0.233	13.00	0.273
07-Sep-14	385	10.72	0.230	12.93	0.269
08-Sep-14	386	10.55	0.224	12.67	0.265
09-Sep-14	387	10.51	0.225	12.61	0.267
10-Sep-14	388	10.75	0.246	13.00	0.283
11-Sep-14	389	10.54	0.230	12.65	0.270
12-Sep-14	390	10.52	0.225	12.53	0.267
13-Sep-14	391	10.82	0.241	12.93	0.279
14-Sep-14	392	10.77	0.238	12.82	0.276
15-Sep-14	393	10.61	0.231	12.57	0.271
16-Sep-14	394	10.40	0.215	12.17	0.257
17-Sep-14	395	10.21	0.199	11.73	0.240
18-Sep-14	396	10.01	0.181	11.25	0.221
19-Sep-14	397	9.84	0.171	10.98	0.211
20-Sep-14	398	9.93	0.183	11.30	0.225
21-Sep-14	399	9.87	0.179	11.20	0.221
22-Sep-14	400	9.72	0.173	10.98	0.215

NR=Not recorded

Table C4 Irrigation scheduling for D21 paddock using GCM meteorological data from 2021 to 2040

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
January	4	2	5	4	4	3	3	3	4	4	2	4	2	3	4	5	3	4	3	1
February	2	3	3	2	2	2	3	0	2	2	1	3	2	1	2	5	2	2	2	1
March	1	2	2	1	1	3	3	3	2	2	2	0	2	0	2	1	1	1	2	2
April	2	2	1	0	2	0	1	1	2	1	1	1	1	1	1	2	1	2	1	1
May	1	0	2	1	1	1	0	0	1	1	0	1	1	2	1	0	1	1	1	1
June	0	1	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	1	1	0
July	0	0	1	1	1	0	0	1	0	0	1	0	1	0	1	0	1	0	0	2
August	1	0	1	1	1	1	1	1	2	1	0	1	1	2	1	1	0	2	0	1
September	2	1	3	2	0	1	2	1	1	2	2	2	3	1	0	0	1	2	2	1
October	3	2	1	2	4	3	2	1	1	3	2	3	2	0	3	1	4	2	0	1
November	2	4	2	3	4	3	3	3	2	3	3	3	2	4	1	2	4	4	2	3
December	2	2	4	3	3	3	1	2	4	4	4	3	3	2	3	2	4	3	2	1

Table C5 Irrigation scheduling for C5 paddock using GCM meteorological data from 2021 to 2040

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
January	2	2	3	2	3	2	2	2	2	2	2	3	0	3	3	4	2	2	2	1
February	1	2	2	1	1	2	2	0	1	1	1	2	2	0	1	2	1	1	2	1
March	0	2	1	2	1	2	2	1	1	2	1	0	2	0	1	1	0	0	1	1
April	1	1	1	0	1	0	0	0	1	1	0	1	1	1	1	0	2	1	1	1
May	1	0	1	1	1	0	1	1	1	1	1	0	1	1	0	1	0	1	0	1
June	0	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0
July	0	0	0	0	1	0	0	1	0	0	0	0	1	0	1	0	0	1	0	1
August	1	0	1	1	1	0	0	0	1	1	0	0	1	1	1	0	1	1	0	0
September	1	1	1	1	0	1	1	1	1	1	1	2	1	0	0	0	0	2	1	1
October	2	1	1	2	2	2	2	0	0	2	2	2	2	0	2	0	3	1	0	1
November	1	2	2	2	3	2	1	3	1	3	2	2	2	3	0	2	2	3	1	2
December	1	3	3	1	2	2	1	2	3	3	3	2	1	1	1	1	2	1	0	1

APPENDIX D: ADDITIONAL DATA RELATED TO CHAPTER 7

Table D1 Column operation data related to column 1, 2 and 3 using tap water as irrigation water in D33 paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
15-Nov-12	1	2000	0.224	0.00	0.000	0.0	0.000	0.0	0.000
16-Nov-12	2	1000	0.224	0.00	0.000	0.0	0.000	50.0	4.850
19-Nov-12	5	1000	0.224	561.00	1.880	665.0	1.815	588.0	0.812
05-Dec-12	21	1000	0.224	215.00	1.068	235.0	0.858	350.0	0.834
13-Dec-12	29	300	0.224	195.00	1.219	190.0	1.084	320.0	1.069
17-Dec-12	33	100	0.224	170.00	1.356	33.0	1.264	25.0	1.050
20-Dec-12	36	100	0.224	70.00	1.356	70.0	1.220	0.0	0.000
24-Dec-12	40	100	0.224	717.00	0.291	751.0	0.267	615.0	0.315
29-Dec-12	45	100	0.224	40.00	0.337	70.0	0.324	15.0	0.589
01-Jan-13	48	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
07-Jan-13	54	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
09-Jan-13	56	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
14-Jan-13	61	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
16-Jan-13	63	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
18-Jan-13	65	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
21-Jan-13	68	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
25-Jan-13	72	100	0.224	0.00	0.000	7.5	0.331	0.0	0.000
29-Jan-13	76	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
01-Feb-13	79	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
04-Feb-13	82	100	0.224	0.00	0.742	20.0	0.446	0.0	0.000
08-Feb-13	86	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
12-Feb-13	90	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
15-Feb-13	93	100	0.224	0.00	0.679	0.0	0.000	0.0	0.000
18-Feb-13	96	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
23-Feb-13	101	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
27-Feb-13	105	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
01-Mar-13	107	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
04-Mar-13	110	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
08-Mar-13	114	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
11-Mar-13	117	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
15-Mar-13	121	100	0.224	10.00	0.567	72.0	0.516	0.0	0.000
18-Mar-13	124	100	0.224	22.00	0.542	27.0	0.627	0.0	0.000
22-Mar-13	128	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
25-Mar-13	131	100	0.224	0.00	0.000	10.0	0.604	0.0	0.000

Table D1 (Contd.) Column operation data related to column 1, 2 and 3 using tap water as irrigation water in D33 paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
28-Mar-13	134	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
02-Apr-13	139	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
08-Apr-13	145	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
10-Apr-13	147	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
15-Apr-13	152	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
18-Apr-13	155	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
22-Apr-13	159	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
23-Apr-13	160	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
26-Apr-13	163	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
29-Apr-13	166	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
02-May-13	169	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
03-May-13	170	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
06-May-13	173	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
08-May-13	175	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
09-May-13	176	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
10-May-13	177	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
13-May-13	180	100	0.224	0.00	0.000	55.0	0.541	0.0	0.000
17-May-13	184	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
20-May-13	187	100	0.224	15.00	1.113	30.0	0.670	0.0	0.000
21-May-13	188	100	0.224	37.00	0.958	7.5	0.757	0.0	0.000
23-May-13	190	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
27-May-13	194	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
28-May-13	195	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
31-May-13	198	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
07-Jun-13	205	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
11-Jun-13	209	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
14-Jun-13	212	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
17-Jun-13	215	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
18-Jun-13	216	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
21-Jun-13	219	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
24-Jun-13	222	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
27-Jun-13	225	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
01-Jul-13	229	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
03-Jul-13	231	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
05-Jul-13	233	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
08-Jul-13	236	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000

Table D1 (Contd.)   Column operation data related to column 1, 2 and 3 using tap water as irrigation water in D33 paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
11-Jul-13	239	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
15-Jul-13	243	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
17-Jul-13	245	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
21-Jul-13	249	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
24-Jul-13	252	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
26-Jul-13	254	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
29-Jul-13	257	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
31-Jul-13	259	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
02-Aug-13	261	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
05-Aug-13	264	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
13-Aug-13	272	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
14-Aug-13	273	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
16-Aug-13	275	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
19-Aug-13	278	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
21-Aug-13	280	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
23-Aug-13	282	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
26-Aug-13	285	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
30-Aug-13	289	200	0.224	0.00	0.000	32.0	0.810	0.0	0.000
02-Sep-13	292	200	0.224	0.00	0.000	30.0	1.000	0.0	0.000
04-Sep-13	294	200	0.224	30.00	1.369	37.0	1.166	0.0	0.000
06-Sep-13	296	200	0.224	27.50	1.716	26.0	1.170	0.0	0.000
09-Sep-13	299	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
11-Sep-13	301	100	0.224	0.00	0.000	39.0	1.045	0.0	0.000
13-Sep-13	303	200	0.224	65.00	1.196	72.0	1.114	40.0	2.900
15-Sep-13	305	100	0.224	73.00	0.989	82.0	1.196	92.0	1.698
17-Sep-13	307	100	0.224	68.00	0.883	75.0	0.979	77.0	1.327
20-Sep-13	310	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
23-Sep-13	313	200	0.224	33.00	1.106	35.0	1.124	25.0	1.325
25-Sep-13	315	100	0.224	0.00	0.000	25.0	1.784	45.0	1.095
27-Sep-13	317	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
01-Oct-13	321	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
04-Oct-13	324	200	0.224	60.00	1.239	75.0	1.024	57.0	1.276
07-Oct-13	327	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000
09-Oct-13	329	100	0.224	0.00	0.000	0.0	0.000	0.0	0.000
10-Oct-13	330	200	0.224	0.00	0.000	0.0	0.000	0.0	0.000

Table D2 Column operation data related to column 1, 2 and 3 using recycled water as irrigation water in D33 paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
15-Nov-12	1	2000	0.806	0.0	0.000	0.0	0.000	0.0	0.000
16-Nov-12	2	1000	0.806	0.0	0.000	0.0	0.000	42.0	4.240
19-Nov-12	5	1000	0.806	615.0	2.076	393.0	2.860	579.0	1.273
05-Dec-12	21	1000	0.806	230.0	1.240	91.0	1.871	300.0	1.229
13-Dec-12	29	300	0.806	190.0	1.377	72.0	1.782	260.0	1.417
17-Dec-12	33	100	0.806	110.0	1.548	58.0	1.727	119.0	1.505
20-Dec-12	36	100	0.806	77.0	1.600	235.0	1.743	0.0	0.000
24-Dec-12	40	100	0.806	550.0	1.332	323.0	1.977	570.0	1.019
29-Dec-12	45	100	0.806	82.0	1.352	58.0	2.108	46.0	1.080
01-Jan-13	48	100	0.806	0.0	0.000	58.0	2.108	0.0	0.000
07-Jan-13	54	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
09-Jan-13	56	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
14-Jan-13	61	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
16-Jan-13	63	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
18-Jan-13	65	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
21-Jan-13	68	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
25-Jan-13	72	100	0.806	11.0	2.690	18.0	3.410	0.0	0.000
29-Jan-13	76	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
01-Feb-13	79	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
04-Feb-13	82	100	0.806	29.0	2.860	19.0	4.760	0.0	0.000
08-Feb-13	86	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
12-Feb-13	90	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
15-Feb-13	93	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
18-Feb-13	96	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
23-Feb-13	101	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
27-Feb-13	105	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
01-Mar-13	107	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
04-Mar-13	110	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
08-Mar-13	114	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
11-Mar-13	117	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
15-Mar-13	121	100	0.806	18.0	4.590	18.0	4.910	0.0	0.000
18-Mar-13	124	100	0.806	23.0	3.040	0.0	0.000	0.0	0.000
22-Mar-13	128	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
25-Mar-13	131	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000

Table D2 (Contd.) Column operation data related to column 1, 2 and 3 using recycled water as irrigation water in D33 paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
28-Mar-13	134	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
02-Apr-13	139	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
08-Apr-13	145	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
10-Apr-13	147	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
15-Apr-13	152	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
18-Apr-13	155	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
22-Apr-13	159	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
23-Apr-13	160	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
26-Apr-13	163	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
29-Apr-13	166	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
02-May-13	169	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
03-May-13	170	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
06-May-13	173	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
08-May-13	175	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
09-May-13	176	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
10-May-13	177	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
13-May-13	180	100	0.806	43.0	1.879	0.0	0.000	0.0	0.000
17-May-13	184	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
20-May-13	187	100	0.806	38.0	2.230	0.0	0.000	0.0	0.000
21-May-13	188	100	0.806	22.0	2.240	7.5	0.000	0.0	0.000
23-May-13	190	100	0.806	0.0	0.000	32.0	0.000	0.0	0.000
27-May-13	194	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
28-May-13	195	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
31-May-13	198	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
07-Jun-13	205	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
11-Jun-13	209	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
14-Jun-13	212	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
17-Jun-13	215	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
18-Jun-13	216	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
21-Jun-13	219	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
24-Jun-13	222	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
27-Jun-13	225	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
01-Jul-13	229	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
03-Jul-13	231	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
05-Jul-13	233	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
08-Jul-13	236	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000

Table D2 (Contd.) Column operation data related to column 1, 2 and 3 using recycled water as irrigation water in D33 paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
11-Jul-13	239	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
15-Jul-13	243	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
17-Jul-13	245	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
21-Jul-13	249	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
24-Jul-13	252	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
26-Jul-13	254	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
29-Jul-13	257	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
31-Jul-13	259	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
02-Aug-13	261	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
05-Aug-13	264	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
13-Aug-13	272	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
14-Aug-13	273	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
16-Aug-13	275	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
19-Aug-13	278	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
21-Aug-13	280	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
23-Aug-13	282	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
26-Aug-13	285	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
30-Aug-13	289	200	0.806	80.0	2.690	45.0	4.470	0.0	0.000
02-Sep-13	292	200	0.806	20.0	4.010	30.0	5.060	0.0	0.000
04-Sep-13	294	200	0.806	55.0	3.120	35.0	4.730	0.0	0.000
06-Sep-13	296	200	0.806	42.5	3.100	0.0	0.000	0.0	0.000
09-Sep-13	299	200	0.806	37.0	3.960	0.0	0.000	0.0	0.000
11-Sep-13	301	100	0.806	0.0	0.000	30.0	5.170	0.0	0.000
13-Sep-13	303	200	0.806	70.0	3.490	65.0	4.510	0.0	0.000
15-Sep-13	305	100	0.806	77.0	3.470	70.0	4.260	63.0	5.840
17-Sep-13	307	100	0.806	75.0	3.060	47.0	4.550	75.0	4.740
20-Sep-13	310	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
23-Sep-13	313	200	0.806	25.0	3.510	43.0	4.440	25.0	4.160
25-Sep-13	315	100	0.806	37.0	4.430	25.0	4.880	35.0	5.020
27-Sep-13	317	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
01-Oct-13	321	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
04-Oct-13	324	200	0.806	67.0	3.720	40.0	5.710	37.0	4.740
07-Oct-13	327	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
09-Oct-13	329	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
10-Oct-13	330	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000

Table D3 Column operation data related to column 1, 2 and 3 using synthetic saline water as irrigation water in D33 paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
15-Nov-12	1	2000	2.003	0.0	0.000	0.0	0.000	0.0	0.000
16-Nov-12	2	1000	2.003	150.0	5.020	310.0	3.940	192.0	5.190
19-Nov-12	5	1000	2.003	630.0	2.780	680.0	2.620	560.0	2.530
05-Dec-12	21	1000	2.003	560.0	2.510	635.0	2.510	580.0	2.450
13-Dec-12	29	300	2.003	120.0	2.540	0.0	0.000	97.0	2.520
17-Dec-12	33	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
20-Dec-12	36	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
24-Dec-12	40	100	2.003	589.0	2.616	33.0	2.622	570.0	2.430
29-Dec-12	45	100	2.003	65.0	3.390	51.0	3.700	20.0	3.200
01-Jan-13	48	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
07-Jan-13	54	200	2.011	0.0	0.000	0.0	0.000	0.0	0.000
09-Jan-13	56	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
14-Jan-13	61	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
16-Jan-13	63	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
18-Jan-13	65	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
21-Jan-13	68	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
25-Jan-13	72	100	2.011	0.0	0.000	6.0	7.900	6.0	7.900
29-Jan-13	76	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
01-Feb-13	79	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
04-Feb-13	82	100	2.011	46.0	5.190	33.0	5.620	33.0	5.620
08-Feb-13	86	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
12-Feb-13	90	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
15-Feb-13	93	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
18-Feb-13	96	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
23-Feb-13	101	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
27-Feb-13	105	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
01-Mar-13	107	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
04-Mar-13	110	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
08-Mar-13	114	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
11-Mar-13	117	100	2.018	50.0	4.870	0.0	0.000	0.0	0.000
15-Mar-13	121	100	2.018	30.0	4.390	58.0	5.070	0.0	0.000
18-Mar-13	124	100	2.018	27.0	0.000	25.0	4.540	0.0	0.000
22-Mar-13	128	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
25-Mar-13	131	100	2.018	10.0	4.910	0.0	0.000	0.0	0.000

Table D3 (Contd.) Column operation data related to column 1, 2 and 3 using synthetic saline water as irrigation water in D33 paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
28-Mar-13	134	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
02-Apr-13	139	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
08-Apr-13	145	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
10-Apr-13	147	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
15-Apr-13	152	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
18-Apr-13	155	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
22-Apr-13	159	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
23-Apr-13	160	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
26-Apr-13	163	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
29-Apr-13	166	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
02-May-13	169	200	2.018	0.0	0.000	0.0	0.000	0.0	0.000
03-May-13	170	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
06-May-13	173	200	2.018	0.0	0.000	0.0	0.000	0.0	0.000
08-May-13	175	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
09-May-13	176	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
10-May-13	177	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
13-May-13	180	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
17-May-13	184	100	2.058	0.0	0.000	0.0	0.000	30.0	9.420
20-May-13	187	100	2.058	38.0	6.820	20.0	9.870	0.0	0.000
21-May-13	188	100	2.058	80.0	6.450	72.0	7.210	20.0	8.650
23-May-13	190	100	2.058	0.0	0.000	0.0	0.000	10.0	8.650
27-May-13	194	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
28-May-13	195	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
31-May-13	198	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
07-Jun-13	205	200	2.003	0.0	0.000	0.0	0.000	0.0	0.000
11-Jun-13	209	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
14-Jun-13	212	200	2.003	0.0	0.000	0.0	0.000	0.0	0.000
17-Jun-13	215	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
18-Jun-13	216	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
21-Jun-13	219	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
24-Jun-13	222	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
27-Jun-13	225	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
01-Jul-13	229	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
03-Jul-13	231	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
05-Jul-13	233	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
08-Jul-13	236	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000

Table D3 (Contd.) Column operation data related to column 1, 2 and 3 using synthetic saline water as irrigation water in D33 paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
11-Jul-13	239	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
15-Jul-13	243	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
17-Jul-13	245	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
21-Jul-13	249	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
24-Jul-13	252	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
26-Jul-13	254	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
29-Jul-13	257	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
31-Jul-13	259	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
02-Aug-13	261	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
05-Aug-13	264	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
13-Aug-13	272	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
14-Aug-13	273	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
16-Aug-13	275	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
19-Aug-13	278	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
21-Aug-13	280	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
23-Aug-13	282	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
26-Aug-13	285	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
30-Aug-13	289	200	2.028	76.0	10.250	50.0	10.180	0.0	0.000
02-Sep-13	292	200	2.028	37.5	12.230	27.5	11.210	0.0	0.000
04-Sep-13	294	200	2.028	46.0	11.390	35.0	13.140	0.0	0.000
06-Sep-13	296	200	2.028	47.5	11.130	40.0	11.870	0.0	0.000
09-Sep-13	299	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
11-Sep-13	301	100	2.028	37.0	12.050	10.0	12.890	0.0	0.000
13-Sep-13	303	200	2.031	75.0	11.270	72.0	12.480	42.5	7.300
15-Sep-13	305	100	2.031	77.0	10.670	77.0	13.700	63.0	8.280
17-Sep-13	307	100	2.031	73.0	10.150	77.0	11.190	70.0	8.860
20-Sep-13	310	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
23-Sep-13	313	200	2.031	12.0	13.370	0.0	0.000	0.0	0.000
25-Sep-13	315	100	2.031	30.0	12.570	27.0	16.570	15.0	10.860
27-Sep-13	317	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
01-Oct-13	321	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
04-Oct-13	324	200	2.031	70.0	12.040	33.0	10.970	33.0	10.970
07-Oct-13	327	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
09-Oct-13	329	100	2.031	25.0	14.830	0.0	0.000	0.0	0.000
10-Oct-13	330	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000

Table D4 Column operation data related to column 1, 2 and 3 using tap water as irrigation water in Yarramundi paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
15-Nov-12	1	2000	0.224	20.0	1.426	46.0	1.537	35.0	1.987
16-Nov-12	2	1000	0.224	915.0	0.566	905.0	0.533	925.0	0.555
19-Nov-12	5	1000	0.224	880.0	0.611	890.0	0.553	1805.0	0.382
05-Dec-12	21	1000	0.224	529.0	0.861	553.0	0.855	445.0	0.373
13-Dec-12	29	300	0.224	0.0	0.000	17.0	0.738	0.0	0.000
17-Dec-12	33	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
20-Dec-12	36	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
24-Dec-12	40	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
29-Dec-12	45	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
01-Jan-13	48	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
07-Jan-13	54	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
09-Jan-13	56	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
14-Jan-13	61	100	0.224	0.0	0.000	65.0	0.000	0.0	0.000
16-Jan-13	63	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
18-Jan-13	65	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
21-Jan-13	68	100	0.224	25.0	0.742	100.0	0.000	0.0	0.000
25-Jan-13	72	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
29-Jan-13	76	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
01-Feb-13	79	100	0.224	15.0	0.679	26.0	0.000	0.0	0.000
04-Feb-13	82	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
08-Feb-13	86	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
12-Feb-13	90	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
15-Feb-13	93	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
18-Feb-13	96	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
23-Feb-13	101	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
27-Feb-13	105	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
01-Mar-13	107	100	0.224	0.0	0.000	35.0	0.000	0.0	0.000
04-Mar-13	110	100	0.224	30.0	0.693	27.0	0.000	0.0	0.000
08-Mar-13	114	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
11-Mar-13	117	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
15-Mar-13	121	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
18-Mar-13	124	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
22-Mar-13	128	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
25-Mar-13	131	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000

Table D4 (Contd.) Column operation data related to column 1, 2 and 3 using tap water as irrigation water in Yarramundi paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
28-Mar-13	134	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
02-Apr-13	139	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
08-Apr-13	145	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
10-Apr-13	147	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
15-Apr-13	152	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
18-Apr-13	155	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
22-Apr-13	159	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
23-Apr-13	160	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
26-Apr-13	163	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
29-Apr-13	166	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
02-May-13	169	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
03-May-13	170	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
06-May-13	173	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
08-May-13	175	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
09-May-13	176	100	0.224	0.0	0.000	27.0	0.878	0.0	0.000
10-May-13	177	100	0.224	0.0	0.000	12.0	0.817	0.0	0.000
13-May-13	180	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
17-May-13	184	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
20-May-13	187	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
21-May-13	188	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
23-May-13	190	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
27-May-13	194	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
28-May-13	195	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
31-May-13	198	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
07-Jun-13	205	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
11-Jun-13	209	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
14-Jun-13	212	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
17-Jun-13	215	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
18-Jun-13	216	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
21-Jun-13	219	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
24-Jun-13	222	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
27-Jun-13	225	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
01-Jul-13	229	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
03-Jul-13	231	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
05-Jul-13	233	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
08-Jul-13	236	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000

Table D4 (Contd.) Column operation data related to column 1, 2 and 3 using tap water as irrigation water in Yarramundi paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
11-Jul-13	239	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
15-Jul-13	243	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
17-Jul-13	245	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
21-Jul-13	249	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
24-Jul-13	252	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
26-Jul-13	254	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
29-Jul-13	257	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
31-Jul-13	259	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
02-Aug-13	261	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
05-Aug-13	264	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
13-Aug-13	272	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
14-Aug-13	273	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
16-Aug-13	275	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
19-Aug-13	278	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
21-Aug-13	280	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
23-Aug-13	282	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
26-Aug-13	285	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
30-Aug-13	289	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
02-Sep-13	292	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
04-Sep-13	294	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
06-Sep-13	296	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
09-Sep-13	299	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
11-Sep-13	301	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
13-Sep-13	303	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
15-Sep-13	305	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
17-Sep-13	307	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
20-Sep-13	310	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
23-Sep-13	313	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
25-Sep-13	315	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
27-Sep-13	317	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
01-Oct-13	321	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
04-Oct-13	324	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
07-Oct-13	327	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000
09-Oct-13	329	100	0.224	0.0	0.000	0.0	0.000	0.0	0.000
10-Oct-13	330	200	0.224	0.0	0.000	0.0	0.000	0.0	0.000

Table D5 Column operation data related to column 1, 2 and 3 using recycled water as irrigation water in Yarramundi paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
15-Nov-12	1	2000	0.806	105.0	1.814	103.0	1.700	21.0	2.450
16-Nov-12	2	1000	0.806	895.0	0.869	910.0	0.847	885.0	0.958
19-Nov-12	5	1000	0.806	880.0	0.965	880.0	0.933	880.0	0.821
05-Dec-12	21	1000	0.806	537.0	1.219	485.0	1.141	449.0	0.926
13-Dec-12	29	300	0.806	0.0	0.000	0.0	0.000	0.0	0.000
17-Dec-12	33	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
20-Dec-12	36	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
24-Dec-12	40	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
29-Dec-12	45	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
01-Jan-13	48	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
07-Jan-13	54	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
09-Jan-13	56	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
14-Jan-13	61	100	0.806	75.0	1.932	0.0	0.000	0.0	0.000
16-Jan-13	63	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
18-Jan-13	65	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
21-Jan-13	68	100	0.806	32.0	1.413	0.0	0.000	0.0	0.000
25-Jan-13	72	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
29-Jan-13	76	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
01-Feb-13	79	100	0.806	22.0	1.416	0.0	0.000	0.0	0.000
04-Feb-13	82	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
08-Feb-13	86	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
12-Feb-13	90	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
15-Feb-13	93	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
18-Feb-13	96	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
23-Feb-13	101	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
27-Feb-13	105	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
01-Mar-13	107	100	0.806	25.0	1.620	0.0	0.000	0.0	0.000
04-Mar-13	110	100	0.806	33.0	1.322	17.0	2.360	0.0	0.000
08-Mar-13	114	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
11-Mar-13	117	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
15-Mar-13	121	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
18-Mar-13	124	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
22-Mar-13	128	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
25-Mar-13	131	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000

Table D5 (Contd.) Column operation data related to column 1, 2 and 3 using recycled water as irrigation water in Yarramundi paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
28-Mar-13	134	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
02-Apr-13	139	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
08-Apr-13	145	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
10-Apr-13	147	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
15-Apr-13	152	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
18-Apr-13	155	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
22-Apr-13	159	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
23-Apr-13	160	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
26-Apr-13	163	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
29-Apr-13	166	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
02-May-13	169	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
03-May-13	170	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
06-May-13	173	200	0.806	38.0	2.520	12.0	4.120	0.0	0.000
08-May-13	175	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
09-May-13	176	100	0.806	50.0	2.340	18.0	4.790	0.0	0.000
10-May-13	177	100	0.806	18.0	2.200	15.0	4.100	0.0	0.000
13-May-13	180	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
17-May-13	184	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
20-May-13	187	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
21-May-13	188	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
23-May-13	190	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
27-May-13	194	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
28-May-13	195	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
31-May-13	198	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
07-Jun-13	205	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
11-Jun-13	209	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
14-Jun-13	212	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
17-Jun-13	215	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
18-Jun-13	216	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
21-Jun-13	219	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
24-Jun-13	222	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
27-Jun-13	225	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
01-Jul-13	229	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
03-Jul-13	231	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
05-Jul-13	233	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
08-Jul-13	236	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000

Table D5 (Contd.) Column operation data related to column 1, 2 and 3 using recycled water as irrigation water in Yarramundi paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
11-Jul-13	239	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
15-Jul-13	243	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
17-Jul-13	245	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
21-Jul-13	249	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
24-Jul-13	252	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
26-Jul-13	254	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
29-Jul-13	257	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
31-Jul-13	259	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
02-Aug-13	261	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
05-Aug-13	264	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
13-Aug-13	272	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
14-Aug-13	273	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
16-Aug-13	275	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
19-Aug-13	278	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
21-Aug-13	280	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
23-Aug-13	282	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
26-Aug-13	285	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
30-Aug-13	289	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
02-Sep-13	292	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
04-Sep-13	294	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
06-Sep-13	296	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
09-Sep-13	299	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
11-Sep-13	301	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
13-Sep-13	303	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
15-Sep-13	305	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
17-Sep-13	307	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
20-Sep-13	310	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
23-Sep-13	313	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
25-Sep-13	315	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
27-Sep-13	317	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
01-Oct-13	321	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
04-Oct-13	324	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
07-Oct-13	327	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000
09-Oct-13	329	100	0.806	0.0	0.000	0.0	0.000	0.0	0.000
10-Oct-13	330	200	0.806	0.0	0.000	0.0	0.000	0.0	0.000

Table D6 Column operation data related to column 1, 2 and 3 using synthetic saline water as irrigation water in Yarramundi paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
15-Nov-12	1	2000	2.003	19.0	3.400	0.0	0.000	0.0	0.000
16-Nov-12	2	1000	2.003	910.0	2.360	890.0	2.370	900.0	2.280
19-Nov-12	5	1000	2.003	870.0	2.230	870.0	2.220	800.0	2.220
05-Dec-12	21	1000	2.003	475.0	2.498	441.0	2.623	451.0	2.613
13-Dec-12	29	300	2.003	0.0	0.000	0.0	0.000	0.0	0.000
17-Dec-12	33	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
20-Dec-12	36	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
24-Dec-12	40	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
29-Dec-12	45	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
01-Jan-13	48	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
07-Jan-13	54	200	2.011	0.0	0.000	0.0	0.000	0.0	0.000
09-Jan-13	56	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
14-Jan-13	61	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
16-Jan-13	63	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
18-Jan-13	65	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
21-Jan-13	68	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
25-Jan-13	72	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
29-Jan-13	76	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
01-Feb-13	79	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
04-Feb-13	82	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
08-Feb-13	86	100	2.011	0.0	0.000	0.0	0.000	0.0	0.000
12-Feb-13	90	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
15-Feb-13	93	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
18-Feb-13	96	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
23-Feb-13	101	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
27-Feb-13	105	100	2.02	0.0	0.000	0.0	0.000	0.0	0.000
01-Mar-13	107	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
04-Mar-13	110	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
08-Mar-13	114	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
11-Mar-13	117	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
15-Mar-13	121	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
18-Mar-13	124	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
22-Mar-13	128	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
25-Mar-13	131	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000

Table D6 (Contd.) Column operation data related to column 1, 2 and 3 using synthetic saline water as irrigation water in Yarramundi paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
28-Mar-13	134	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
02-Apr-13	139	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
08-Apr-13	145	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
10-Apr-13	147	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
15-Apr-13	152	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
18-Apr-13	155	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
22-Apr-13	159	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
23-Apr-13	160	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
26-Apr-13	163	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
29-Apr-13	166	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
02-May-13	169	200	2.018	0.0	0.000	0.0	0.000	0.0	0.000
03-May-13	170	100	2.018	0.0	0.000	0.0	0.000	0.0	0.000
06-May-13	173	200	2.018	12.0	13.400	0.0	0.000	0.0	0.000
08-May-13	175	100	2.018	0.0	0.000	0.0	0.000	30.0	9.420
09-May-13	176	100	2.018	43.0	10.860	0.0	0.000	0.0	0.000
10-May-13	177	100	2.018	26.0	9.820	0.0	0.000	20.0	8.650
13-May-13	180	100	2.018	0.0	0.000	10.0	0.000	0.0	0.000
17-May-13	184	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
20-May-13	187	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
21-May-13	188	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
23-May-13	190	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
27-May-13	194	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
28-May-13	195	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
31-May-13	198	100	2.058	0.0	0.000	0.0	0.000	0.0	0.000
07-Jun-13	205	200	2.003	0.0	0.000	0.0	0.000	0.0	0.000
11-Jun-13	209	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
14-Jun-13	212	200	2.003	0.0	0.000	0.0	0.000	0.0	0.000
17-Jun-13	215	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
18-Jun-13	216	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
21-Jun-13	219	100	2.003	0.0	0.000	0.0	0.000	0.0	0.000
24-Jun-13	222	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
27-Jun-13	225	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
01-Jul-13	229	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
03-Jul-13	231	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
05-Jul-13	233	100	2.028	0.0	0.000	45.0	4.090	0.0	0.000
08-Jul-13	236	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000

Table D6 (Contd.) Column operation data related to column 1, 2 and 3 using synthetic saline water as irrigation water in Yarramundi paddock soil columns

Date	Day	Water added (mL)	ECiw (dS/m)	Column 1		Column 2		Column 3	
				Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)	Leached amount (ml)	EC of leachate (dS/m)
11-Jul-13	239	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
15-Jul-13	243	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
17-Jul-13	245	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
21-Jul-13	249	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
24-Jul-13	252	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
26-Jul-13	254	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
29-Jul-13	257	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
31-Jul-13	259	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
02-Aug-13	261	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
05-Aug-13	264	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
13-Aug-13	272	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
14-Aug-13	273	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
16-Aug-13	275	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
19-Aug-13	278	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
21-Aug-13	280	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
23-Aug-13	282	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
26-Aug-13	285	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
30-Aug-13	289	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
02-Sep-13	292	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
04-Sep-13	294	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
06-Sep-13	296	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
09-Sep-13	299	200	2.028	0.0	0.000	0.0	0.000	0.0	0.000
11-Sep-13	301	100	2.028	0.0	0.000	0.0	0.000	0.0	0.000
13-Sep-13	303	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
15-Sep-13	305	100	2.031	0.0	0.000	0.0	0.000	0.0	0.000
17-Sep-13	307	100	2.031	0.0	0.000	0.0	0.000	0.0	0.000
20-Sep-13	310	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
23-Sep-13	313	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
25-Sep-13	315	100	2.031	0.0	0.000	0.0	0.000	0.0	0.000
27-Sep-13	317	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
01-Oct-13	321	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
04-Oct-13	324	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
07-Oct-13	327	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000
09-Oct-13	329	100	2.031	0.0	0.000	0.0	0.000	0.0	0.000
10-Oct-13	330	200	2.031	0.0	0.000	0.0	0.000	0.0	0.000

Table D7 Parameters measured by sensors at 0.2 m depth in D33 columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
15-Nov-12	1	7.08	0.091	4.59	0.320	15.38	0.320
16-Nov-12	2	18.80	0.130	16.76	0.433	17.48	0.433
17-Nov-12	3	19.72	0.178	17.66	0.514	17.78	0.514
18-Nov-12	4	18.64	0.209	16.80	0.515	17.27	0.515
19-Nov-12	5	17.82	0.239	16.24	0.524	16.99	0.524
20-Nov-12	6	17.38	0.261	16.02	0.534	16.98	0.534
21-Nov-12	7	17.59	0.276	16.03	0.542	16.79	0.542
22-Nov-12	8	17.12	0.296	15.71	0.558	16.67	0.558
23-Nov-12	9	16.92	0.316	15.30	0.573	16.57	0.573
24-Nov-12	10	16.54	0.332	14.99	0.583	16.32	0.583
25-Nov-12	11	16.06	0.342	14.69	0.596	16.23	0.596
26-Nov-12	12	15.84	0.356	14.74	0.609	16.17	0.609
27-Nov-12	13	15.80	0.369	14.81	0.610	15.96	0.610
28-Nov-12	14	15.71	0.373	14.70	0.603	15.95	0.603
29-Nov-12	15	15.53	0.367	14.61	0.586	16.11	0.586
30-Nov-12	16	15.51	0.357	14.49	0.556	15.82	0.556
1-Dec-12	17	15.45	0.346	14.39	0.528	16.00	0.528
2-Dec-12	18	15.37	0.337	14.38	0.508	15.97	0.508
3-Dec-12	19	15.35	0.321	14.42	0.471	15.95	0.471
4-Dec-12	20	15.21	0.298	14.50	0.439	15.87	0.439
5-Dec-12	21	14.83	0.295	14.78	0.473	15.82	0.473
6-Dec-12	22	15.40	0.350	15.01	0.568	15.98	0.568
7-Dec-12	23	15.57	0.353	14.90	0.577	15.85	0.577
8-Dec-12	24	15.47	0.346	14.81	0.578	15.98	0.578
9-Dec-12	25	15.33	0.338	14.79	0.573	15.90	0.573
10-Dec-12	26	15.30	0.318	14.83	0.537	15.95	0.537
11-Dec-12	27	15.30	0.298	14.85	0.495	15.97	0.495
12-Dec-12	28	15.02	0.278	14.77	0.459	15.62	0.459
13-Dec-12	29	14.58	0.273	14.79	0.464	15.41	0.464
14-Dec-12	30	14.36	0.307	14.90	0.545	15.21	0.545
15-Dec-12	31	14.29	0.319	14.95	0.553	14.88	0.553
16-Dec-12	32	14.29	0.323	14.92	0.555	14.84	0.555
17-Dec-12	33	14.40	0.328	14.95	0.560	14.91	0.560
18-Dec-12	34	14.57	0.326	15.04	0.563	15.08	0.563
19-Dec-12	35	14.61	0.324	14.92	0.564	15.06	0.564

Table D7 (Contd.) Parameters measured by sensors at 0.2 m depth in D33 columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
20-Dec-12	36	14.66	0.311	14.95	0.571	15.11	0.571
21-Dec-12	37	14.77	0.328	14.98	0.576	15.15	0.576
22-Dec-12	38	14.72	0.322	14.93	0.569	15.10	0.569
23-Dec-12	39	14.60	0.305	14.83	0.568	15.06	0.568
24-Dec-12	40	14.64	0.307	14.84	0.568	15.14	0.568
25-Dec-12	41	14.77	0.326	14.94	0.585	15.22	0.585
26-Dec-12	42	14.79	0.322	14.96	0.580	15.23	0.580
27-Dec-12	43	14.69	0.291	14.80	0.555	15.22	0.555
28-Dec-12	44	14.59	0.261	14.65	0.515	15.19	0.515
29-Dec-12	45	14.65	0.258	14.78	0.515	15.21	0.515
30-Dec-12	46	14.71	0.288	14.91	0.548	15.19	0.548
31-Dec-12	47	14.62	0.279	14.78	0.535	15.15	0.535
1-Jan-13	48	14.73	0.277	14.85	0.536	15.24	0.536
2-Jan-13	49	14.89	0.287	14.91	0.551	15.29	0.551
3-Jan-13	50	14.85	0.273	14.77	0.528	15.31	0.528
4-Jan-13	51	14.77	0.253	14.64	0.498	15.25	0.498
5-Jan-13	52	14.73	0.235	14.56	0.471	15.16	0.471
6-Jan-13	53	14.62	0.223	14.48	0.455	15.03	0.455
7-Jan-13	54	14.59	0.228	14.72	0.460	15.01	0.460
8-Jan-13	55	14.32	0.253	14.91	0.490	14.84	0.490
9-Jan-13	56	14.35	0.249	14.85	0.501	14.88	0.501
10-Jan-13	57	14.43	0.256	14.92	0.508	14.90	0.508
11-Jan-13	58	14.51	0.249	14.83	0.506	14.81	0.506
12-Jan-13	59	14.51	0.236	14.65	0.488	14.72	0.488
13-Jan-13	60	14.45	0.225	14.52	0.470	14.71	0.470
14-Jan-13	61	14.48	0.224	14.71	0.478	14.75	0.478
15-Jan-13	62	14.43	0.232	14.78	0.486	14.72	0.486
16-Jan-13	63	14.49	0.227	14.84	0.483	14.76	0.483
17-Jan-13	64	14.51	0.233	14.94	0.497	14.79	0.497
18-Jan-13	65	14.46	0.227	14.87	0.489	14.73	0.489
19-Jan-13	66	14.55	0.239	15.06	0.506	14.81	0.506
20-Jan-13	67	14.50	0.238	14.94	0.502	14.77	0.502
21-Jan-13	68	14.52	0.241	15.03	0.503	14.80	0.503
22-Jan-13	69	14.95	0.248	15.12	0.510	15.16	0.510
23-Jan-13	70	15.25	0.246	15.08	0.508	15.43	0.508
24-Jan-13	71	15.15	0.237	14.94	0.488	15.34	0.488

Table D7 (Contd.) Parameters measured by sensors at 0.2 m depth in D33 columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
25-Jan-13	72	15.24	0.238	15.01	0.485	15.53	0.485
26-Jan-13	73	15.48	0.247	15.14	0.504	15.75	0.504
27-Jan-13	74	15.45	0.243	15.11	0.502	15.69	0.502
28-Jan-13	75	15.42	0.239	15.08	0.495	15.60	0.495
29-Jan-13	76	15.41	0.239	15.14	0.496	15.59	0.496
30-Jan-13	77	15.53	0.247	15.26	0.506	15.63	0.506
31-Jan-13	78	15.52	0.243	15.19	0.504	15.61	0.504
1-Feb-13	79	15.32	0.240	15.21	0.501	15.36	0.501
2-Feb-13	80	15.22	0.243	15.38	0.510	15.20	0.510
3-Feb-13	81	15.30	0.242	15.35	0.510	15.24	0.510
4-Feb-13	82	15.25	0.241	15.34	0.509	15.25	0.509
5-Feb-13	83	15.06	0.239	15.43	0.513	15.28	0.513
6-Feb-13	84	15.19	0.241	15.32	0.512	15.29	0.512
7-Feb-13	85	15.25	0.235	15.22	0.496	15.29	0.496
8-Feb-13	86	15.16	0.230	15.12	0.484	15.26	0.484
9-Feb-13	87	15.28	0.238	15.31	0.510	15.46	0.510
10-Feb-13	88	15.30	0.237	15.24	0.504	15.46	0.504
11-Feb-13	89	15.28	0.231	15.15	0.490	15.37	0.490
12-Feb-13	90	15.23	0.227	15.10	0.486	15.43	0.486
13-Feb-13	91	15.33	0.233	15.26	0.514	15.66	0.514
14-Feb-13	92	15.28	0.227	15.12	0.490	15.37	0.490
15-Feb-13	93	15.22	0.222	15.07	0.482	15.38	0.482
16-Feb-13	94	15.42	0.232	15.33	0.515	15.65	0.515
17-Feb-13	95	15.42	0.230	15.27	0.502	15.48	0.502
18-Feb-13	96	15.40	0.228	15.28	0.503	15.58	0.503
19-Feb-13	97	15.38	0.229	15.41	0.514	15.77	0.514
20-Feb-13	98	15.44	0.230	15.35	0.508	15.59	0.508
21-Feb-13	99	15.40	0.225	15.23	0.493	15.38	0.493
22-Feb-13	100	15.30	0.217	15.06	0.472	15.22	0.472
23-Feb-13	101	15.23	0.214	15.02	0.470	15.22	0.470
24-Feb-13	102	15.41	0.226	15.35	0.522	15.57	0.522
25-Feb-13	103	15.49	0.227	15.36	0.517	15.51	0.517
26-Feb-13	104	15.46	0.225	15.28	0.505	15.42	0.505
27-Feb-13	105	15.44	0.222	15.26	0.504	15.46	0.504
28-Feb-13	106	15.49	0.226	15.43	0.534	15.62	0.534
1-Mar-13	107	15.56	0.226	15.49	0.531	15.56	0.531

Table D7 (Contd.) Parameters measured by sensors at 0.2 m depth in D33 columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
2-Mar-13	108	15.53	0.225	15.50	0.546	15.63	0.546
3-Mar-13	109	15.53	0.224	15.37	0.546	15.58	0.546
4-Mar-13	110	15.57	0.225	15.27	0.545	15.58	0.545
5-Mar-13	111	15.50	0.224	15.34	0.541	15.59	0.541
6-Mar-13	112	15.54	0.224	15.43	0.536	15.52	0.536
7-Mar-13	113	15.57	0.224	15.39	0.535	15.49	0.535
8-Mar-13	114	15.59	0.224	15.43	0.529	15.43	0.529
9-Mar-13	115	15.54	0.224	15.40	0.544	15.52	0.544
10-Mar-13	116	15.58	0.225	15.21	0.545	15.51	0.545
11-Mar-13	117	15.59	0.225	15.28	0.543	15.49	0.543
12-Mar-13	118	15.53	0.224	15.28	0.551	15.53	0.551
13-Mar-13	119	15.57	0.224	15.17	0.551	15.52	0.551
14-Mar-13	120	15.59	0.223	15.22	0.539	15.43	0.539
15-Mar-13	121	15.62	0.223	15.16	0.532	15.41	0.532
16-Mar-13	122	15.60	0.224	15.18	0.552	15.57	0.552
17-Mar-13	123	15.64	0.225	15.14	0.555	15.55	0.555
18-Mar-13	124	15.69	0.225	15.28	0.552	15.53	0.552
19-Mar-13	125	15.72	0.226	15.26	0.567	15.61	0.567
20-Mar-13	126	15.64	0.223	15.16	0.540	15.41	0.540
21-Mar-13	127	15.58	0.218	15.03	0.511	15.20	0.511
22-Mar-13	128	15.50	0.214	15.01	0.509	15.15	0.509
23-Mar-13	129	15.57	0.219	15.38	0.549	15.39	0.549
24-Mar-13	130	15.61	0.220	15.25	0.534	15.31	0.534
25-Mar-13	131	15.60	0.218	15.27	0.536	15.34	0.536
26-Mar-13	132	15.58	0.218	15.45	0.566	15.56	0.566
27-Mar-13	133	15.63	0.220	15.31	0.544	15.38	0.544
28-Mar-13	134	15.66	0.220	15.29	0.541	15.36	0.541
29-Mar-13	135	15.71	0.222	15.51	0.571	15.54	0.571
30-Mar-13	136	15.62	0.215	15.28	0.533	15.26	0.533
31-Mar-13	137	15.55	0.210	15.04	0.512	15.09	0.512
1-Apr-13	138	15.46	0.204	14.88	0.492	14.96	0.492
2-Apr-13	139	15.50	0.205	14.93	0.486	14.94	0.486
3-Apr-13	140	15.54	0.206	14.95	0.500	14.96	0.500
4-Apr-13	141	15.42	0.197	14.72	0.464	14.78	0.464
5-Apr-13	142	15.27	0.189	14.57	0.442	14.66	0.442
6-Apr-13	143	15.16	0.182	14.46	0.424	14.55	0.424

Table D7 (Contd.) Parameters measured by sensors at 0.2 m depth in D33 columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
7-Apr-13	144	15.08	0.177	14.37	0.411	14.45	0.411
8-Apr-13	145	15.12	0.178	14.36	0.409	14.44	0.409
9-Apr-13	146	15.42	0.187	14.61	0.435	14.66	0.435
10-Apr-13	147	15.34	0.183	14.53	0.426	14.60	0.426
11-Apr-13	148	15.55	0.191	14.74	0.453	14.76	0.453
12-Apr-13	149	15.29	0.180	14.50	0.425	14.58	0.425
13-Apr-13	150	15.08	0.173	14.30	0.401	14.40	0.401
14-Apr-13	151	14.94	0.168	14.14	0.385	14.27	0.385
15-Apr-13	152	15.04	0.169	14.16	0.388	14.29	0.388
16-Apr-13	153	15.20	0.175	14.31	0.405	14.44	0.405
17-Apr-13	154	15.01	0.167	14.13	0.384	14.29	0.384
18-Apr-13	155	15.00	0.165	14.08	0.380	14.24	0.380
19-Apr-13	156	15.11	0.168	14.23	0.389	14.34	0.389
20-Apr-13	157	14.83	0.156	13.97	0.367	14.12	0.367
21-Apr-13	158	14.68	0.143	13.85	0.356	14.00	0.356
22-Apr-13	159	14.70	0.137	13.79	0.356	13.94	0.356
23-Apr-13	160	14.99	0.146	14.03	0.378	14.18	0.378
24-Apr-13	161	15.05	0.154	14.13	0.388	14.28	0.388
25-Apr-13	162	14.80	0.149	13.92	0.369	14.08	0.369
26-Apr-13	163	14.75	0.140	13.81	0.363	13.99	0.363
27-Apr-13	164	14.78	0.141	13.84	0.367	14.02	0.367
28-Apr-13	165	14.61	0.129	13.70	0.355	13.89	0.355
29-Apr-13	166	14.65	0.126	13.63	0.360	13.63	0.360
30-Apr-13	167	14.65	0.126	13.63	0.360	13.63	0.360
1-May-13	168						
2-May-13	169	15.47	0.118	13.73	0.383	14.83	0.383
3-May-13	170	14.94	0.127	13.72	0.371	14.06	0.371
4-May-13	171	15.79	0.130	14.02	0.432	15.30	0.432
5-May-13	172	15.98	0.143	14.27	0.455	15.51	0.455
6-May-13	173	15.87	0.145	14.18	0.425	15.31	0.425
7-May-13	174	16.04	0.154	14.31	0.463	15.69	0.463
8-May-13	175	16.33	0.169	14.66	0.524	16.08	0.524
9-May-13	176	16.27	0.170	14.55	0.488	15.70	0.488
10-May-13	177	16.43	0.179	14.76	0.551	16.19	0.551
11-May-13	178	16.45	0.188	14.97	0.595	16.42	0.595
12-May-13	179	16.39	0.193	15.16	0.605	16.27	0.605

Table D7 (Contd.) Parameters measured by sensors at 0.2 m depth in D33 columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
13-May-13	180	16.26	0.193	15.04	0.585	16.06	0.585
14-May-13	181	16.33	0.195	15.08	0.579	15.96	0.579
15-May-13	182	16.40	0.198	15.19	0.591	16.04	0.591
16-May-13	183	16.22	0.192	14.86	0.551	15.83	0.551
17-May-13	184	16.13	0.186	14.51	0.494	15.50	0.494
18-May-13	185	16.15	0.186	14.36	0.484	15.41	0.484
19-May-13	186	16.09	0.184	14.38	0.482	15.40	0.482
20-May-13	187	15.81	0.170	14.21	0.456	15.22	0.456
21-May-13	188	15.93	0.175	14.16	0.458	15.21	0.458
22-May-13	189	16.17	0.182	14.28	0.475	15.32	0.475
23-May-13	190	16.25	0.186	14.37	0.491	15.40	0.491
24-May-13	191	16.15	0.181	14.25	0.478	15.29	0.478
25-May-13	192	16.31	0.190	14.36	0.500	15.42	0.500
26-May-13	193	16.04	0.178	14.21	0.473	15.22	0.473
27-May-13	194	15.80	0.168	14.08	0.453	15.06	0.453
28-May-13	195	15.87	0.171	13.98	0.452	15.04	0.452
29-May-13	196	16.19	0.183	14.12	0.478	15.24	0.478
30-May-13	197	16.35	0.191	14.29	0.508	15.42	0.508
31-May-13	198	16.14	0.182	14.21	0.484	15.26	0.484
1-Jun-13	199	16.21	0.185	14.14	0.491	15.28	0.491
2-Jun-13	200	16.26	0.188	14.22	0.499	15.33	0.499
3-Jun-13	201	16.06	0.179	14.15	0.482	15.22	0.482
4-Jun-13	202	16.11	0.179	14.05	0.479	15.17	0.479
5-Jun-13	203	16.20	0.183	14.11	0.492	15.26	0.492
6-Jun-13	204	15.89	0.171	13.94	0.468	15.05	0.468
7-Jun-13	205	15.63	0.163	13.74	0.449	14.83	0.449
8-Jun-13	206	15.61	0.165	13.56	0.445	14.73	0.445
9-Jun-13	207	16.19	0.188	13.91	0.510	15.30	0.510
10-Jun-13	208	16.00	0.180	13.97	0.498	15.24	0.498
11-Jun-13	209	15.88	0.173	13.88	0.489	15.14	0.489
12-Jun-13	210	15.81	0.170	13.77	0.478	15.02	0.478
13-Jun-13	211	15.96	0.176	13.85	0.494	15.12	0.494
14-Jun-13	212	15.73	0.166	13.75	0.477	14.94	0.477
15-Jun-13	213	15.76	0.169	13.63	0.470	14.80	0.470
16-Jun-13	214	16.31	0.190	13.92	0.529	15.25	0.529
17-Jun-13	215	16.07	0.180	13.94	0.512	15.15	0.512

Table D7 (Contd.) Parameters measured by sensors at 0.2 m depth in D33 columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
18-Jun-13	216	16.09	0.179	13.86	0.510	15.10	0.510
19-Jun-13	217	16.18	0.183	13.92	0.522	15.17	0.522
20-Jun-13	218	16.03	0.176	13.81	0.505	15.02	0.505
21-Jun-13	219	16.12	0.180	13.85	0.517	15.08	0.517
22-Jun-13	220	15.94	0.173	13.74	0.501	14.93	0.501
23-Jun-13	221	16.03	0.177	13.79	0.511	15.00	0.511
24-Jun-13	222	15.80	0.168	13.76	0.493	14.84	0.493
25-Jun-13	223	15.78	0.169	13.63	0.488	14.73	0.488
26-Jun-13	224	15.98	0.176	13.69	0.512	14.89	0.512
27-Jun-13	225	15.76	0.168	13.65	0.499	14.80	0.499
28-Jun-13	226	15.89	0.174	13.62	0.504	14.79	0.504
29-Jun-13	227	16.46	0.196	13.96	0.576	15.29	0.576
30-Jun-13	228	16.25	0.190	13.93	0.556	15.19	0.556
1-Jul-13	229	16.04	0.181	13.89	0.538	15.05	0.538
2-Jul-13	230	16.02	0.181	13.77	0.534	15.00	0.534
3-Jul-13	231	16.16	0.187	13.71	0.553	15.06	0.553
4-Jul-13	232	16.07	0.180	13.60	0.537	14.90	0.537
5-Jul-13	233	16.21	0.185	13.72	0.552	14.89	0.552
6-Jul-13	234	15.92	0.178	13.69	0.533	14.75	0.533
7-Jul-13	235	15.66	0.181	13.78	0.544	14.90	0.544
8-Jul-13	236	15.36	0.170	13.74	0.521	14.69	0.521
9-Jul-13	237	15.25	0.169	13.47	0.513	14.43	0.513
10-Jul-13	238	15.30	0.173	13.31	0.528	14.30	0.528
11-Jul-13	239	15.03	0.164	13.21	0.504	14.10	0.504
12-Jul-13	240	14.75	0.158	13.13	0.490	13.78	0.490
13-Jul-13	241	14.74	0.160	13.26	0.507	13.69	0.507
14-Jul-13	242	14.53	0.152	13.16	0.487	13.50	0.487
15-Jul-13	243	14.34	0.141	13.07	0.472	13.32	0.472
16-Jul-13	244	14.70	0.138	13.07	0.476	13.56	0.476
17-Jul-13	245	15.12	0.140	13.24	0.497	13.92	0.497
18-Jul-13	246	15.06	0.137	13.20	0.492	13.79	0.492
19-Jul-13	247	15.19	0.141	13.28	0.513	13.91	0.513
20-Jul-13	248	15.04	0.134	13.23	0.498	13.77	0.498
21-Jul-13	249	14.80	0.125	13.08	0.479	13.57	0.479
22-Jul-13	250	14.59	0.119	12.97	0.469	13.31	0.469
23-Jul-13	251	14.67	0.118	13.01	0.493	13.38	0.493

Table D7 (Contd.) Parameters measured by sensors at 0.2 m depth in D33 columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
24-Jul-13	252	14.42	0.110	12.92	0.471	13.15	0.471
25-Jul-13	253	14.41	0.105	12.86	0.460	13.16	0.460
26-Jul-13	254	14.53	0.103	12.91	0.463	13.26	0.463
27-Jul-13	255	14.41	0.102	12.80	0.455	13.10	0.455
28-Jul-13	256	14.81	0.110	13.01	0.505	13.55	0.505
29-Jul-13	257	14.78	0.107	13.09	0.500	13.49	0.500
30-Jul-13	258	14.71	0.103	12.99	0.496	13.51	0.496
31-Jul-13	259	14.86	0.106	13.01	0.512	13.80	0.512
1-Aug-13	260	14.72	0.104	12.99	0.507	13.58	0.507
2-Aug-13	261	14.74	0.107	13.01	0.519	13.44	0.519
3-Aug-13	262	14.77	0.103	13.02	0.506	13.38	0.506
4-Aug-13	263	15.08	0.103	13.16	0.518	13.80	0.518
5-Aug-13	264	15.04	0.101	13.16	0.514	13.74	0.514
6-Aug-13	265	14.92	0.102	13.09	0.519	13.59	0.519
7-Aug-13	266	15.10	0.114	13.26	0.567	13.84	0.567
8-Aug-13	267	14.93	0.115	13.21	0.554	13.66	0.554
9-Aug-13	268	14.64	0.110	13.08	0.529	13.28	0.529
10-Aug-13	269	14.38	0.100	12.91	0.503	13.02	0.503
11-Aug-13	270	14.05	0.095	12.71	0.480	12.76	0.480
12-Aug-13	271	13.77	0.092	12.55	0.458	12.54	0.458
13-Aug-13	272	13.53	0.091	12.40	0.446	12.40	0.446
14-Aug-13	273	13.48	0.091	12.33	0.450	12.77	0.450
15-Aug-13	274	13.87	0.098	12.56	0.505	13.36	0.505
16-Aug-13	275	14.24	0.107	12.86	0.550	13.38	0.550
17-Aug-13	276	14.27	0.109	12.97	0.555	13.32	0.555
18-Aug-13	277	14.88	0.129	13.44	0.649	13.96	0.649
19-Aug-13	278	14.78	0.127	13.45	0.620	13.87	0.620
20-Aug-13	279	14.91	0.134	13.41	0.654	14.12	0.654
21-Aug-13	280	15.28	0.153	13.64	0.706	14.50	0.706
22-Aug-13	281	15.20	0.153	13.70	0.714	14.62	0.714
23-Aug-13	282	15.66	0.172	14.08	0.773	15.05	0.773
24-Aug-13	283	15.57	0.171	13.79	0.772	14.99	0.772
25-Aug-13	284	16.02	0.186	13.98	0.871	15.82	0.871
26-Aug-13	285	15.84	0.185	13.81	0.842	15.64	0.842
27-Aug-13	286	15.89	0.187	13.85	0.853	15.50	0.853
28-Aug-13	287	16.14	0.198	14.17	0.909	15.70	0.909

Table D7 (Contd.) Parameters measured by sensors at 0.2 m depth in D33 columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
29-Aug-13	288	15.86	0.194	13.92	0.854	15.47	0.854
30-Aug-13	289	15.56	0.186	13.92	0.790	15.23	0.790
31-Aug-13	290	15.76	0.189	14.03	0.800	15.45	0.800
1-Sep-13	291	16.15	0.205	14.38	0.883	15.97	0.883
2-Sep-13	292	15.88	0.201	14.20	0.844	15.58	0.844
3-Sep-13	293	15.97	0.203	14.22	0.852	15.69	0.852
4-Sep-13	294	16.29	0.216	14.51	0.858	15.59	0.858
5-Sep-13	295	16.15	0.215	14.36	0.878	15.88	0.878
6-Sep-13	296	16.40	0.224	14.58	0.886	15.92	0.886
7-Sep-13	297	16.28	0.226	14.39	0.894	16.08	0.894
8-Sep-13	298	16.45	0.233	14.48	0.901	15.99	0.901
9-Sep-13	299	16.28	0.233	14.31	0.885	15.85	0.885
10-Sep-13	300	16.24	0.233	14.25	0.901	16.05	0.901
11-Sep-13	301	16.37	0.236	14.28	0.913	16.12	0.913
12-Sep-13	302	16.19	0.235	14.13	0.914	16.16	0.914
13-Sep-13	303	16.15	0.235	14.18	0.914	16.08	0.914
14-Sep-13	304	16.00	0.231	14.09	0.884	15.94	0.884
15-Sep-13	305	16.47	0.241	14.49	0.988	16.78	0.988
16-Sep-13	306	16.39	0.241	14.35	0.986	16.57	0.986
17-Sep-13	307	16.44	0.241	14.29	0.979	16.18	0.979
18-Sep-13	308	16.21	0.236	14.15	0.981	16.18	0.981
19-Sep-13	309	16.12	0.236	14.19	0.985	16.12	0.985
20-Sep-13	310	15.86	0.227	13.87	0.957	16.01	0.957
21-Sep-13	311	15.81	0.225	13.96	0.922	15.78	0.922
22-Sep-13	312	16.05	0.233	14.31	1.042	16.41	1.042
23-Sep-13	313	15.97	0.231	14.13	1.029	16.27	1.029
24-Sep-13	314	15.94	0.231	14.21	1.063	16.61	1.063
25-Sep-13	315	15.80	0.229	14.33	1.054	16.44	1.054
26-Sep-13	316	15.73	0.225	14.10	1.068	16.66	1.068
27-Sep-13	317	15.71	0.223	14.10	1.068	16.60	1.068
28-Sep-13	318	15.81	0.225	14.17	1.082	16.69	1.082
29-Sep-13	319	15.73	0.226	14.35	1.129	16.95	1.129
30-Sep-13	320	15.68	0.224	14.14	1.101	16.67	1.101
1-Oct-13	321	15.61	0.219	13.95	1.062	16.42	1.062
2-Oct-13	322	15.64	0.220	14.14	1.074	16.57	1.074
3-Oct-13	323	15.59	0.221	14.22	1.133	16.92	1.133

4-Oct-13	324	15.55	0.215	13.86	0.997	15.97	0.997
5-Oct-13	325	15.69	0.221	14.09	1.038	16.22	1.038
6-Oct-13	326	15.60	0.221	14.13	1.134	16.71	1.134
7-Oct-13	327	15.51	0.217	13.95	1.128	16.74	1.128
8-Oct-13	328	15.55	0.219	13.99	1.163	17.04	1.163
9-Oct-13	329	15.47	0.220	14.01	1.208	17.29	1.208
10-Oct-13	330	15.45	0.218	13.92	1.200	17.21	1.200

Table D8 Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
15-Nov-12	1	16.81	0.070	16.46	0.134	14.76	0.405
16-Nov-12	2	16.53	0.069	16.57	0.138	14.95	0.408
17-Nov-12	3	16.71	0.064	16.50	0.141	14.98	0.399
18-Nov-12	4	16.63	0.069	16.28	0.146	14.81	0.399
19-Nov-12	5	16.78	0.072	16.38	0.148	14.84	0.398
20-Nov-12	6	17.18	0.072	16.67	0.150	14.91	0.399
21-Nov-12	7	16.64	0.079	16.48	0.156	14.78	0.400
22-Nov-12	8	16.49	0.085	16.40	0.164	14.72	0.404
23-Nov-12	9	16.92	0.090	16.21	0.167	14.47	0.402
24-Nov-12	10	16.86	0.095	15.91	0.163	13.98	0.390
25-Nov-12	11	16.65	0.101	15.47	0.166	13.66	0.387
26-Nov-12	12	16.46	0.108	15.29	0.172	13.52	0.387
27-Nov-12	13	15.71	0.108	15.16	0.173	13.52	0.387
28-Nov-12	14	15.69	0.102	15.18	0.168	13.56	0.387
29-Nov-12	15	15.67	0.093	15.16	0.159	13.46	0.386
30-Nov-12	16	15.70	0.083	15.30	0.147	13.40	0.382
1-Dec-12	17	15.77	0.075	15.48	0.135	13.43	0.377
2-Dec-12	18	15.76	0.069	15.43	0.127	13.36	0.371
3-Dec-12	19	15.80	0.064	15.62	0.119	13.45	0.362
4-Dec-12	20	15.97	0.061	15.46	0.113	13.39	0.352
5-Dec-12	21	15.85	0.065	15.75	0.132	13.73	0.372
6-Dec-12	22	16.32	0.080	17.25	0.185	15.10	0.460
7-Dec-12	23	16.48	0.075	17.32	0.175	14.94	0.452
8-Dec-12	24	16.51	0.072	17.13	0.164	14.79	0.446
9-Dec-12	25	16.45	0.071	16.88	0.158	14.57	0.440
10-Dec-12	26	16.42	0.071	17.12	0.155	14.56	0.438
11-Dec-12	27	16.56	0.071	17.11	0.150	14.42	0.435
12-Dec-12	28	16.63	0.073	17.18	0.147	14.05	0.432
13-Dec-12	29	16.77	0.078	16.90	0.157	14.05	0.445
14-Dec-12	30	17.11	0.092	17.03	0.194	14.58	0.496
15-Dec-12	31	17.25	0.094	17.00	0.193	14.62	0.503
16-Dec-12	32	17.18	0.097	16.87	0.194	14.56	0.510
17-Dec-12	33	17.11	0.101	16.92	0.195	14.54	0.517
18-Dec-12	34	17.12	0.110	16.96	0.204	14.63	0.534

Table D8 (Contd.) Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
19-Dec-12	35	17.03	0.115	16.93	0.205	14.52	0.537
20-Dec-12	36	16.92	0.122	16.93	0.207	14.48	0.544
21-Dec-12	37	16.94	0.131	16.96	0.214	14.57	0.557
22-Dec-12	38	16.84	0.135	16.94	0.213	14.46	0.557
23-Dec-12	39	16.67	0.139	16.78	0.212	14.31	0.557
24-Dec-12	40	16.67	0.142	16.91	0.211	14.35	0.559
25-Dec-12	41	16.78	0.146	17.08	0.216	14.53	0.569
26-Dec-12	42	16.79	0.147	17.30	0.213	14.48	0.565
27-Dec-12	43	16.67	0.146	17.32	0.208	14.30	0.557
28-Dec-12	44	16.56	0.144	17.34	0.201	14.12	0.549
29-Dec-12	45	16.53	0.143	17.21	0.201	14.14	0.553
30-Dec-12	46	16.51	0.144	17.23	0.206	14.23	0.563
31-Dec-12	47	16.48	0.143	17.37	0.202	14.14	0.558
1-Jan-13	48	16.51	0.144	17.45	0.205	14.19	0.563
2-Jan-13	49	16.53	0.146	17.59	0.208	14.26	0.568
3-Jan-13	50	16.49	0.143	17.74	0.202	14.14	0.560
4-Jan-13	51	16.40	0.140	17.47	0.196	13.97	0.552
5-Jan-13	52	16.47	0.132	16.99	0.190	13.79	0.543
6-Jan-13	53	16.40	0.128	16.50	0.187	13.59	0.534
7-Jan-13	54	16.48	0.132	16.58	0.196	13.80	0.545
8-Jan-13	55	16.52	0.142	17.10	0.211	14.12	0.572
9-Jan-13	56	16.47	0.143	17.21	0.210	14.06	0.573
10-Jan-13	57	16.50	0.147	17.38	0.214	14.18	0.580
11-Jan-13	58	16.46	0.145	17.46	0.209	14.03	0.573
12-Jan-13	59	16.39	0.143	17.23	0.203	13.85	0.567
13-Jan-13	60	16.41	0.138	16.85	0.200	13.74	0.563
14-Jan-13	61	16.45	0.139	17.07	0.203	13.88	0.569
15-Jan-13	62	16.43	0.140	17.14	0.205	13.89	0.572
16-Jan-13	63	16.45	0.142	17.14	0.207	13.92	0.576
17-Jan-13	64	16.37	0.146	17.14	0.210	13.97	0.582
18-Jan-13	65	16.22	0.147	17.04	0.209	13.91	0.582
19-Jan-13	66	16.21	0.152	17.13	0.216	14.05	0.594
20-Jan-13	67	16.14	0.152	17.06	0.213	13.95	0.590
21-Jan-13	68	16.22	0.155	17.16	0.218	14.04	0.597
22-Jan-13	69	17.25	0.159	17.38	0.223	14.09	0.605
23-Jan-13	70	18.07	0.158	17.55	0.219	13.95	0.600

Table D8 (Contd.) Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
24-Jan-13	71	17.90	0.155	17.42	0.214	13.81	0.594
25-Jan-13	72	17.92	0.154	17.48	0.216	13.88	0.600
26-Jan-13	73	17.93	0.154	17.56	0.222	13.98	0.610
27-Jan-13	74	17.85	0.154	17.50	0.220	13.91	0.609
28-Jan-13	75	17.83	0.152	17.51	0.219	13.88	0.607
29-Jan-13	76	17.89	0.156	17.54	0.223	13.94	0.615
30-Jan-13	77	17.86	0.163	17.57	0.231	14.04	0.627
31-Jan-13	78	17.73	0.162	17.49	0.228	13.96	0.623
1-Feb-13	79	17.67	0.163	17.42	0.229	13.94	0.627
2-Feb-13	80	17.72	0.168	17.52	0.235	14.05	0.638
3-Feb-13	81	17.65	0.167	17.51	0.232	14.00	0.635
4-Feb-13	82	17.65	0.169	17.40	0.233	13.98	0.638
5-Feb-13	83	17.79	0.174	17.41	0.241	14.10	0.651
6-Feb-13	84	17.62	0.172	17.31	0.236	14.02	0.646
7-Feb-13	85	17.47	0.168	17.19	0.229	13.91	0.639
8-Feb-13	86	17.58	0.161	17.09	0.227	13.86	0.641
9-Feb-13	87	17.69	0.162	17.20	0.236	14.01	0.656
10-Feb-13	88	17.60	0.161	17.10	0.234	13.93	0.654
11-Feb-13	89	17.59	0.159	17.08	0.230	13.87	0.650
12-Feb-13	90	17.58	0.158	16.93	0.230	13.86	0.653
13-Feb-13	91	17.61	0.163	16.97	0.239	13.96	0.667
14-Feb-13	92	17.56	0.159	16.89	0.232	13.84	0.660
15-Feb-13	93	17.51	0.158	16.66	0.230	13.82	0.661
16-Feb-13	94	17.54	0.163	16.85	0.241	13.96	0.680
17-Feb-13	95	17.50	0.162	16.83	0.238	13.90	0.677
18-Feb-13	96	17.61	0.163	16.83	0.241	13.91	0.685
19-Feb-13	97	17.61	0.169	16.86	0.249	13.99	0.701
20-Feb-13	98	17.53	0.166	16.80	0.245	13.92	0.696
21-Feb-13	99	17.57	0.163	16.63	0.239	13.85	0.691
22-Feb-13	100	17.41	0.159	16.30	0.232	13.75	0.685
23-Feb-13	101	17.31	0.158	16.23	0.231	13.72	0.687
24-Feb-13	102	17.25	0.167	16.64	0.249	13.94	0.718
25-Feb-13	103	17.23	0.167	16.67	0.248	13.91	0.718
26-Feb-13	104	17.15	0.166	16.61	0.245	13.85	0.716
27-Feb-13	105	17.20	0.167	16.56	0.248	13.86	0.723
28-Feb-13	106	17.24	0.173	16.68	0.259	13.97	0.743

Table D8 (Contd.) Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
1-Mar-13	107	17.34	0.174	16.81	0.261	13.96	0.749
2-Mar-13	108	17.44	0.182	16.96	0.269	14.02	0.770
3-Mar-13	109	17.35	0.182	16.96	0.268	13.97	0.765
4-Mar-13	110	17.31	0.184	16.89	0.270	13.98	0.775
5-Mar-13	111	17.37	0.190	16.89	0.279	14.05	0.799
6-Mar-13	112	17.28	0.189	16.86	0.274	13.96	0.787
7-Mar-13	113	17.17	0.185	16.78	0.269	13.92	0.778
8-Mar-13	114	17.19	0.182	16.75	0.269	13.94	0.785
9-Mar-13	115	17.22	0.187	16.82	0.279	14.01	0.808
10-Mar-13	116	17.13	0.186	16.76	0.276	13.95	0.803
11-Mar-13	117	17.15	0.188	16.73	0.278	13.97	0.811
12-Mar-13	118	17.22	0.195	16.78	0.288	14.04	0.838
13-Mar-13	119	17.15	0.192	16.75	0.282	13.94	0.825
14-Mar-13	120	17.03	0.189	16.66	0.277	13.91	0.815
15-Mar-13	121	17.09	0.185	16.62	0.277	13.93	0.822
16-Mar-13	122	17.17	0.190	16.71	0.290	14.03	0.852
17-Mar-13	123	17.13	0.188	16.65	0.287	13.96	0.845
18-Mar-13	124	17.19	0.188	16.66	0.286	13.95	0.848
19-Mar-13	125	17.21	0.192	16.66	0.292	13.96	0.862
20-Mar-13	126	17.17	0.184	16.53	0.282	13.89	0.845
21-Mar-13	127	17.08	0.178	16.12	0.272	13.83	0.834
22-Mar-13	128	16.92	0.176	15.91	0.270	13.82	0.838
23-Mar-13	129	16.89	0.183	16.19	0.284	13.92	0.865
24-Mar-13	130	16.80	0.181	16.13	0.281	13.87	0.861
25-Mar-13	131	16.85	0.182	16.08	0.283	13.87	0.868
26-Mar-13	132	16.89	0.187	16.19	0.294	13.94	0.890
27-Mar-13	133	16.80	0.184	16.13	0.288	13.88	0.881
28-Mar-13	134	16.79	0.184	16.05	0.288	13.89	0.887
29-Mar-13	135	16.86	0.189	16.20	0.299	13.95	0.909
30-Mar-13	136	16.81	0.182	16.03	0.288	13.85	0.891
31-Mar-13	137	16.73	0.178	15.77	0.280	13.80	0.883
1-Apr-13	138	16.62	0.174	15.58	0.272	13.71	0.874
2-Apr-13	139	16.57	0.174	15.60	0.275	13.72	0.883
3-Apr-13	140	16.59	0.175	15.64	0.278	13.76	0.892
4-Apr-13	141	16.48	0.169	15.45	0.268	13.62	0.878
5-Apr-13	142	16.31	0.165	15.28	0.259	13.48	0.865

Table D8 (Contd.) Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
6-Apr-13	143	16.13	0.160	15.12	0.253	13.34	0.853
7-Apr-13	144	15.97	0.156	15.00	0.248	13.25	0.846
8-Apr-13	145	15.82	0.156	14.95	0.251	13.26	0.851
9-Apr-13	146	16.01	0.163	15.17	0.263	13.46	0.881
10-Apr-13	147	15.91	0.161	15.10	0.262	13.43	0.880
11-Apr-13	148	16.07	0.167	15.28	0.273	13.61	0.905
12-Apr-13	149	15.77	0.161	14.96	0.261	13.41	0.886
13-Apr-13	150	15.48	0.155	14.75	0.251	13.24	0.869
14-Apr-13	151	15.21	0.151	14.59	0.245	13.11	0.856
15-Apr-13	152	15.30	0.153	14.69	0.252	13.21	0.871
16-Apr-13	153	15.45	0.157	14.80	0.258	13.32	0.890
17-Apr-13	154	15.15	0.152	14.57	0.248	13.15	0.872
18-Apr-13	155	15.11	0.153	14.60	0.251	13.19	0.881
19-Apr-13	156	15.26	0.155	14.70	0.255	13.27	0.895
20-Apr-13	157	14.82	0.148	14.35	0.241	13.03	0.866
21-Apr-13	158	14.54	0.143	14.18	0.234	12.89	0.850
22-Apr-13	159	14.39	0.143	14.13	0.236	12.89	0.849
23-Apr-13	160	14.96	0.153	14.51	0.255	13.20	0.897
24-Apr-13	161	15.06	0.155	14.55	0.257	13.25	0.911
25-Apr-13	162	14.57	0.148	14.23	0.243	13.01	0.883
26-Apr-13	163	14.49	0.148	14.18	0.244	13.03	0.883
27-Apr-13	164	14.50	0.149	14.16	0.245	13.02	0.886
28-Apr-13	165	14.23	0.145	14.00	0.237	12.88	0.868
29-Apr-13	166	14.34	0.150	14.13	0.252	13.11	0.907
30-Apr-13	167	14.34	0.150	14.13	0.252	13.11	0.907
1-May-13	168						
2-May-13	169	14.62	0.157	14.59	0.272	13.46	0.967
3-May-13	170	14.45	0.153	14.27	0.257	13.18	0.922
4-May-13	171	15.03	0.165	14.81	0.283	13.51	0.983
5-May-13	172	15.27	0.171	15.01	0.294	13.60	1.003
6-May-13	173	15.05	0.165	14.85	0.285	13.50	0.986
7-May-13	174	15.35	0.176	15.08	0.304	13.63	1.027
8-May-13	175	15.78	0.190	15.39	0.327	13.77	1.066
9-May-13	176	15.66	0.187	15.30	0.325	13.78	1.062
10-May-13	177	15.88	0.201	15.46	0.344	13.98	1.110
11-May-13	178	16.04	0.211	15.57	0.357	14.07	1.140

Table D8 (Contd.) Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
12-May-13	179	16.16	0.220	15.63	0.368	14.08	1.159
13-May-13	180	16.14	0.215	15.68	0.364	13.97	1.140
14-May-13	181	16.12	0.217	15.66	0.367	14.02	1.152
15-May-13	182	16.19	0.222	15.70	0.375	14.11	1.177
16-May-13	183	16.05	0.210	15.63	0.359	13.94	1.134
17-May-13	184	15.75	0.197	15.41	0.340	13.81	1.098
18-May-13	185	15.61	0.193	15.16	0.337	13.78	1.100
19-May-13	186	15.55	0.192	15.11	0.336	13.73	1.099
20-May-13	187	15.45	0.183	15.05	0.322	13.52	1.077
21-May-13	188	15.32	0.185	14.93	0.328	13.60	1.096
22-May-13	189	15.43	0.191	14.99	0.340	13.74	1.136
23-May-13	190	15.48	0.195	15.00	0.346	13.81	1.158
24-May-13	191	15.33	0.192	14.91	0.344	13.79	1.159
25-May-13	192	15.43	0.198	14.95	0.352	13.90	1.186
26-May-13	193	15.16	0.190	14.73	0.338	13.70	1.154
27-May-13	194	15.08	0.182	14.71	0.326	13.48	1.133
28-May-13	195	14.90	0.183	14.60	0.330	13.58	1.152
29-May-13	196	15.11	0.194	14.77	0.350	13.93	1.228
30-May-13	197	15.24	0.200	14.87	0.361	14.10	1.270
31-May-13	198	14.99	0.193	14.67	0.349	13.91	1.232
1-Jun-13	199	15.01	0.195	14.71	0.356	14.03	1.267
2-Jun-13	200	15.09	0.199	14.76	0.362	14.09	1.284
3-Jun-13	201	15.02	0.194	14.73	0.355	13.91	1.262
4-Jun-13	202	14.97	0.195	14.64	0.357	13.98	1.279
5-Jun-13	203	15.10	0.201	14.65	0.363	14.10	1.304
6-Jun-13	204	14.79	0.192	14.40	0.348	13.84	1.260
7-Jun-13	205	14.46	0.184	14.17	0.333	13.59	1.225
8-Jun-13	206	14.37	0.186	14.17	0.339	13.70	1.259
9-Jun-13	207	15.18	0.214	14.66	0.381	14.35	1.391
10-Jun-13	208	15.12	0.208	14.61	0.372	14.13	1.355
11-Jun-13	209	14.87	0.203	14.41	0.364	14.02	1.328
12-Jun-13	210	14.77	0.202	14.31	0.362	14.01	1.334
13-Jun-13	211	14.89	0.209	14.37	0.372	14.16	1.365
14-Jun-13	212	14.61	0.200	14.17	0.358	13.87	1.323
15-Jun-13	213	14.64	0.205	14.22	0.368	14.02	1.369
16-Jun-13	214	15.18	0.229	14.59	0.406	14.57	1.477

Table D8 (Contd.) Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
17-Jun-13	215	15.15	0.220	14.53	0.394	14.25	1.430
18-Jun-13	216	15.03	0.222	14.44	0.396	14.35	1.439
19-Jun-13	217	15.07	0.227	14.43	0.401	14.43	1.454
20-Jun-13	218	14.92	0.223	14.31	0.395	14.35	1.441
21-Jun-13	219	14.99	0.228	14.33	0.402	14.44	1.461
22-Jun-13	220	14.87	0.223	14.24	0.396	14.31	1.446
23-Jun-13	221	14.98	0.229	14.30	0.405	14.39	1.467
24-Jun-13	222	14.91	0.221	14.26	0.392	14.06	1.436
25-Jun-13	223	14.74	0.221	14.14	0.393	14.17	1.447
26-Jun-13	224	14.86	0.233	14.24	0.408	14.46	1.491
27-Jun-13	225	14.66	0.224	14.07	0.394	14.22	1.456
28-Jun-13	226	14.85	0.240	14.24	0.418	14.65	1.542
29-Jun-13	227	15.32	0.271	14.57	0.461	15.32	1.670
30-Jun-13	228	15.23	0.262	14.45	0.447	15.04	1.623
1-Jul-13	229	15.26	0.255	14.44	0.436	14.74	1.592
2-Jul-13	230	15.19	0.257	14.36	0.439	14.93	1.603
3-Jul-13	231	15.44	0.266	14.40	0.450	15.05	1.630
4-Jul-13	232	15.42	0.263	14.31	0.445	15.02	1.620
5-Jul-13	233	15.47	0.269	14.30	0.454	15.17	1.641
6-Jul-13	234	15.13	0.264	14.20	0.447	15.15	1.628
7-Jul-13	235	14.88	0.269	14.35	0.453	15.11	1.645
8-Jul-13	236	14.88	0.258	14.36	0.435	14.69	1.608
9-Jul-13	237	14.77	0.258	14.23	0.436	14.93	1.618
10-Jul-13	238	14.86	0.264	14.23	0.444	15.14	1.637
11-Jul-13	239	14.66	0.250	14.06	0.422	14.84	1.596
12-Jul-13	240	14.59	0.246	13.91	0.417	14.77	1.598
13-Jul-13	241	14.62	0.250	13.76	0.423	14.80	1.616
14-Jul-13	242	14.31	0.237	13.59	0.403	14.44	1.576
15-Jul-13	243	14.16	0.226	13.57	0.389	14.04	1.552
16-Jul-13	244	13.90	0.234	13.59	0.403	14.48	1.591
17-Jul-13	245	13.77	0.239	13.65	0.410	14.65	1.611
18-Jul-13	246	13.86	0.241	13.66	0.415	14.74	1.630
19-Jul-13	247	14.07	0.248	13.72	0.423	14.85	1.655
20-Jul-13	248	13.80	0.237	13.56	0.406	14.57	1.622
21-Jul-13	249	13.52	0.226	13.38	0.389	14.23	1.588
22-Jul-13	250	13.63	0.226	13.43	0.390	14.25	1.603

Table D8 (Contd.) Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
23-Jul-13	251	13.71	0.233	13.39	0.398	14.52	1.627
24-Jul-13	252	13.24	0.217	13.12	0.371	14.04	1.569
25-Jul-13	253	13.13	0.215	13.10	0.371	14.16	1.586
26-Jul-13	254	13.06	0.213	13.04	0.365	13.99	1.578
27-Jul-13	255	13.07	0.215	13.11	0.377	14.22	1.623
28-Jul-13	256	13.57	0.235	13.43	0.412	14.84	1.718
29-Jul-13	257	13.43	0.224	13.38	0.396	14.40	1.682
30-Jul-13	258	13.31	0.226	13.27	0.401	14.70	1.695
31-Jul-13	259	13.48	0.233	13.33	0.414	14.95	1.718
1-Aug-13	260	13.33	0.230	13.28	0.415	14.97	1.727
2-Aug-13	261	13.43	0.233	13.25	0.418	14.96	1.737
3-Aug-13	262	13.26	0.227	13.18	0.412	14.85	1.726
4-Aug-13	263	13.32	0.233	13.35	0.424	14.90	1.755
5-Aug-13	264	13.18	0.226	13.28	0.414	14.66	1.741
6-Aug-13	265	13.08	0.226	13.20	0.418	14.89	1.751
7-Aug-13	266	13.07	0.227	13.15	0.420	14.91	1.754
8-Aug-13	267	12.70	0.213	12.91	0.395	14.43	1.696
9-Aug-13	268	12.34	0.198	12.65	0.370	13.87	1.630
10-Aug-13	269	11.86	0.183	12.40	0.346	13.29	1.556
11-Aug-13	270	11.43	0.167	12.11	0.321	12.86	1.490
12-Aug-13	271	11.15	0.154	11.91	0.302	12.52	1.434
13-Aug-13	272	10.87	0.146	11.67	0.289	12.38	1.389
14-Aug-13	273	10.81	0.146	11.80	0.305	12.88	1.464
15-Aug-13	274	11.23	0.169	12.24	0.349	13.66	1.586
16-Aug-13	275	11.31	0.175	12.21	0.349	13.52	1.578
17-Aug-13	276	11.23	0.172	12.19	0.348	13.52	1.584
18-Aug-13	277	11.91	0.203	12.60	0.392	14.28	1.690
19-Aug-13	278	11.70	0.193	12.46	0.375	13.90	1.653
20-Aug-13	279	11.62	0.194	12.44	0.377	14.03	1.657
21-Aug-13	280	11.66	0.197	12.46	0.376	13.92	1.646
22-Aug-13	281	11.46	0.189	12.34	0.366	13.75	1.627
23-Aug-13	282	11.48	0.191	12.32	0.365	13.67	1.621
24-Aug-13	283	11.23	0.183	12.15	0.353	13.49	1.598
25-Aug-13	284	11.31	0.191	12.21	0.363	13.60	1.616
26-Aug-13	285	11.14	0.181	12.07	0.346	13.22	1.574
27-Aug-13	286	11.11	0.178	12.01	0.343	13.30	1.578

Table D8 (Contd.) Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
28-Aug-13	287	11.34	0.186	12.08	0.352	13.46	1.599
29-Aug-13	288	11.09	0.176	11.83	0.329	13.04	1.538
30-Aug-13	289	10.87	0.165	11.58	0.308	12.64	1.471
31-Aug-13	290	10.88	0.167	11.64	0.319	13.14	1.522
1-Sep-13	291	11.36	0.192	12.01	0.355	13.76	1.632
2-Sep-13	292	11.21	0.184	11.86	0.338	13.36	1.589
3-Sep-13	293	11.10	0.182	11.82	0.339	13.49	1.597
4-Sep-13	294	11.24	0.191	11.90	0.348	13.59	1.616
5-Sep-13	295	11.09	0.184	11.79	0.340	13.53	1.604
6-Sep-13	296	11.29	0.196	11.91	0.353	13.78	1.639
7-Sep-13	297	11.15	0.190	11.80	0.344	13.71	1.627
8-Sep-13	298	11.38	0.202	11.95	0.360	13.99	1.669
9-Sep-13	299	11.20	0.193	11.83	0.345	13.62	1.632
10-Sep-13	300	11.16	0.193	11.81	0.346	13.79	1.649
11-Sep-13	301	11.39	0.207	11.92	0.359	14.07	1.686
12-Sep-13	302	11.23	0.197	11.77	0.343	13.62	1.641
13-Sep-13	303	11.36	0.206	11.80	0.351	13.51	1.637
14-Sep-13	304	11.19	0.196	11.67	0.337	13.18	1.605
15-Sep-13	305	11.34	0.207	11.86	0.354	13.42	1.642
16-Sep-13	306	11.31	0.205	11.86	0.354	13.54	1.664
17-Sep-13	307	11.64	0.224	12.08	0.377	13.94	1.728
18-Sep-13	308	11.53	0.221	12.00	0.372	14.04	1.735
19-Sep-13	309	11.71	0.234	12.05	0.380	14.20	1.761
20-Sep-13	310	11.41	0.217	11.77	0.352	13.54	1.681
21-Sep-13	311	11.21	0.205	11.63	0.338	13.24	1.637
22-Sep-13	312	11.38	0.215	11.78	0.353	13.41	1.670
23-Sep-13	313	11.25	0.208	11.66	0.342	13.21	1.641
24-Sep-13	314	11.19	0.211	11.67	0.349	13.52	1.676
25-Sep-13	315	11.23	0.217	11.67	0.352	13.53	1.678
26-Sep-13	316	11.07	0.209	11.56	0.342	13.48	1.667
27-Sep-13	317	11.15	0.215	11.61	0.349	13.52	1.678
28-Sep-13	318	11.25	0.222	11.75	0.365	14.06	1.754
29-Sep-13	319	11.55	0.244	12.01	0.393	14.60	1.844
30-Sep-13	320	11.37	0.234	11.88	0.381	14.34	1.813
1-Oct-13	321	11.17	0.224	11.70	0.363	13.86	1.751
2-Oct-13	322	11.08	0.219	11.64	0.358	13.84	1.743

Table D8 (Contd.) Parameters measured by sensors at 0.2 m depth in Yarramundi columns

Date	Day	Tap water		Recycled water		Synthetic saline water	
		Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)	Permittivity	EC_{bulk} (dS/m)
3-Oct-13	323	11.09	0.223	11.61	0.355	13.65	1.726
4-Oct-13	324	10.83	0.206	11.37	0.328	12.94	1.621
5-Oct-13	325	11.00	0.216	11.56	0.351	13.61	1.718
6-Oct-13	326	11.26	0.235	11.75	0.372	13.90	1.780
7-Oct-13	327	11.10	0.227	11.62	0.361	13.74	1.748
8-Oct-13	328	11.09	0.229	11.64	0.366	14.42	1.836
9-Oct-13	329	11.17	0.236	11.64	0.369	14.83	1.898
10-Oct-13	330	11.05	0.229	11.58	0.363	14.76	1.896

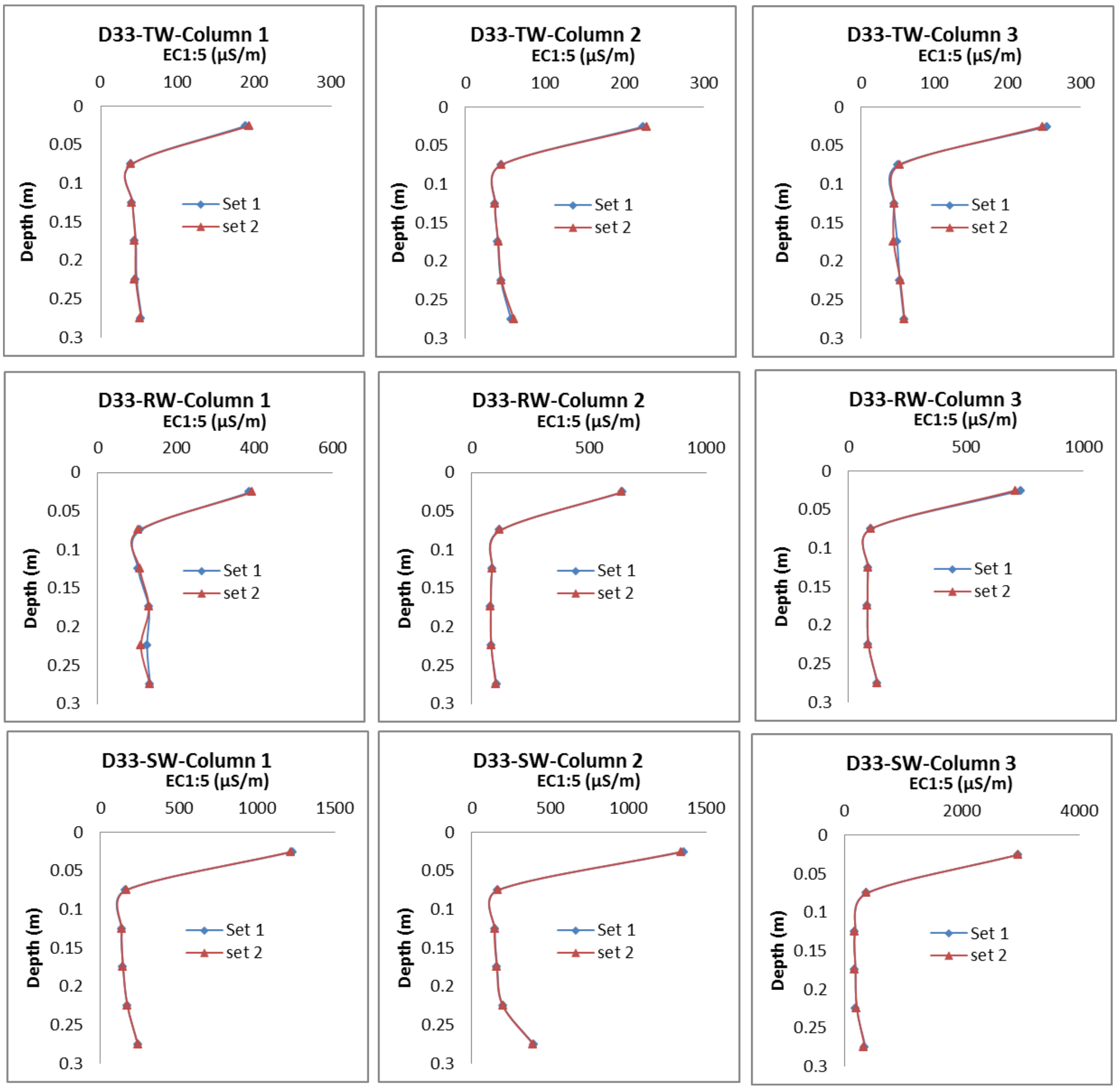

Figure D.1 Salinity profile in all 9 columns of D33 paddock soil in terms of $EC_{1:5}$ using tap water (TW), recycled water (RW) and synthetic saline water (SW)

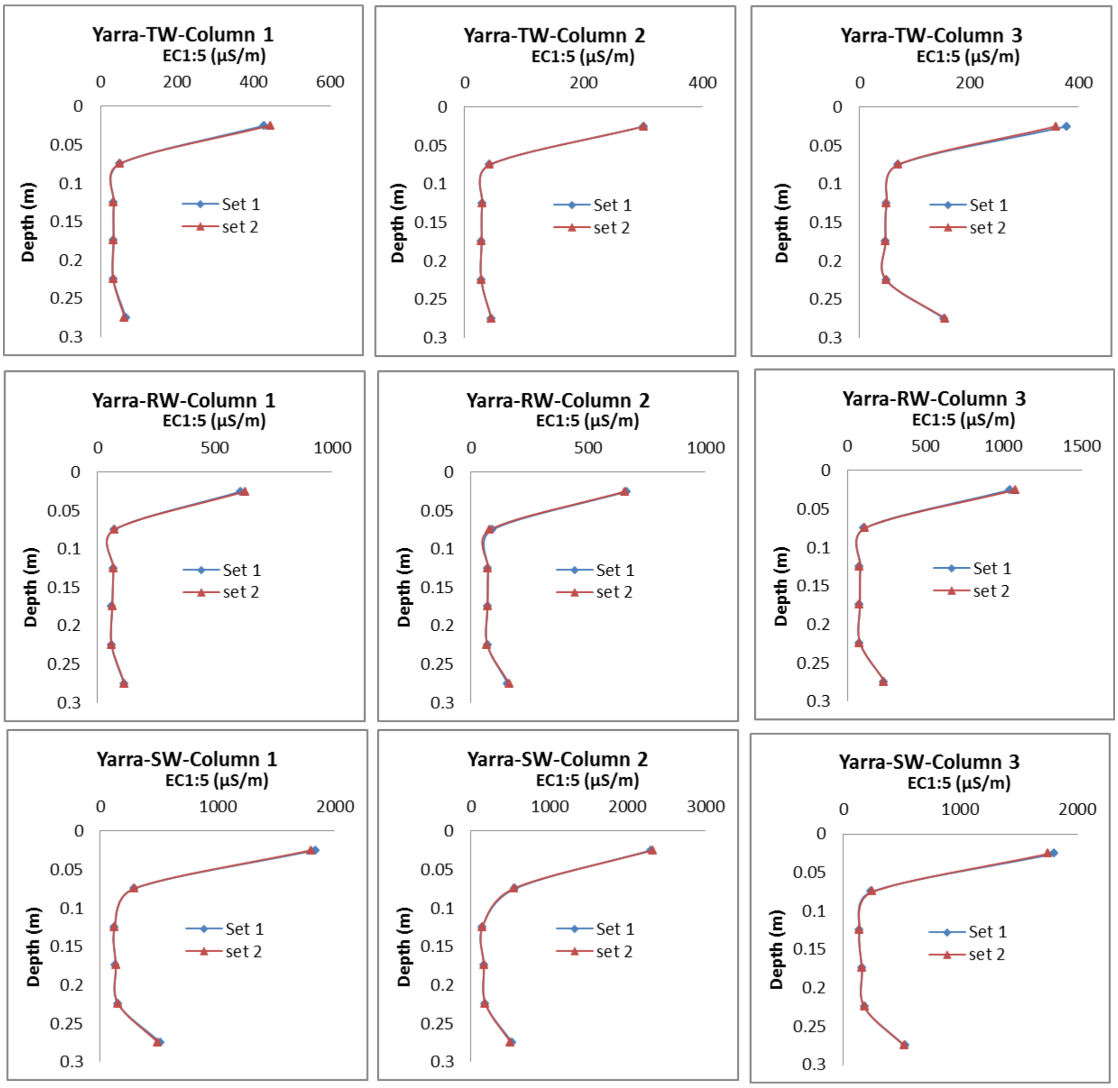

Figure D.2 Salinity profile in all 9 columns of Yarramundi paddock soil in terms of $EC_{1:5}$ using tap water (TW), recycled water (RW) and synthetic saline water (SW)

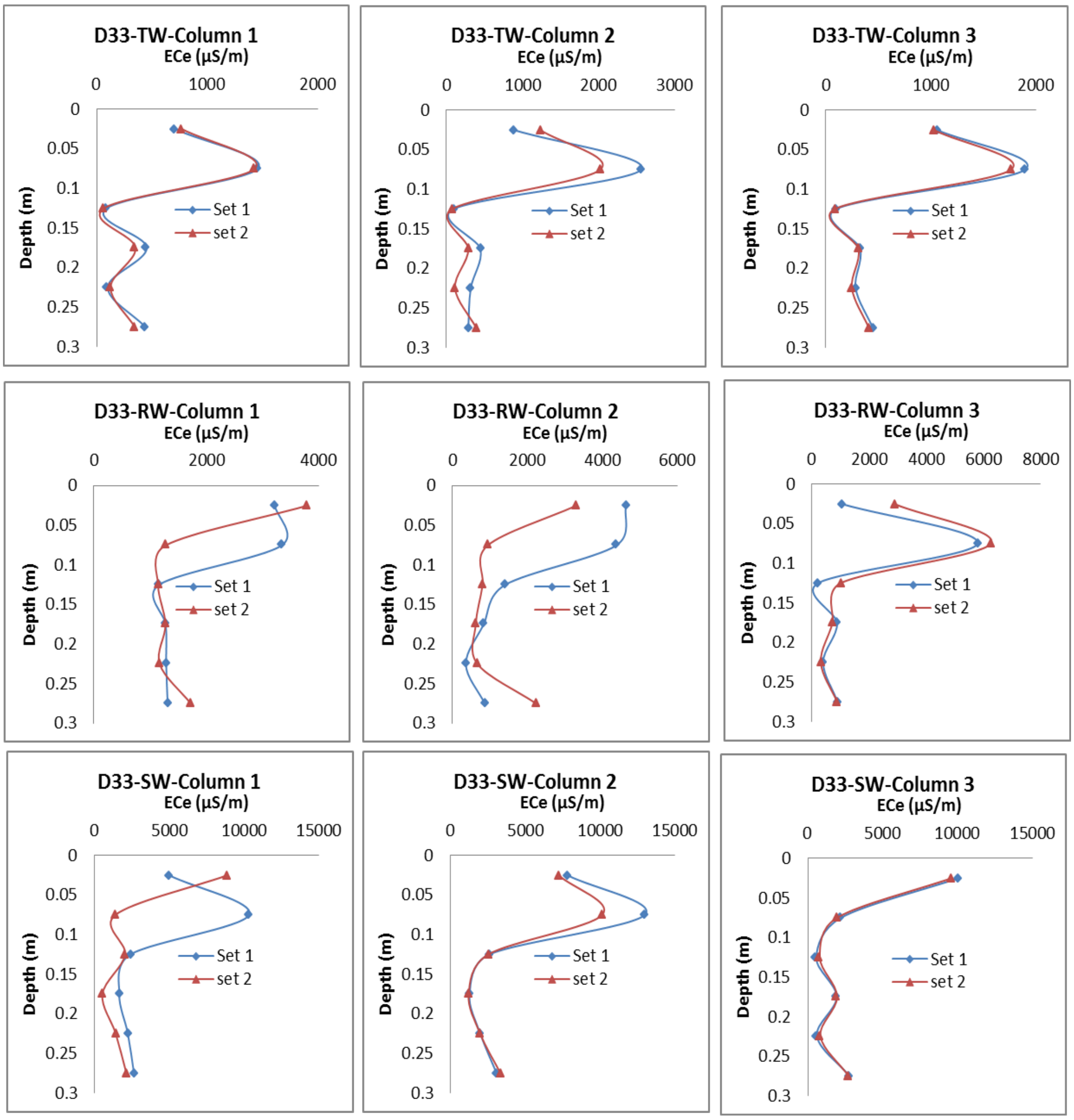

Figure D.3 Salinity profile in all 9 columns of D33 paddock soil in terms of EC_e using tap water (TW), recycled water (RW) and synthetic saline water (SW)

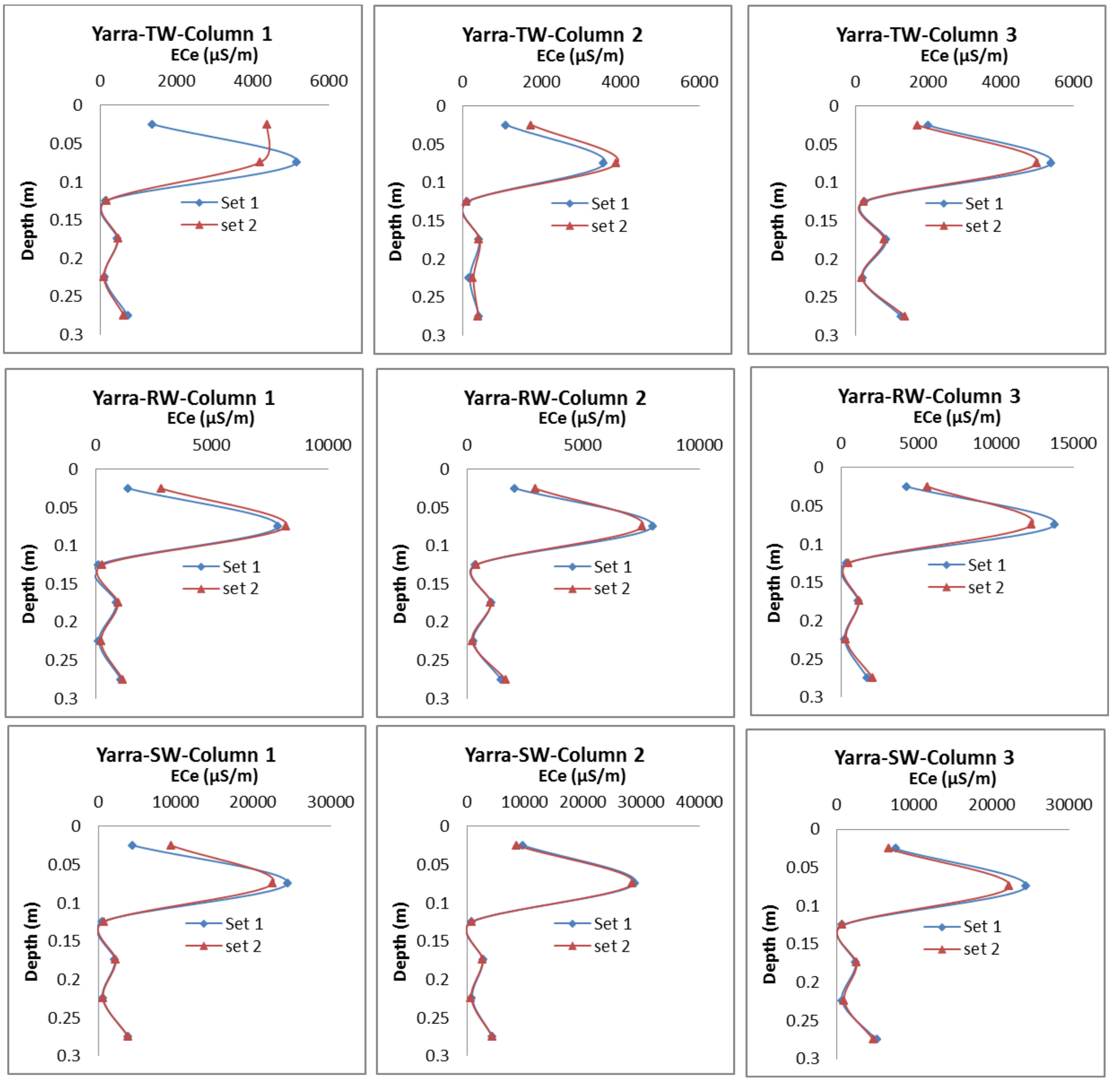

Figure D.4 Salinity profile in all 9 columns of Yarramundi paddock soil in terms of EC_e using tap water (TW), recycled water (RW) and synthetic saline water (SW)

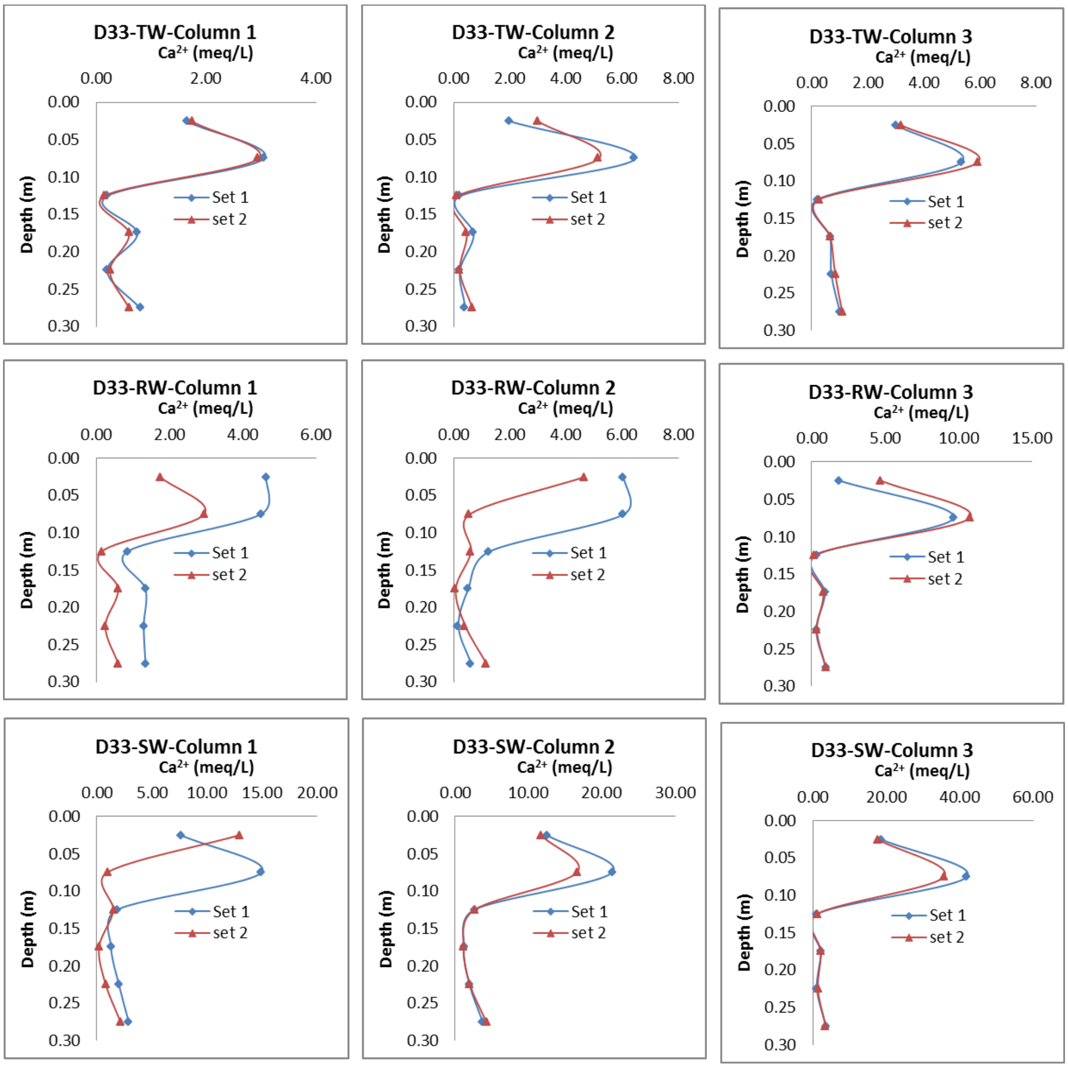

Figure D.5 Soluble Ca^{2+} profile in all 9 columns of D33 paddock soil in terms of using tap water (TW), recycled water (RW) and synthetic saline water (SW)

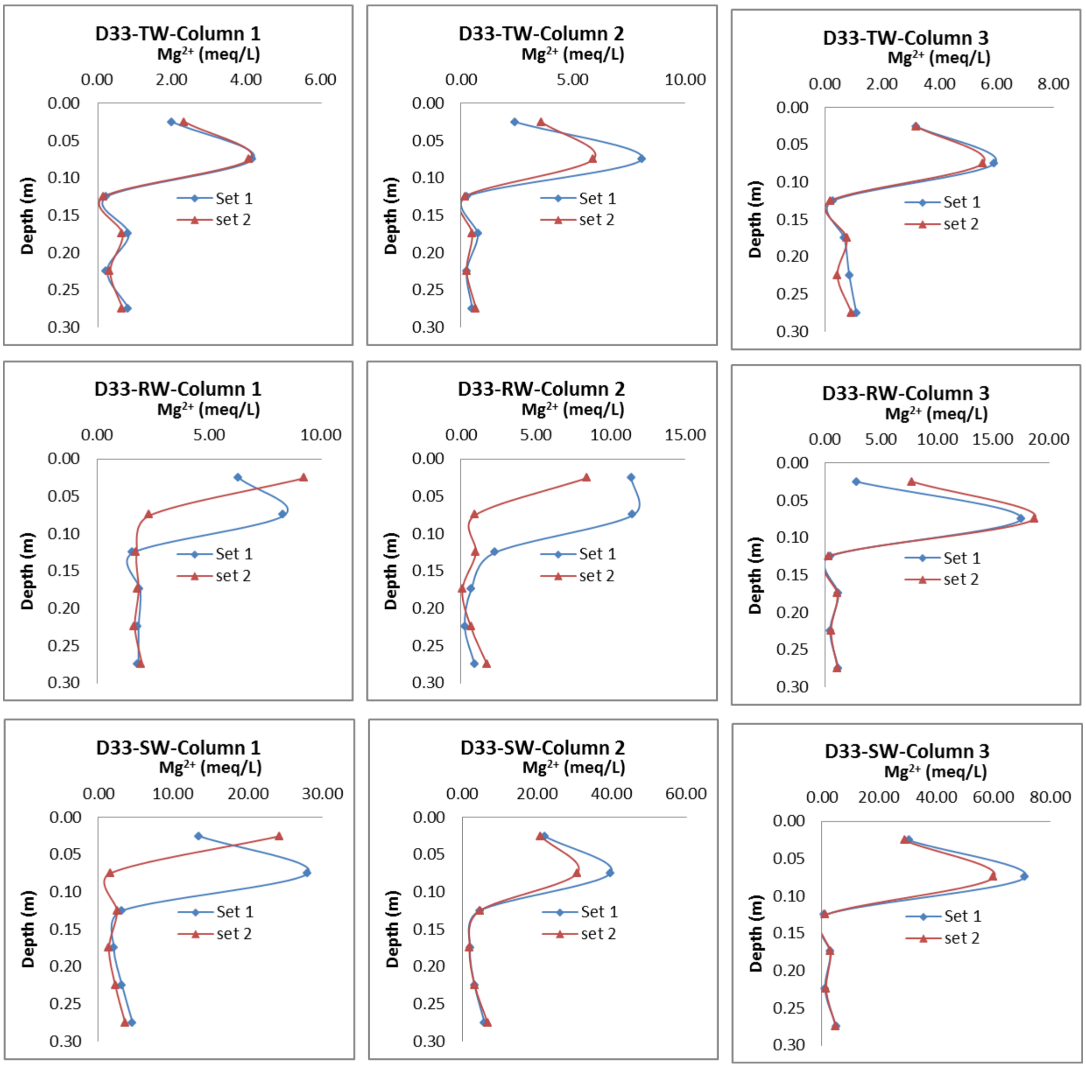

Figure D.6 Soluble Mg^{2+} profile in all 9 columns of D33 paddock soil in terms of using tap water (TW), recycled water (RW) and synthetic saline water (SW)

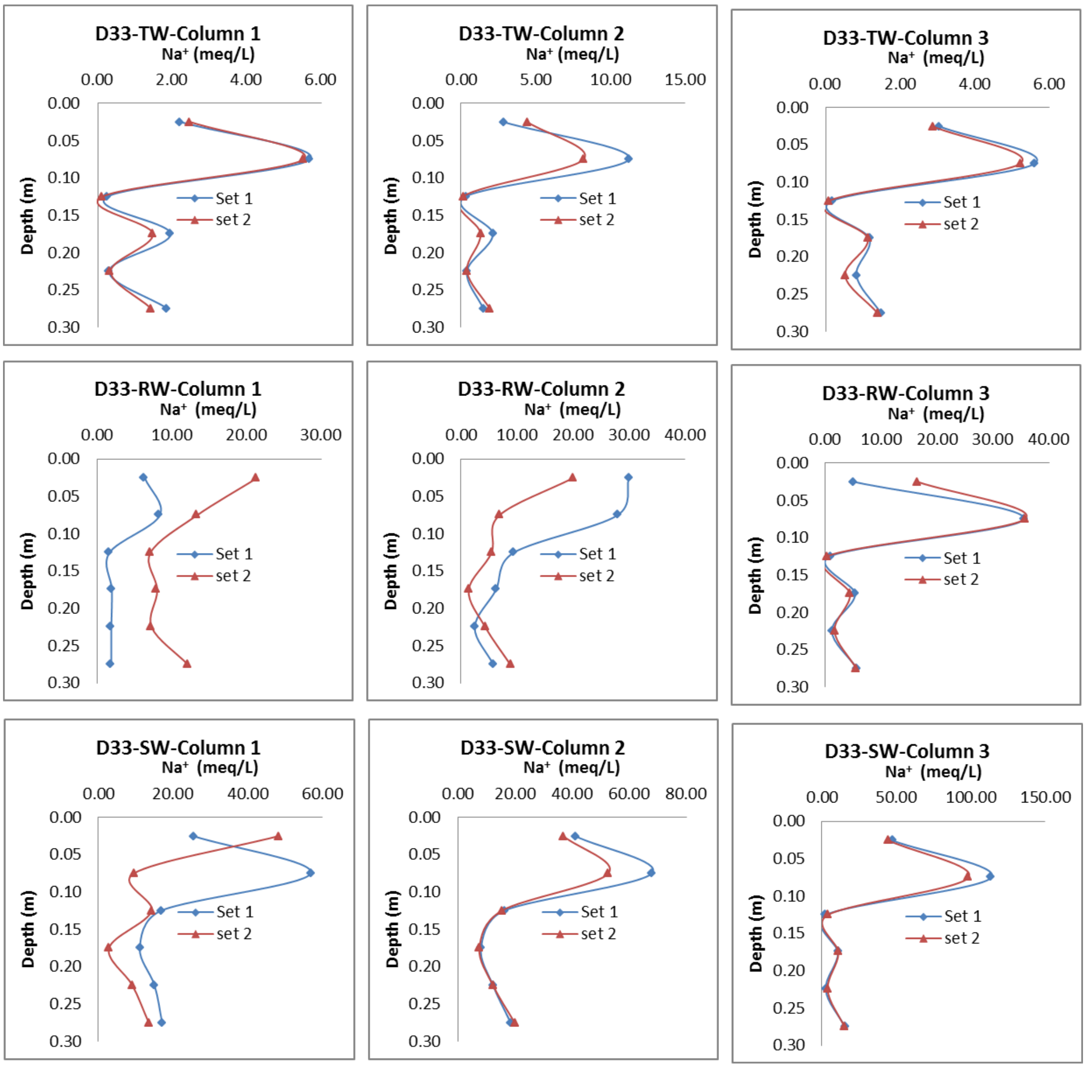

Figure D.7 Soluble Na^+ profile in all 9 columns of D33 paddock soil in terms of using tap water (TW), recycled water (RW) and synthetic saline water (SW)

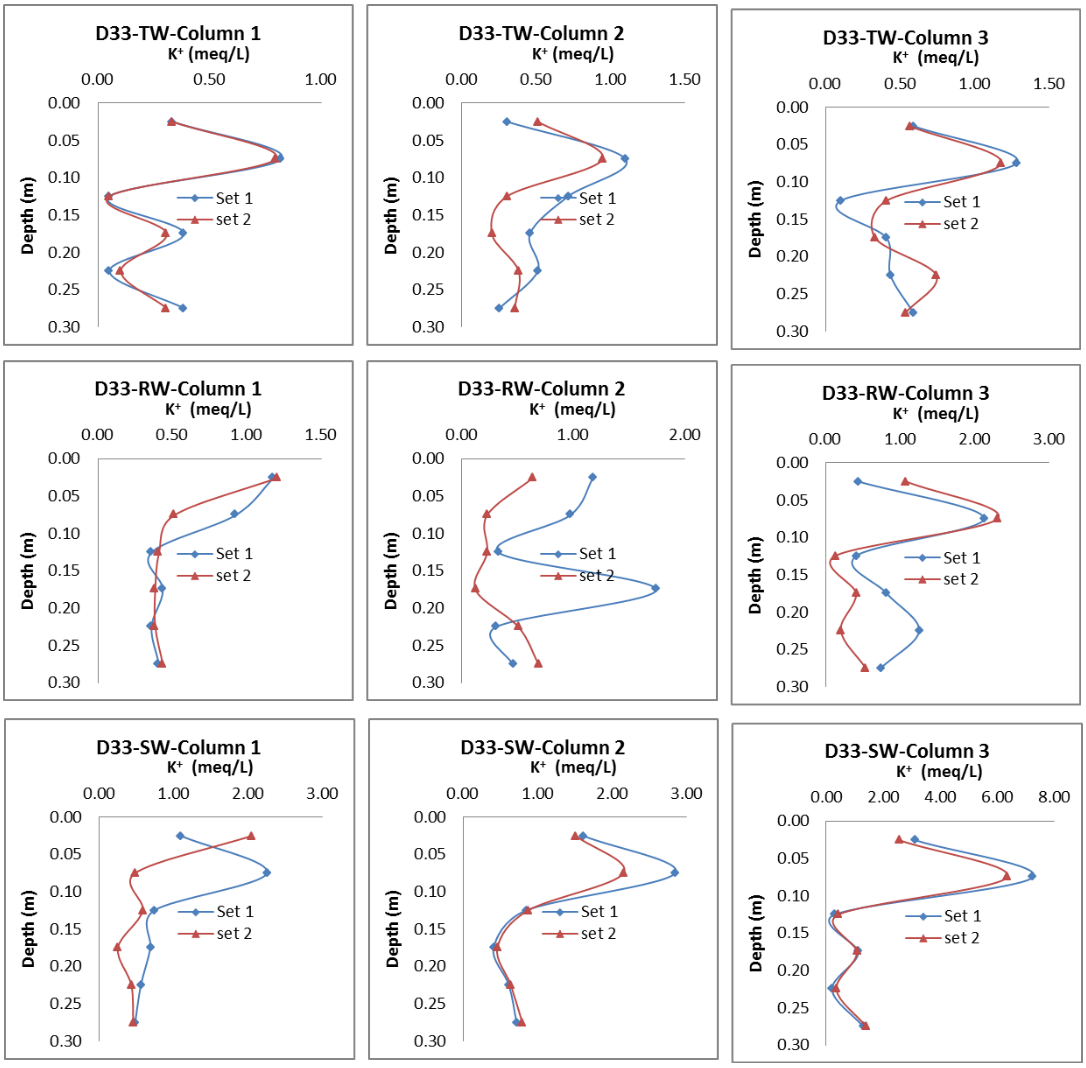

Figure D.8 Soluble K^+ profile in all 9 columns of D33 paddock soil in terms of using tap water (TW), recycled water (RW) and synthetic saline water (SW)

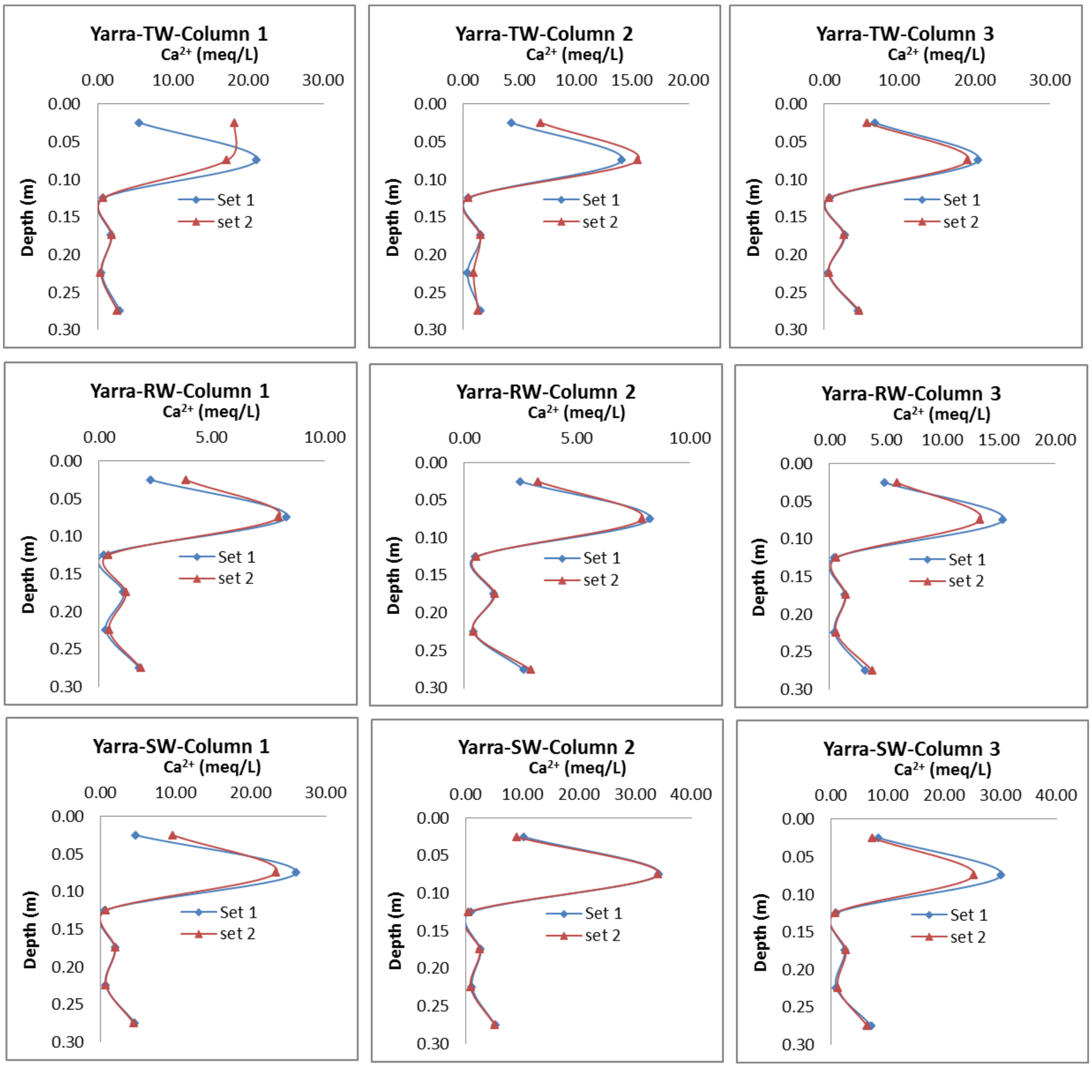

Figure D.9 Soluble Ca^{2+} profile in all 9 columns of Yarramundi paddock soil in terms of using tap water (TW), recycled water (RW) and synthetic saline water (SW)

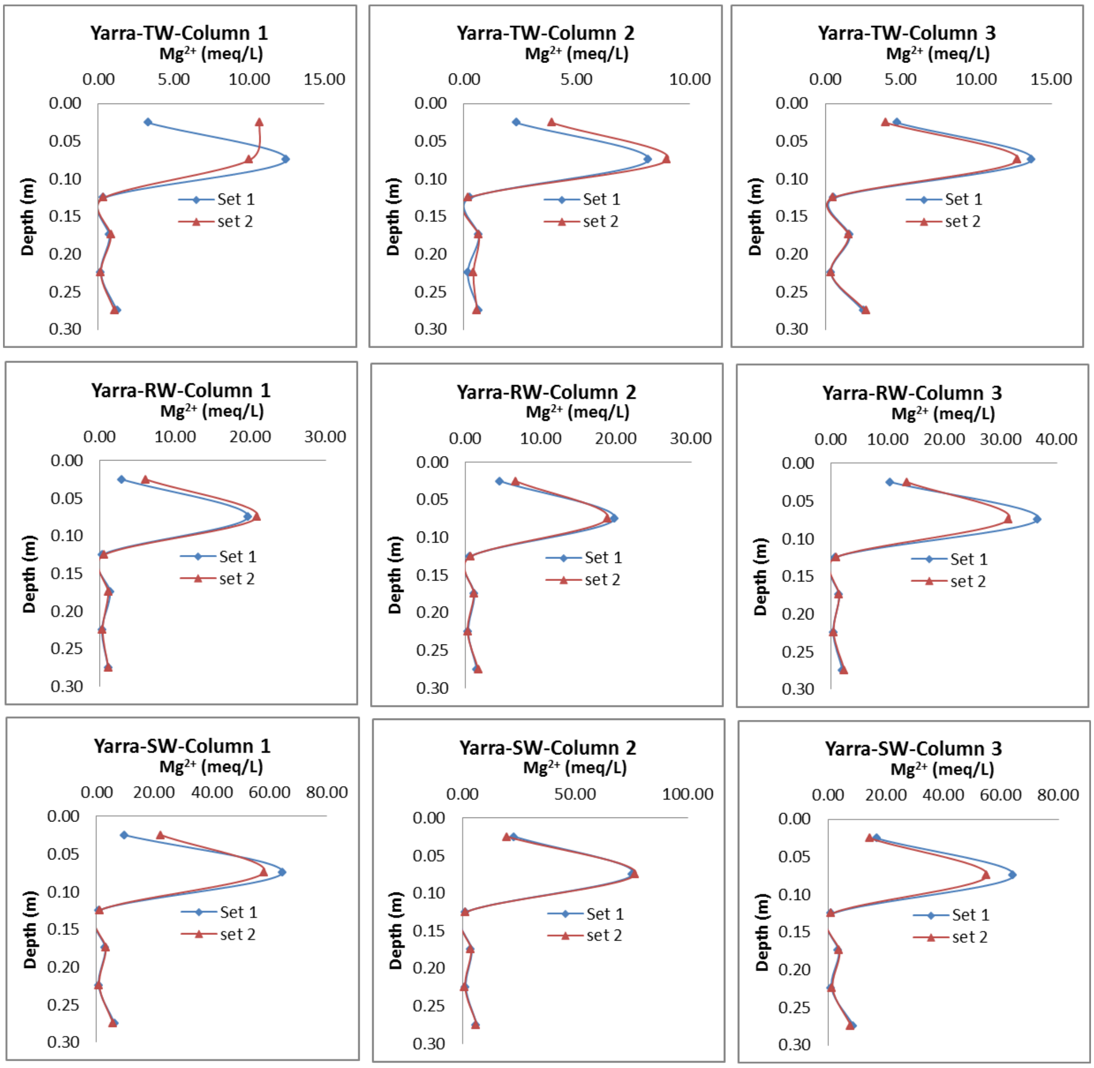

Figure D.10 Soluble Mg^{2+} profile in all 9 columns of Yarramundi paddock soil in terms of using tap water (TW), recycled water (RW) and synthetic saline water (SW)

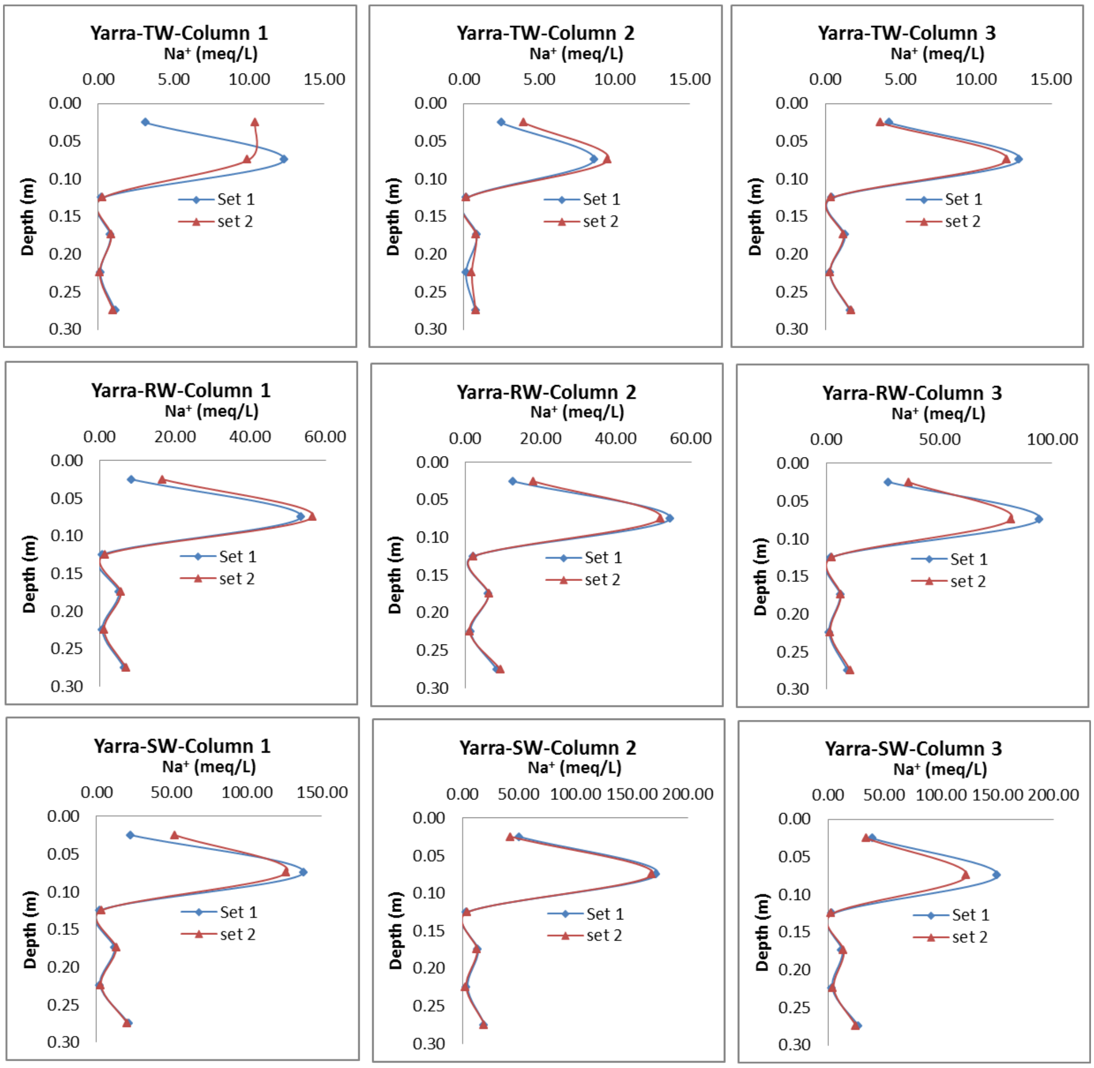

Figure D.11 Soluble Na^+ profile in all 9 columns of Yarramundi paddock soil in terms of using tap water (TW), recycled water (RW) and synthetic saline water (SW)

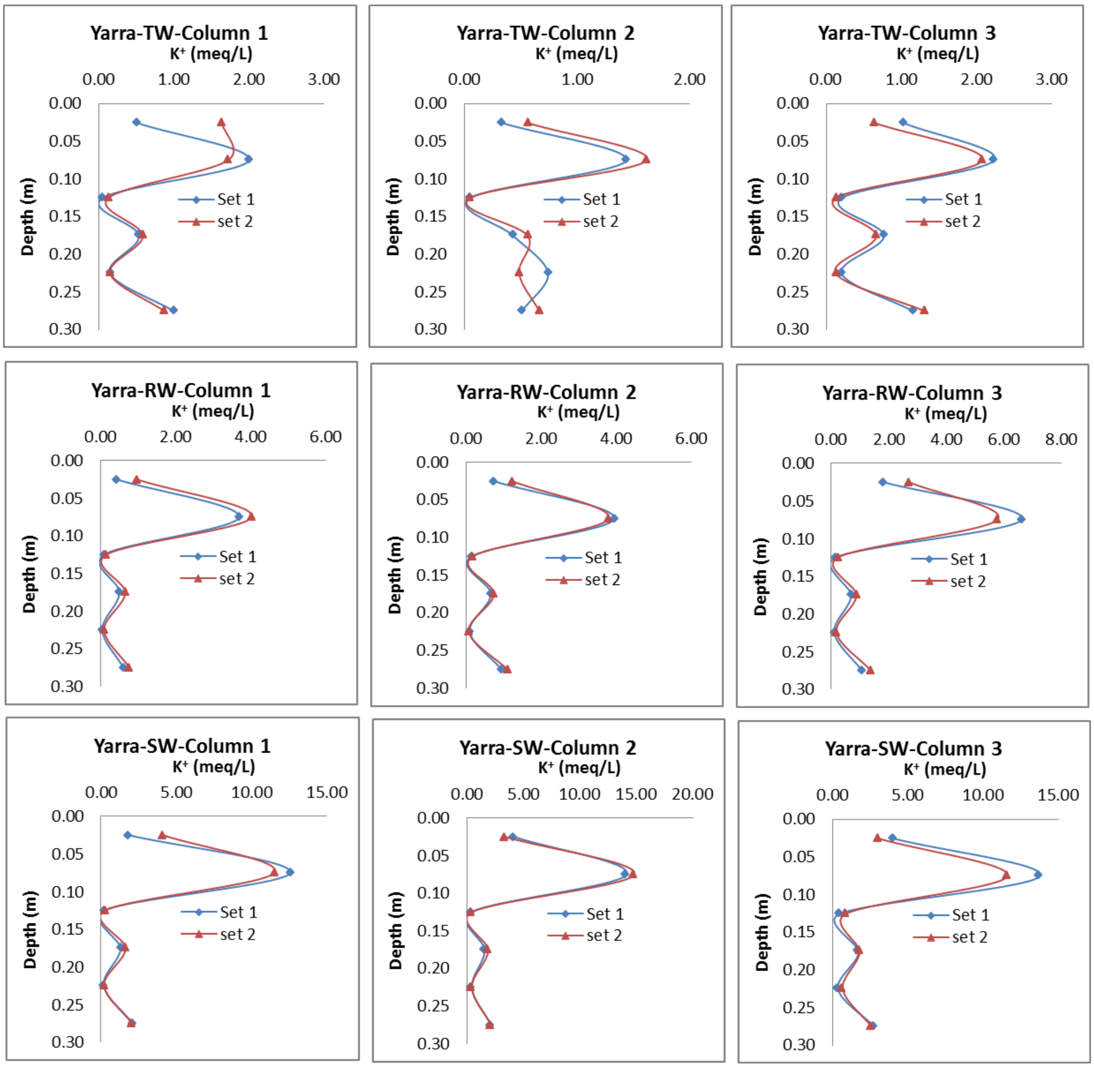

Figure D.12 Soluble K^+ profile in all 9 columns of Yarramundi paddock soil in terms of using tap water (TW), recycled water (RW) and synthetic saline water (SW)

APPENDIX E: ADDITIONAL DATA RELATED TO CHAPTER 9

Table E1 Data Sheet for textural classification of soil from Greygums oval

Sample ID	Time (min)	Hydrometer Reading (g/l) Rt	Average Hydrometer reading at 5 min. Rt5	Average Hydrometer reading at 90 min. Rt90	Blank Reading at 5 min (g/l) Ro	Blank Reading at 90 min (g/l) Ro	Blank Temp at 5 min T Deg Cel	Blank Temp at 90 min T Deg Cel	Temperature Correction at 5 min T5 oC=[T-19.5]*0.3	Temperature Correction at 90 min T90 oC=[T-19.5]*0.3	Corrected Hydrometer Reading at 5 min Ct5=(Rt5-Ro) + T5 oC	Corrected Hydrometer Reading at 90 min Ct90=(Rt90-Ro) + T90 oC	Summation Percentage P1 at 5 min = (Ct5/Wt of soil)*100	Summation Percentage P2 at 90 min = (Ct90/Wt of soil)*100
GG-1	5	13	13.5	8.75	2	2	23.5	23.5	1.2	1.2	12.7	7.95	25.4	15.9
	90	8.5												
GG-2	5	14												
	90	9												

Rt5 = Represents the silt and clay fraction suspended in the sample
Rt90 = Represents the clay fraction suspended in the sample

Sand = 74.6 % 100- P1 = % Sand
Silt = 9.5 % P1-P2 = % Silt
Clay = 15.9 % P2 = % Clay; Soil Textural Classification: Sandy loam

Table E2 Calculation of moisture content at field condition of Greygums oval

ID	Wt of container, W1 (gm)	Wt of Crucible + wet soil, W2 (gm)	Wt of Crucible + dry soil, W3 (gm)	Wt of moisture, W4 =(W2-W1)-(W3-W1) (gm)	Air dry moisture content (g/g)	Average (g/g)	Air dry moisture content (%)	Average (%)
0 to 0.25 m-1	12.32	203.8	172.18	31.62	0.198	0.196	19.78	19.56
0 to 0.25 m-2	12.31	203.55	172.55	31	0.193		19.35	
0.25 to 0.35 m-1	12.33	327.69	296.73	30.96	0.109	0.109	10.89	10.89
0.25 to 0.35 m-2	12.32	327.35	296.53	30.82	0.108		8.76	

Table E3 Calculation of bulk density at field condition of Greygums oval

Site	Air dry soil (g)	Volume of ring (cm^3)	Bulk density (g/cm^3)	Average bulk density (g/cm^3)
0 to 0.25 m-1	159.86	209.79	0.762	0.763
0 to 0.25 m-2	160.24	209.79	0.764	
0.25 to 0.35 m-1	284.4	209.79	1.356	1.355
0.25 to 0.35 m-2	284.21	209.79	1.355	

Table E4 Determination of $pH_{1:5}$ and $EC_{1:5}$ for soil from Greygums oval

Sample ID	pH 1:5	Avg. pH 1:5	EC 1:5	Avg. EC 1:5 (uS/cm)
GG-1	7.51	7.55	341	352
GG-2	7.56		356	
GG-3	7.57		358	

Table E5 Determination of pH_{SE} and EC_e for soil from Greygums oval

Sample ID	pH_{SE}	Avg. pH_{SE}	EC_e (uS/cm)	Avg. EC_e (uS/cm)
GG-1	8.00	8.12	2680	2650
GG-2	8.04		2750	
GG-3	8.19		2540	
GG-4	8.23		2630	