THE IMPACT OF SUBSURFACE DRAINAGE DESIGN AND MANAGEMENT ON SALINITY AND IRRIGATION WATER USE IN A SEMI-ARID ENVIRONMENT

John Wesley Hornbuckle

BE (Hons Class 1) (Environmental Engineering) (University of New England)

A thesis submitted for the degree of Doctor of Philosophy of the University of New England.

September 2003

ABSTRACT

Irrigated agriculture depends upon the provision of adequate drainage to maintain a rootzone salt balance that prevents damage to crops. While in some cases natural drainage rates can provide an adequate level of drainage, in many irrigated areas artificial subsurface drainage is required. A major problem limiting the use of subsurface drainage systems relates to the generation and disposal of saline drainage effluent. To overcome this problem alternative methodologies in subsurface drainage design and management are required.

Two alternative approaches were investigated for reducing salt loads from subsurface horizontal (tile) drainage systems. These were modification of the drainage design to reduce salt mobilization from below the rootzone and active management of the drainage system to reduce drainage discharge and hence salt loads.

Investigations into new subsurface drainage designs led to the development of a multi-level drainage strategy that utilized a series of closely spaced shallow drains underlain by widely spaced deeper drains. The use of such systems was tested using mathematical techniques and field trials. Options for drainage management were found to be by preventing discharge completely for certain periods, e.g. turning pumps off, or by restricting drainage using flow limiting devices. The use of weirs at the end of drain laterals to restrict flows was investigated as the best option to reduce discharge whilst promoting uptake of shallow saline groundwater by the plant and reducing non-beneficial leaching of salt from below the active rootzone. Both field trials were undertaken over two years in irrigated vineyards in the Murrumbidgee Irrigation Area

Mathematical modeling of the multi-level drainage system was undertaken and an analytical solution developed which allowed direct comparisons of drain flow characteristics to be made between single-level and multi-level drainage systems. Analysing the predicted streamlines found that with a multi-level drainage system the depth of water flow paths was decreased and so the drainage water salinity would be reduced. It was also found that the deep drain spacing could be considerably increased compared to a single-level system.

The field trial of multi-level drainage compared a system with drains at 0.85m depth and 3.3m spacing underlain with drains at 1.8m depth and 20m spacing with a single level system with drains at 1.8m depth and 20m spacing. Detailed studies of drain flows and salinities, water tables and salt leaching found that the multi-level drainage system had several advantages over the single level system. These were: drain water salinities and hence salt loads were lower, there was more effective removal of salts from within the plant rootzone and less from below the root zone, the drainage water from the shallow drains was less saline (six fold) than the deeper drains and waterlogging of the rootzone was much more effectively controlled.

The drainage management field trial compared a normal free flowing system to a controlled drainage system. Measurements were taken of drain flows and salinities, changes in soil salinity, water tables, evapotranspiration and vine yield. Reductions in salt loads of up to 90% were achieved through the use of controlled drainage. The resulting shallow water table contributed up to 60% of the vine water use in some cases, thus improving the overall irrigation water use efficiency of the vineyard. These large contributions to evapotranspiration from the shallow saline water table were found to only occur when the salinity of the water table was below 4 dS/m.

The rootzone soil salinity in the controlled drainage block showed an increasing trend due to the uptake of saline groundwater by the grapevines. This highlights the need for careful salinity management when undertaking controlled drainage practices to ensure acceptable rootzone soil salinity levels are maintained in the long term.

The research has been able to show that there is potential to significantly improve the performance of subsurface drainage systems in terms of reducing salt loads and thus minimizing the problem of disposal of saline drainage effluent. The alternative subsurface drainage design and management practices developed in this research begin to address the environmental aspects associated with subsurface drainage while still maintaining productive irrigated lands.

PREFACE

The research presented is the authors own with the exception of contributions from those acknowledged in the text and described below.

The Crop Water Stress Index Maps shown in Chapter 7 were obtained by airbourne infrared thermal image analysis undertaken by Dr Moshe Meron of MIGAL Galilee Technology Center, Crop Ecology Laboratory, Kiryat Shmona, Israel.

Roy Zandona, Brad Fawcett and David Smith of CSIRO Land and Water Griffith assisted in installation of piezometers and Enviroscan probes.

Mention of trade names throughout the dissertation is provided for the benefit of the reader and does not imply endorsement by the author or the University of New England or CSIRO Land and Water.

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification.

I certify that any help received in preparing this thesis, and all sources used, have been acknowledged in this thesis.

....

Signature

Acknowledgements

Firstly, I would like to thank my two supervisors throughout the project, Dr Evan Christen from CSIRO Land and Water, Griffith and Dr Richard Faulkner from the University of New England, Armidale, who, from the onset of this project until completion, have provided complete support and sound advice throughout. Your willingness to help and patience have been greatly appreciated on my behalf.

Dr Jim Ayars from the USDA Water Management Research Laboratory in Fresno, California is also gratefully acknowledged for his advice and support, during sabbatical leave, when stationed at CSIRO.

All three have been a great source of inspiration and have had a strong influence on not only the development of my research skills, but also on my personal development as an engineering scientist, which I thank them greatly for.

I would also like to thank Brad Fawcett and David Smith of CSIRO for their help in installing piezometers at the experimental site and Brad also for help with soil coring work. It's been great to have such expert help on hand when needed. Also, thanks go to Roy Zandona for help and advice with all things electronic associated with the project. I enjoyed the many long hair pulling hours we spent configuring dataloggers – they were never dull !

I would also like to mention the support provided by all those in management, administration and support roles, from CSIRO, UNE and Land and Water Australia who have provided guidance throughout the duration of the project. The financial support provided by Land and Water Australia through their National Program for Irrigation Research and Development postgraduate scholarship is gratefully acknowledged, without which, this project would not have been possible.

Thanks also go to Mr. Michael Snaidero and Mr. John Dal Broi for allowing the experimental work to be conducted in their vineyards. Your patience and flexibility have been extremely appreciated along with your generous hospitality.

Lastly, thank you to all my family members who have been extremely supportive throughout the work and provided encouragement to pursue my goals. The last three years have been a wonderful learning experience and a time of my life I won’t easily forget.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATION

β - Bowen Ratio, dimensionless

γ - Psychometric constant, kPa/^{0}C

q - Volumetric water content, m^3/m^3

ρ_B - Soil bulk density, kg/m^3

ϕ_{DD} – Hydraulic head component associated with the deep drains in a multi-level drainage system, m

ϕ_{MLS} – Total hydraulic head of the multi-level drainage system, m

ϕ_{SD} – Hydraulic head component associated with the shallow drainage tubes in a multi-level drainage system, m

μ_w and μ_s - First order rate constants for solutes in the liquid and solid phases, T^{-1}

γ_w and γ_s - Zero order rate constants for solutes in the liquid and solid phases, $ML^{-3}T^{-1}$

a – Drain spacing of parallel drains, m

c - Solution concentration, ML^{-3}

C – Water table shape factor used in bi-level drainage system, dimensionless

C_{DD}, C_{SD} – Constants in the expressions for the hydraulic head functions F_{DD}, F_{SD}

C_{np} - Raw count of neutron probe

C_{npw} - Raw Count of neutron probe in water

c_s - Concentration of sink term, ML^{-3}

CWM – Controlled Water table Management

CWSI – Crop Water Stress Index

D – Depth below drain depth to impermeable layer, m

d – Height of soil above drain reference level, m

D_1 – Depth of deep drain in bi-level drainage system to impermeable layer, m

D_2 – Depth of shallow drain in bi-level drainage system to impermeable layer, m

D_a – Average saturated depth of soil, m

D_{ij} - Dispersion coefficient tensor, L^2T^{-1}

e – Constant approximately given by 2.718281

E = Aquifer diffusivity

$EC_{1:5}$ – Electrical conductivity of a 1:5 soil:water suspension

EC_{SAT} – Saturated paste electrical conductivity, dS/m

EMh – EM38 horizontal dipole reading, mS/m

EMv – EM38 vertical dipole reading, mS/m

ET – Evapotranspiration, mm/day

ET_o – Reference Crop Evapotranspiration, mm/day

e_v - Vapour pressure, kPa

F – Drainable porosity, m^3/m^3

G - Heat Flux into Earth, MJ/m^2

h – Depth of the impervious barrier below the soil surface, m

H – Depth of water above drains, m

H_d – Depth of water in drainage ditches, m

h_m - Water table height above shallow drains in a multi-level drainage system, m

h_p - Pressure head (m)

k – Saturated hydraulic conductivity of the soil, m/day

k_c – Crop coefficient

k_{ij}^A and k_{iz}^A - Components of a dimensionless anisotropy tensor k^A

K_{unsat} - Unsaturated hydraulic conductivity (m/day)

L - Latent Heat of vaporization, MJ/m^2

m – Number of shallow drains in the multi-level drainage system

MLD – Multi-Level Drainage

n – Summation integer; n goes from -8 to +8, inclusive n equal to 0

Q_d – Deep drain discharge of deep drains in a bi-level drainage system

q_{DD} – Hydraulic head coefficient associated with the deep drainage tube in a multi-level drainage system, m

Q_{DD} – Total inflow into the deep drain tube per unit length of tube per unit time in a multi-level drainage system, m^3/m/day

q_i - i^{th} component of volumetric flux, LT^{-1}

Q_{MLS} – Combined inflow of the deep and shallow drain tubes per unit length of tube per unit time in a multi-level drainage system, m^3/m/day

Q_s – Shallow drain discharge of shallow drains in a bi-level drainage system

q_{SDm} – Hydraulic head coefficient, associated with the shallow drainage tubes in a multi-level drainage system, m

Q_{SDm} – Total inflow into the deep drain tube per unit length of tube per unit time in a multi-level drainage system, m^3/m/day

r – Radius of drain pipe, m

R_N - Net Radiation, MJ/m^2

Rs – Resistance, Ohms

s - Adsorbed solute concentration, ML^{-3}

S - Sink term, T^{-1}

SAR – Sodium absorption Ratio

SWP - Soil Water Potential, kPa

Sy – Specific yield of soil

t – Height of the ponded water surface above the soil surface, m

T – Time, days

Ts – Temperature of soil, ^0C

v – Rainfall Rate, m/day

W - Sink term for evapotranspiration, m^3/day

W_{DD} – Summation coefficients for the deep drain tubes used in the expression for hydraulic head for a multi-level drainage system, dimensionless

W_{SD} – Summation coefficients for the shallow drain tubes used in the expression for hydraulic head for a multi-level drainage system, dimensionless

x,y,z - Spatial coordinates, m

Z_{DD} – Summation coefficients for the deep drain tubes used in the expression for stream function in a multi-level drainage system, dimensionless

Z_{SD} – Summation coefficients for the shallow drain tubes used in the expression for stream function in a multi-level drainage system, dimensionless

d – Height of the soil surface above the shallow drain tubes in multi-level drainage system, m

?, ? – Rectangular coordinates of a point P near a shallow tube in the right upper corner of the flow region under consideration, m

p – Constant, approximately given by 3.14159

? – Radius of the shallow drain tubes in multi-level drainage system, m

$?_{DD}$ – Stream function component associated with the deep drainage system in the multi-level drainage system, m^2/day

$?_{MLS}$ – Combined stream function in the flow region of the multi-level drainage system, m^2/day

$?_{SD}$ – Stream function component associated with the shallow drainage system in the multi-level drainage system, m2/day

1 Introduction

Subsurface drainage has been used extensively throughout semi-arid irrigated areas of the world for both waterlogging and salinity control. The success of such methods has been well documented, although in many instances it has come at a considerable cost to the environment through the disposal of saline drainage water. This investigation assesses a revised philosophy of design and management, which can be applied to subsurface drainage systems to minimize these detrimental environmental consequences of subsurface drainage.

In any irrigation development the application of water for irrigation involves some degree of deep percolation below the root zone. When saline irrigation water is used, a leaching fraction has to be used to prevent soil salinisation. This leads to an increase in the level of groundwater or development of transient perched water tables on material of very low permeability at shallow depth. The degree to which groundwater approaches the soil surface depends on a number of factors, such as the potential for lateral dissipation, the rate of groundwater accession and the potential for storage of water in the soil. These factors are related to the soil, topography and stratigraphy both in the irrigated area and also surrounding areas.

Subsurface drainage has been used for protection against both salinisation and waterlogging. Waterlogging occurs when water tables rise into the soil root zone, or when excessive wetting of the soil from surface infiltration occurs. Waterlogging causes a reduction in the oxygen concentration in the soil, which in turn leads to plant stress. Waterlogged conditions also provide problems for trafficking of agricultural equipment due to a decrease in soil strength (Smedema and Rycroft 1983).

Salinisation has been defined by Richards (1954) as an increase in the concentration of soluble salts in the rootzone of the soil. In many arid zone irrigated areas soils contain natural stores of geological salts, which in many instances become mobilized by irrigation practices. Underlying groundwater in such areas contribute salts to the root zone through capillary rise and application of saline irrigation water may further exacerbate the problem. Evaporation and transpiration processes then extract water from the soil while leaving behind salt, causing it to accumulate in the soil. The problem has existed for millennia (e.g. ancient Egypt and Mesopotamia) with irrigation inducing the twin phenomena of waterlogging and salinisation, leading to land degradation threatening the sustainability of such areas, (Hillel 2000).

In the Murrumbidgee Irrigation Area (MIA) the development of high water table areas has been a major concern. Within the horticultural areas of the scheme, large losses in agricultural production have been experienced through waterlogging and salinity problems throughout their history. Extensive subsurface drainage schemes have been implemented and currently 70% (12000 ha) of all horticultural areas are protected with subsurface drainage, (Polkinghorne 1992). The success in preventing waterlogging and salinisation is clearly evident and success from an agronomic perspective has been reported in a number of studies (Talsma and Haskew 1959; van der Lely 1978). However, a major effect, not envisaged at the time of design and development of the subsurface drainage systems, in the MIA, were the environmental consequences associated with disposal of saline drainage water.

Major environmental problems are emerging through secondary effects associated with land drainage. These include water quality deterioration due to sediment, nutrients and pesticides occurring in drainage waters in the MIA (Bowmer et al. 1998) and problems associated with the saline drainage water (Blackwell et al. 2000; Christen and Shekan 1999; van der Lely and Ellis 1974; van der Lely 1984; van der Lely and Tiwari 1995). These impacts affect both instream ecosystems and their associated organisms, such as fish and other aquatic biota, as well as downstream consumptive users i.e. irrigators. Within the MIA the issues and restrictions on drainage water disposal have come from problems faced by downstream consumptive water in the Wah Wah Irrigation Area, whose irrigation water contains drainage water from the Murrumbidgee Irrigation Area.

Saline drainage water disposal has now become a major issue facing irrigation practitioners in the MIA. The existing subsurface drainage has a significant impact on the salt load in streams and rivers. The 7% of the area that is currently drained in the MIA, contributes 30% of the salt load leaving the area, (MIA and Districts Land and Water Management Plan, 1998).

Monitoring of salt loads generated in the MIA show that salt loading is declining slowly over time. Surveys undertaken by the Department of Land and Water Conservation (DLWC) at regular intervals – 1970, 1980, 1990 and 1999 show that salt loads increased until about 1975, then peaked at about 23000t and fell back to 18000t in 1990. Currently, salt loads from subsurface drainage systems in the MIA are around 12-15000 t/year, (Christen and Hornbuckle, 2001).

Figure 1-1 shows the current estimated trends for salt loads from horticulture in the MIA based on trends until 1990. The increases after 1997 are hypothetical, assuming that new irrigation of horticultural land were able to discharge their salt load to the drainage system. After this analysis was conducted it was decided that future discharges would not be permitted. Any new enterprises are required to use evaporation basins for disposal of their drainage water.

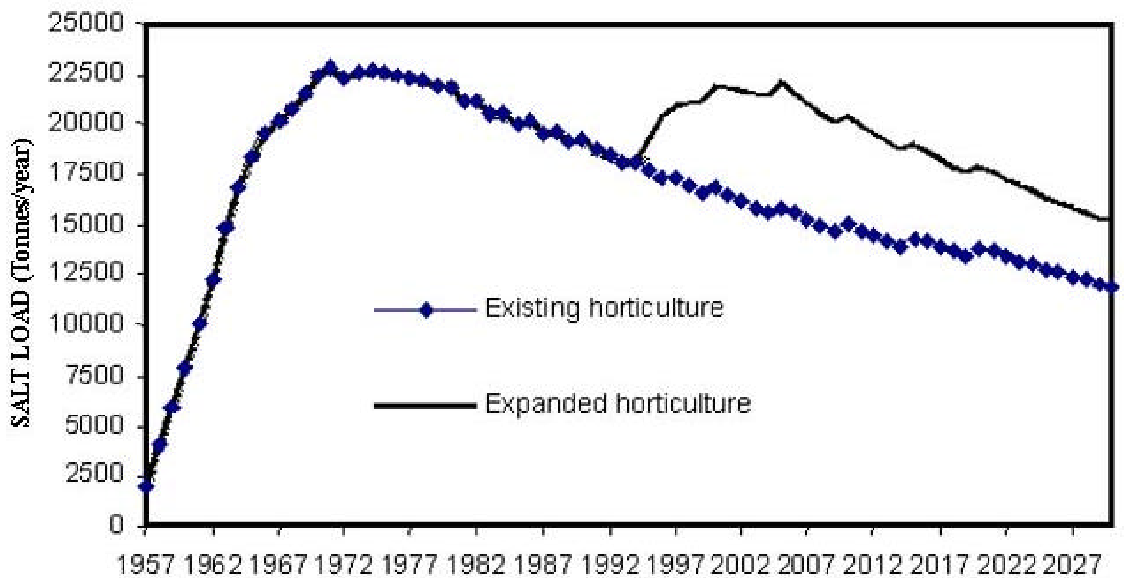


Figure 1-1. Past, current and predicted trends in salt load discharges from the MIA, including alternative prediction for scenarios involving expansion of the horticultural area, after van der Lely (1984)

While the trend in Figure 1-1 is favorable in the absence of no further discharges, the MIA and Districts Land and Water Management Plan (1998) aims to lower salt loads by 20-30% compared to a 1995 baseline. Previously, the criteria for acceptable water quality in the Wah Wah irrigation area was based on a salinity level of 0.7 dS/m and in practice average water salinity provided to the area for irrigation was 0.5-0.6 dS/m. Wah Wah irrigators are currently demanding a new maximum level of salinity of 400 EC, which they believe will allow the area to be sustainable (MIA and Districts Land and Water Management Plan, 1998). Therefore, the drainage problem has shifted from being primarily concerned with agronomic production to also include environmental factors, namely salinity and the volume of drainage water, which must be accounted for and the problem now relates to the disposal of subsurface drainage water.

Such problems related to the disposal of saline drainage water are not confined to the MIA or indeed Australia. Similar problems exist throughout the world in nearly all the major irrigated semi-arid regions (Tanji 1990; Hillel 2000), which face problems with salinisation and waterlogging and its control.

In order to address these problems then re-assessing subsurface drainage design and management incorporating drainage salinity impacts may offer benefits over existing design and management methodologies, which focus only on agronomic aspects of the crop. Previous research (Ayars, Grismer & Guitjens 1997; Fio and Deverel 1991; Guitjens et al. 1997 & Jury 1975a) has shown that drainage design and management can have a large effect on the quantity of subsurface drainage water and subsequently the salt loads generated. This is due to water flow paths to drains being controlled by a number of variables, such as drain depth and spacing as well as irrigation management.

In a review of subsurface drainage systems (Christen, Ayars and Hornbuckle, 2001), in irrigation areas in Australia, it was shown that in many cases the drainage salt loads are often 5-10 times greater than that applied through the irrigation water, even after the reclamation phase was completed. Thus indicating that such systems typically remove stored salt as well as that applied with the irrigation water, Figure 1-2. Often this stored salt may originate from below the root zone with its removal offering little benefit to the crop.

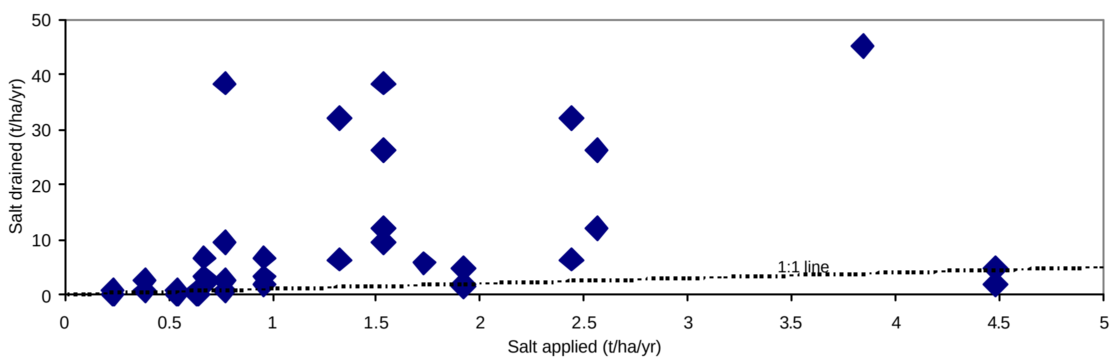


Figure 1-2. Salt applied and salt drained based on studies undertaken in Australia in 10 irrigation areas, Christen, Ayars & Hornbuckle (2001)

Considering this, then the design and management of sub surface drainage systems may be modified to reduce such high salt loadings in subsurface drainage waters and mitigate impacts caused by the disposal of subsurface drainage water. This thesis deals with investigating options in subsurface drainage design and management that may be implemented at the field level to achieve a reduction in the problems associated with the disposal of saline drainage water.

1.1 Objectives

The overall aim of this investigation is to develop design methodologies for new subsurface drainage systems and management practices for existing subsurface drainage systems, which minimize saline drainage water whilst maintaining agronomic productivity.

1.1.1 Design of New Systems

The overall aim of this component of the research was to investigate design alternatives that offer reductions in saline drainage water, while maintaining productive soil conditions for agronomic practices and remain economically viable.

Specific objectives that are necessary to meet this aim are:

1. Develop drainage designs incorporating salinity disposal issues whilst maintaining productivity

2. Determine the effects of improved drainage design on agronomic production, rootzone soil salinity and drainage water (quantity and quality) compared with drainage systems designed with existing criteria

1.1.2 Management of Existing Systems

The overall aim of this component of the research was to investigate management options, which may be undertaken on existing subsurface drainage systems to minimize disposal issues related to saline drainage water disposal.

Specific objectives that were undertaken to meet this aim are:

1. Investigate design criteria previously used in existing drainage design and how this relates to current irrigation/agronomic/environmental aspects

2. Determine management alternatives which may be applied to existing drainage systems that result in reductions in drainage quantity and salt load

3. Investigate management changes to an existing drainage system and determine effects on agronomic production, rootzone soil salinity and drainage water (quantity and quality)

2 Review of Literature

2.1 Introduction

Subsurface drainage has been used extensively in arid and semi-arid irrigated agriculture for the control of waterlogging and salinisation. Although techniques for draining land have been well developed this has often been without due consideration given to the impact that these practices have on the environment and other water users (Dougherty and Hall 1995).

Recently, attitudes and drainage techniques have began to emerge which focus on incorporating external factors, such as environmental impacts, into drainage design and also management options on existing drainage systems to mitigate these detrimental effects associated with disposal of subsurface drainage water.

This review outlines previous research focused at mitigating the problem associated with disposal of saline drainage water and focuses on options, which can be undertaken at the field level using drainage efficiency improvement options, i.e. limiting the amount of drainage water which needs to be disposed off. Two main areas of drainage efficiency improvement at the field level are reviewed with these being firstly the design of new subsurface drainage systems and secondly the management of existing subsurface drainage systems. The review has been limited to arid and semi-arid irrigation and drainage studies due to the controlling process in humid irrigation and drainage areas differing significantly from arid and semi-arid areas (Ayars 1996a).

2.2 The Problem

Irrigated agriculture has for many millennia faced the problem of sustaining production of croplands and preventing waterlogging and salinisation. History has continuously shown that irrigated agriculture cannot exist indefinitely without maintaining an adequate salt balance. In lands that lack natural drainage characteristics drainage has to be provided (Hillel 2000).

Tanji (1990) stated that the duration of time that irrigated agriculture can survive without adequate drainage depends on a number of variables, such as the salinity of the applied irrigation water, salinity of the native soil and the rate of leaching. Waterlogging may hasten the onset of salinisation if restricting soil layers are present. However, in all situations some form of drainage is a necessity to ensure an adequate salt balance is maintained in the rootzone. In some instances, such as sloping lands with permeable soil or hydrological conditions that facilitates downward or lateral water flow, the natural drainage may provide enough capacity to maintain an adequate rootzone salt balance. However in many arid and semi-arid climates, irrigated agriculture requires artificial drainage to ensure an adequate rootzone salt balance due to the complex hydrogeological and modified hydrological settings.

In the past drainage water from agriculture would be disposed of 'somewhere, somehow' (Tanji 1990) however in today's changing social climate the disposal of this saline drainage water has become a contentious issue due to the degradation of natural environments it causes and problems for downstream consumptive water users (Beltran 1999; Schultz and Wrachien 2002; Smedema, Adbel-Dayem and Ochs 2000).

It is now no longer considered sustainable or acceptable to dispose of saline drainage water without regard to the consequences associated with its disposal. Therefore, the major problem challenging the sustainability of irrigated agriculture in many arid and semi-arid regions of the world today is the disposal of saline drainage water (Christen, Ayars and Hornbuckle 2001; Tanji 1990; Hillel 2000).

2.3 Control and Management of Subsurface Drainage Water

From a study of information provided in reviews and studies of irrigated salinity (Blackwell et al. 2000; Evans 1989; Hillel 2000; Tanji 1990; Westcot 1998) the main control and management options of subsurface drainage water are depicted in Figure 2-1. Water initiates from leaching of agricultural fields through the removal of excess water applied to the field either through irrigation or rainfall. Volumes of water leaving the system are controlled by management variables shown in Figure 2-1.

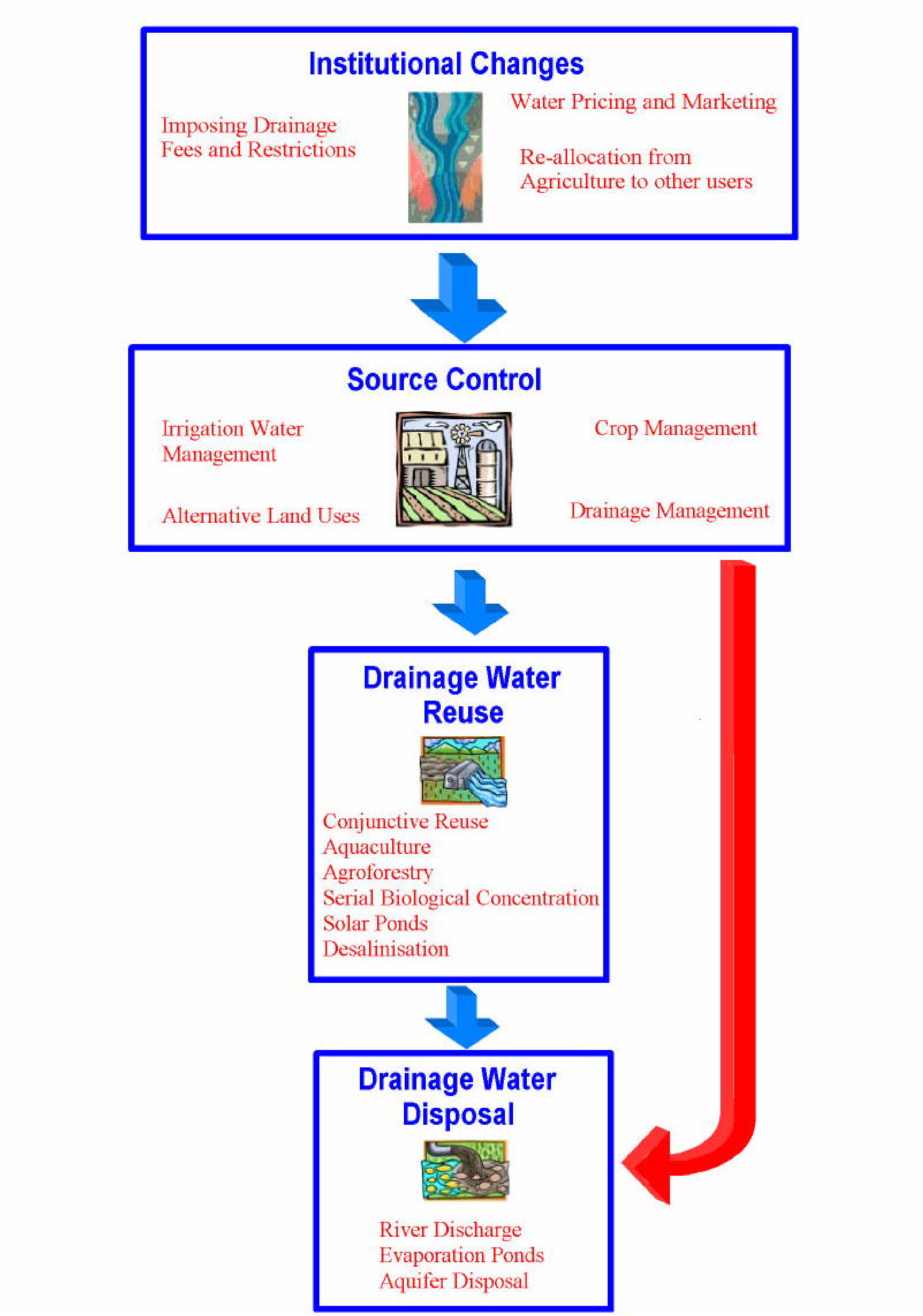


Figure 2-1. Options available for reducing subsurface drainage water from irrigated agriculture

Four main options exist for managing saline subsurface drainage water and these are institutional changes, drainage efficiency improvement, drainage water reuse and drainage water disposal. While each of these options is important and may play a vital role in sustaining irrigation, central to all options is drainage efficiency improvement. Many of the other options rely heavily on drainage efficiency improvement to provide a manageable volume of drainage water that needs to be disposed of in order for the economics of such systems to be favourable (Blackwell et al. 2000; Evans 1989).

This thesis focuses on researching methodologies associated with drainage efficiency improvement to reduce problems associated with subsurface drainage water at the field scale. It is realized, however, that any approach to combating the enormous problems associated with saline drainage water will need to take a holistic approach incorporating components from each of the four main options identified in Figure 2-1.

This review firstly assesses previous design and management tools that have been used in the past and highlights problems with these methods when factors such as water disposal problems are incorporated as design parameters. Design criteria used in these methods are also reviewed and discussed along with alternative criteria, which incorporate drainage water salinity. Newer design tools incorporating numerical methods are reviewed which offer more insight in the design process. A review of drainage configuration effects on drainage water quantity and quality is then undertaken and alternative configurations, which offer potential benefits to reduce disposal problems of drainage waters are developed. Management of existing drainage systems is also reviewed and effects of improvements to management investigated for its benefit to reduce drainage volumes and salinity.

2.4 Drainage Efficiency Improvement Options for Reducing Subsurface Drainage Volumes

In reviewing options for drainage efficiency improvement for reduction in subsurface drainage water it is interesting to look at how in the past subsurface drainage systems have been implemented. Figure 2-2 shows from a past perspective how the implementation of a subsurface drainage system develops after (in many cases decades) the irrigation system. After identification of salinisation and/or waterlogging problems design and implementation then occurs. After this stage in many instances no further management occurs with many systems simply left to operate continuously with a 'solution finished attitude'. Such processes, however, often lead to extensive problems with large volumes of drainage water being generated and hence disposal problems, (Christen, Ayars and Hornbuckle 2001).

Figure 2-2 shows recent emerging thought processes behind subsurface drainage design with views of creating a sustainable, both agriculturally and environmentally, irrigation and drainage system, shown in green in Figure 2-2. This process involves considering at early stages the consequences of subsurface drainage and possible impacts and incorporating these factors into the design process to minimize impacts associated with irrigation and subsurface drainage.

It can be seen from Figure 2-2 that depending upon the history of the subsurface drainage system two main practices may be implemented at the field level to improve subsurface drainage practices. Both have the ultimate aim of reducing impacts associated with disposal of drainage water. These two practices are firstly incorporating water quality aspects as a drainage design criteria in the initial design process, which can only occur with new systems, and secondly modifying existing systems to incorporate water quality targets from drain water, commonly referred to as controlled drainage, (Ayars, Grismer and Guitjens 1997; Christen, Ayars and Hornbuckle 2001; Thomas, Hunt and Gilliam 1992).

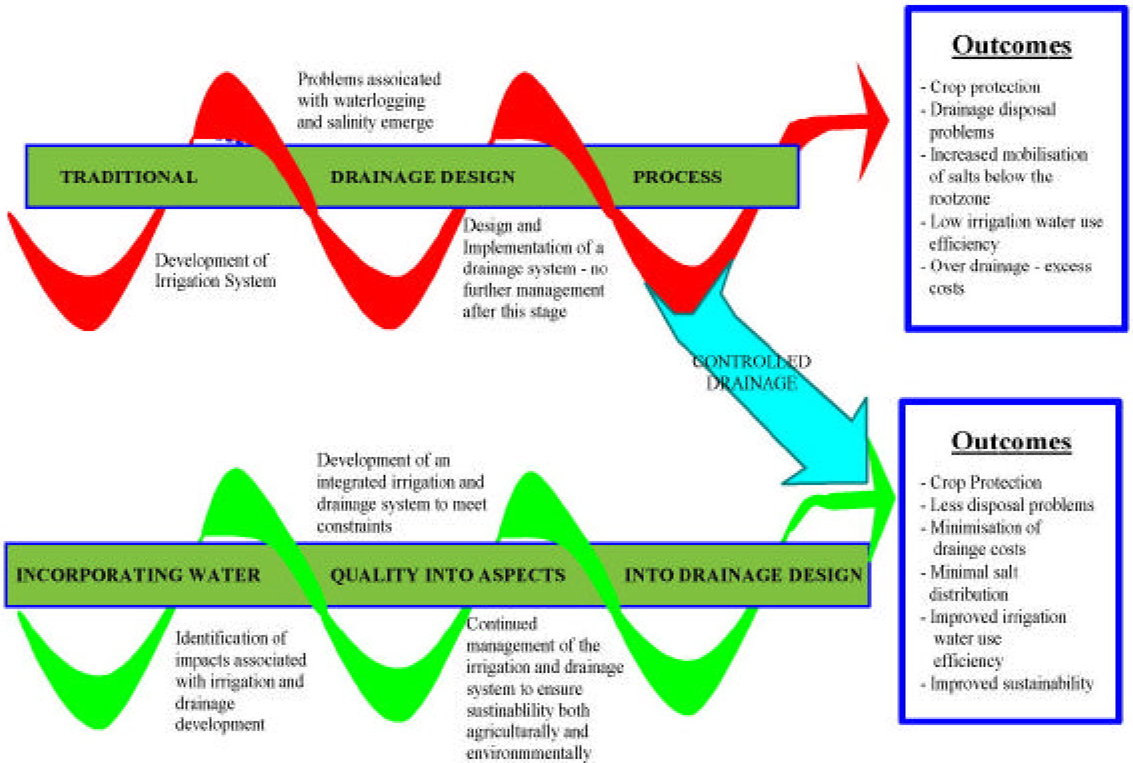


Figure 2-2. Subsurface drainage design processes from a past and future perspective and introducing improvements to existing systems

2.5 Subsurface Drainage Design Approaches

The general process in designing a subsurface drainage system firstly involves establishing a design purpose, which the drainage systems must meet. This may for instance be for waterlogging control, for salinity control or for both and then determining the characteristics, which the drainage system needs to meet. This may be a minimum depth to water table for the growing season or a discharge rate, which the drainage system must be able to achieve. Once this criteria is decided, mathematical tools are then used to design a system that will meet the criteria.

2.5.1 Drainage Criteria

Drainage criteria can generally be broken into a number of categories depending upon the purpose of the drainage system and the method used to solve the problem. Drainage criteria can be evaluated for a steady-state condition, a falling water table, a fluctuating water table, salinity control, or trafficability of the soil, depending upon the main function of the drainage system, (Bouwer 1965).

Generally, in semi-arid and arid irrigation areas the main focus of the drainage system centers on salinity control, however in some areas waterlogging control may also be an important aspect of the drainage system. Commonly, either analytical steady state or transient design equations, which focus on calculating water table height at mid-drain spacing are used in the design process. Hence, drainage criteria relates to parameters described in these equations, namely discharge rate and water table height from which a design depth and spacing of the drainage system is calculated.

2.5.1.1 Steady State Design

The steady state design equation of Hooghoudt has been previously used extensively in Australia, U.S. and many other arid and semi-arid irrigation areas of the world. Within Australia drainage criteria were developed by Maasland and Haskew (1958) for the Murrumbidgee Irrigation Area and have been widely adopted to protect against waterlogging on a 1 in 100 year rainfall event, CSIRO (1965). This resulted in an equivalent drainage design discharge of 5mm/day when the water table was 0.45m from the soil surface for the lighter textural soils and 2.5mm/day for the heavier textured soils. Drain depth was set at 1.8m for economic and technical reasons connected with trenching machinery. Hydraulic conductivity measurements and depth to impermeable layer were investigated using the auger hole method developed by Maasland and Haskew (1958) for the region. Therefore, the only unknown of the Hooghoudt equation remains the lateral spacing of the drains.

Field investigations by Talsma and Haskew (1959) found good agreement between design discharge rates and those actually realized in the field once drain spacing was calculated. The authors found that for the given design criteria proposed and used by Maasland and Haskew (1958) the water table dropped from 0.45m (design depth) to 0.75m in a three-day period, which was considered acceptable, (van der Lely 1978).

Drainage criteria for salinity control is generally focused on maintaining a minimum depth to water table to prevent upward capillary flux and salinisation. Work undertaken by Talsma (1963) in the Murrumbidgee Irrigation Area found that for steady state conditions (i.e. water table at a constant level) then the critical depth of the water table to prevent salinisation resulted in a maximum upward flux of 1 mm/day, with the actual depth to water table depending upon a number of soil physical properties.

Once the required depth to water table is selected then calculation of the design discharge rate is undertaken. This is generally based on a leaching fraction component, which needs to be removed to ensure an adequate salt balance for the rootzone. The amount of leaching needed to maintain a viable irrigated crop depends on a number of factors, namely the salt content of the irrigation water, soil and groundwater, the salt tolerance of the crop, the climate and soil and water management. The leaching fraction is generally determined from a salt balance of the rootzone given below:

$$\mathbf{S_s = D_rC_r + D_gC_g + D_iC_i - D_dC_d + S_m + S_f - S_p - S_c}$$

Equation 2-1

Where C is the salt concentration; D is an equivalent depth of water, S_m is the salt dissolved from minerals in the soil; S_f is the salt added to the soil as fertilizer or amendment; S_p is the salt precipitated; S_c is the salt removed in the harvested crop and the subscripts r,i,g and d are rainfall, irrigation, groundwater and drainage components respectively (Hoffman 1990). It is generally assumed that the upward movement of salt is negligible, the quantity $(S_m + S_f)$-$(S_p + S_c)$ is zero and that under steady state conditions the change in salt storage is zero. Equation 2-1 can then be written in terms of a leaching fraction:

$$L_r = \frac{D_d}{D_a} = \frac{C_a}{C_d} = \frac{EC_a}{EC_d}$$

Equation 2-2

where L_r is the leaching fraction, EC is the electrical conductivity and the subscripts a and d designate the applied and drainage waters (Hoffman 1990). Once the leaching fraction has been calculated then a design discharge can be calculated to be used in the design process.

2.5.1.2 Transient Design

The transient design process has more commonly been used in the western arid and semi-arid irrigation areas of the United States. Design criteria based on transient equations presented by Dumm (1954) are the common method used by the U.S. Bureau of reclamation (USBR), which was involved extensively with the design and installation of drainage systems.

Information required for the design process and routinely collected included the soil hydraulic properties, soil layering, depths to restricting layer, cropping patterns, irrigation schedule, irrigation system, irrigation efficiency, climate data, depth to water table, other sources of drainage water (lateral inflows, canal seepage) and the salinity status of soils and groundwaters (Ayars, Grismer and Guitjens, 1997).

Boumans (1986) recommended that when using transient design tools for drainage design then two independent water table depth criteria should be used which are shown in Figure 2-3. These two critical periods relate to the cropping period when the water table needs to be maintained at a critical depth to prevent waterlogging and secondly during the fallow season when the critical depth relates to maintaining a water table depth to prevent salinisation from capillary upflow. However, if there is no rainfall, irrigation or lateral seepage into the area then the water table will drop during the fallow period, therefore this second criteria is only useful in some circumstances.

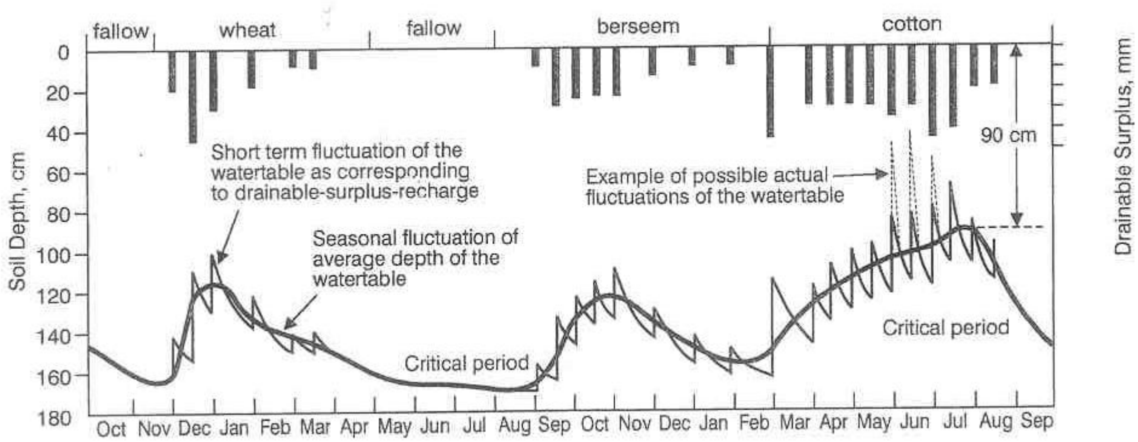


Figure 2-3. Water table fluctuations in a drained field, after Boumans (1986)

Drain spacing calculations using the USBR method take a different approach, that assumes a representative crop rotation and irrigation schedule developed from soil water holding capacity, allowable soil-water depletion and representative climate data. The deep percolation value is calculated based on the irrigation system and irrigation efficiency and the leaching requirement derived from salt tolerance data (Hoffman 1990). The leaching requirement component is calculated using crop salt tolerance data developed by Maas (1990) and the irrigation water quality. This is then compared to the actual deep percolation to determine whether actual deep percolation meets or exceeds the leaching requirement after irrigation adequacy and uniformity are determined.

The USBR recommendations that drains be installed at a 2.4m depth to provide a balance between the system cost and spacing. Deeper placement of the drains generally results in a wide drain spacing which lowers the system cost relative to closely spaced shallower drains (Ayars, Grismer and Guitjens 1997). The minimum water table depth at mid spacing between the drains is from 1.1 to 1.5m below the soil surface depending upon rooting depth of the crop. Such criteria in previous experience results in achieving at least 90% of maximum crop yield (Drainage Manual 1993).

2.5.2 Mathematical Tools

A number of mathematical tools have been used in the past for the design of subsurface drainage systems in semi-arid and arid irrigation areas of the world. Most design tools used previously have generally been centered on analytical solutions to steady state representations of the drainage problem, although analytical solutions to falling water table and fluctuating water table conditions have been developed and applied. A description of these commonly used methods is given in the following sections.

2.5.2.1 Steady-State Analytical Solutions

One of the most commonly used steady state analytical solutions is that developed by Hooghoudt (1940). The Hooghoudt spacing formula (Luthin 1966) is expressed as

$$a^2 = \frac{4k(H^2 - H_d^2 + 2DH - 2DH_d)}{v}$$

Equation 2-3

for the situation depicted in Figure 2-4.

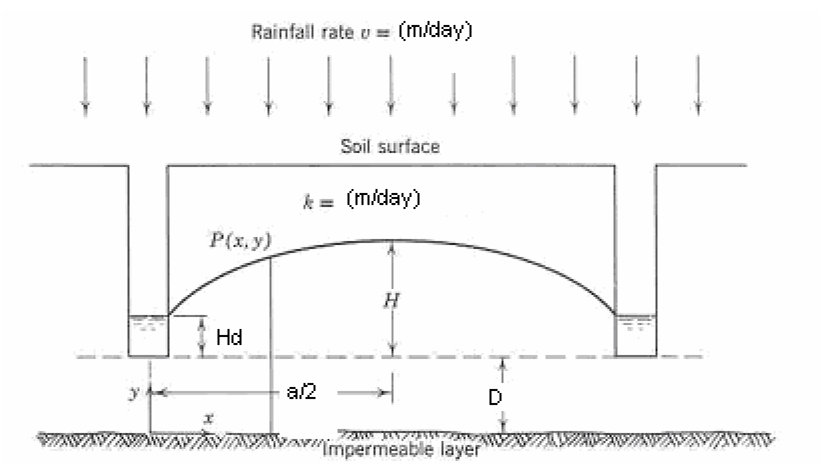


Figure 2-4. Diagram for Hooghoudt's drain-spacing formula, after Luthin (1966)

Generally for practical purposes the drain is considered to be empty and Equation 2-3 reduces to:

$$a^2 = \frac{4kH}{v}(2D + H)$$

Equation 2-4

This is the equation previously used extensively in Australia (Massland 1956 and Talsma 1967) and the United States (Donnan, Aronovici and Blaney 1947).

Hooghoudt made a number of assumptions in developing the solution which are summarized below (Luthin 1966):

1. The soil is homogenous and of uniform hydraulic conductivity k
2. The drains are evenly spaced a distance a apart
3. The hydraulic gradient at any point is equal to the slope of the water table above the point, $\frac{dy}{dx}$
4. Darcy's law is valid for flow of water through the soils
5. An impermeable layer underlies the drain at a depth D
6. Rain or irrigation is applied at a steady rate v
7. The origin of coordinates is taken on the impermeable layer below the centre of one of the drains

In order to simplify the mathematical analysis Hooghoudt used the Dupuit-Forchheimer (D-F) assumption, which is approximate theory and applies where drains are deep and flow is predominantly horizontal. Unless the drains are installed on the impervious layer, then D-F theory is not well suited to the problem, since in the vicinity of the drains a considerable portion of the flow towards the drain occurs as radial flow to which D-F theory does not apply. An explanation of the paradoxes associated with D-F theory is given in Kirkham (1967) who outlines the situations where D-F theory applies and where the theory fails to adequately represent the problem. Indeed, one of the major drawbacks of the theory it that it only assumes horizontal flow components, with an equilivalent drain depth used to incorporate radial aspects of the flow and convergence of streamlines near the drain. Vertical flow is neglected.

A number of other researchers, Kirkham and Toksoz, Wesseling, Dagan, Lovel and Youngs, Hammad, Childs and List have also developed approximate solutions to the problem of water flow to drains using both physical and a combination of physical and mathematical approximations (For further details see Kirkham 1966 and Van Der Ploeg, Horton and Kirkham 1999). However, the use of these solutions for subsurface drainage design has not been widely adopted.

Kirkham (1958) and Kirkham and Powers (1984) presented an exact solution of the problem of water flow to subsurface drains using the Laplace equation for an appropriate set of boundary conditions. Kirkhams formula is given as:

$$H = \left(\frac{1}{1 - \frac{v}{k}} \right) \left(\frac{av}{k} \right) F$$

Equation 2-5

where H = maximum height of the water table above the drains

v = Rate of Rainfall

k = Hydraulic conductivity

D = Distance from impermeable layer to water table immediately over drains

a = Spacing of drains

r = Radius of drain

and F is given by:

$$F = \frac{1}{p}\left\{\ln\frac{a}{pr} + \Sigma_{n=1}^{\infty}\left[\frac{1}{n}\left(\cos\frac{npr}{\frac{a}{2}} - \cos np\right)\left(\coth\frac{npD}{\frac{a}{2}} - 1\right)\right]\right\}$$

Equation 2-6

A diagrammatic representation of the problem is shown in Figure 2-5.

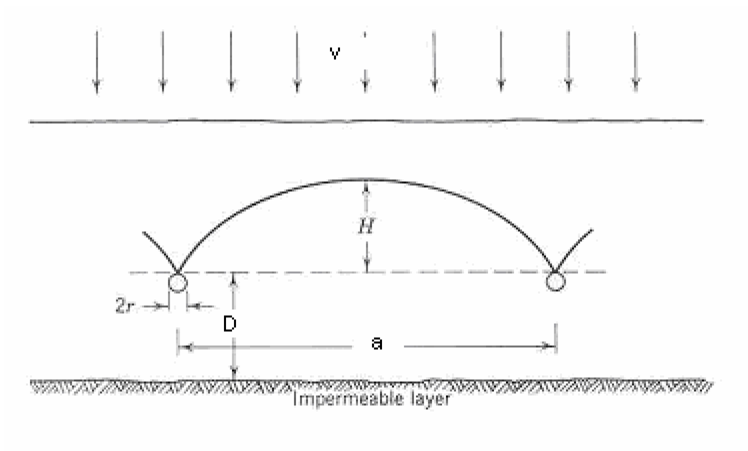


Figure 2-5. Diagram for Kirkham exact mathematical treatment of flow to drains, after Luthin (1966)

Although the solution presented above provides an exact mathematical solution to the steady state problem and is indeed a mathematical triumph, difficulties in carrying out the numerical calculations (at the time) have seen little wide-spread use of the method for drainage design with the simpler Hooghoudt equation (Equation 2-4) used for practical purposes. Wesseling (1964), in comparing solutions using the Hooghoudt (approximate solution) and Kirkham (exact solution) formulae found the two equations differed by less than 5% and hence for practical purposes the increased numerical calculations associated with the Kirkham formula provide little benefit to practical problems.

The Hooghoudt equation as presented in Equation 2-4 has been used extensively in Australia for designing subsurface drainage systems in irrigated regions. Previously all subsurface drainage systems designed in the Murrumbidgee Irrigation Area used this method (Christen and Hornbuckle 2001).

Steady-state analytical solutions have been developed for layered soils (Kirkham 1951), however their use in drainage design has not been widely adopted.

2.5.2.2 Transient Analytical Solutions

In areas with periodic irrigations, such as in arid and semi-arid irrigation areas, the assumption of a steady state recharge is not justified. Design methods in these situations need to adequately describe the movement of the water table through the soil profile, a transient or non-steady state situation.

Dumm (1954) reported on the problem of a falling water table situation and formed a model based on linearising the general 1-D saturated transient groundwater flow equation to give:

$$\frac{kD_a}{Sy}\frac{\partial^2 y}{dx^2} = \frac{\partial y}{\partial T}$$

Equation 2-7

where

k = hydraulic conductivity
D_a = average saturated depth
Sy = specific yield of the soil
x,y = vertical and horizontal dimensions
T = time

The equation was then solved for the following initial and boundary conditions:

y = 0 when x = 0

y = 0 when x = a

y = y_0 when t = 0 for 0<x<a (Initially flat water table conditions)

Where a is the distance between the drains. An analytical solution for the given boundary conditions was then found as:

$$y(x,T) = \frac{4y_0}{p} \sum_{n=1,3,5.....}^{n=\infty} \frac{e^{\frac{-an^2p^2T}{a^2}}}{n} Sin \frac{np}{a} x$$

Equation 2-8

where $a = \frac{kD_a}{Sy}$

A simplified version of Equation 2-8 was then given based on the assumption that mid drain spacing water table height was the point of interest for design calculations, which allowed the sinusoidal term to be removed from Equation 2-8. Sufficient accuracy was also found by Dumm (1954) when only maintaining the first term in Equation 2-8 with successive terms having little impact. Hence a sufficient approximation was given as:

$$y(T) = y_0 \frac{4}{p} e^{-\frac{ap^2T}{a^2}} = 1.27 y_0 e^{-\frac{ap^2T}{a^2}}$$

Equation 2-9

Latter, Dumm (1968) proposed an analytical solution for the above situation with an initial water table shape represented as a fourth degree parabola, which was believed to represent typical field conditions better than the assumption of an initially flat water table. The analytical solution for this situation is given as:

$$y(x,T) = \frac{192 y_0}{p^5} \sum_{n=0}^{\infty} \frac{(2n+1)^2 p^2 - 8}{(2n+1)^5} e^{-\frac{(2n+1)^2 p^2 aT}{a^2}} \sin \frac{(2n+1)px}{a}$$

Equation 2-10

Which, for the case of the mid spacing water table height can be simplified to:

$$y(T) = 1.16 y_0 e^{-\frac{ap^2 T}{a^2}}$$

Equation 2-11

which upon solving for a yields:

$$a = p \sqrt{\frac{kD_a T}{Sy \ln\left(\frac{y_0}{y(T)}\right)}}$$

Equation 2-12

which is known as the Glover-Dumm equation.

McWhorter (1977) later expanded on the work undertaken by Maasland (1959, 1964) to overcome assumptions in the Glover-Dumm equation that are not in accordance with the mathematical theory of linear systems, which were that the hydraulic system reinitialised upon recharge, and drainage proceeded as dictated by the initial condition established by adding the water table build-up to the water table elevation immediately before the recharge event.

The Glover-Dumm equation has formed the basis for the transient design of subsurface drainage systems adopted by the U.S. Bureau of reclamation (USBR). The method of design undertaken by the USBR is based on the concept of dynamic equilibrium, which aims to ensure that the range of water table fluctuations throughout the year remains at or below the design level and returns to the same depth position at the end of the design cycle, which is usually annually. The design process starts when the water table is nearest the soil surface – assumed at the end of the irrigation season- and ends when the final irrigation in the design cycle results in a build up of the water table to the prescribed design depth, with the lateral spacing being adjusted until the midpoint water table depth criterion is met through a trial and error procedure.

It has also been shown by a number of authors (Arnold, Boast and Lembke 1984; Pandey and Gupta 1990; Rassam and Cook 2002) that evaporation plays an important part in lowering water tables in arid and semi-arid irrigations areas. However in the previous mentioned design equations no evaporative component is considered. Theoretical investigations into incorporating evapotranspiration into the analytical solutions presented above have been undertaken (Cook and Rassam 2002; Pandey and Gupta, 1990; Wenyan, Bing and Zhilu1994), however their use in subsurface drainage design has been limited.

2.5.3 Limitations of Drainage Design and Criteria using Existing Methods

Recently Guitjens et al. (1997) and Ayars, Grismer and Guitjens (1997) reviewed design procedures in relation to water quality aspects and noted a number of problems with implementing such design procedures, when the objective of reducing impacts associated with disposing drainage water is also included. Guitjens et al. (1997) highlights that the USBR methods (as well as the Hooghoudt method) consider only the gross amount of water removed and do not consider water flow paths which have been shown by a number of authors (Doering, Benz and Reichman 1982; Deverel and Fio 1991; Fio and Deverel 1991; Jury 1975) to have a large effect on the quality of water from subsurface drainage systems.

Ayars, Grismer and Guitjens (1997) also note that a number of assumptions used in the design criteria with the USBR method are not always found in the field. The assumption of the highest water table occurring at the end of the irrigation season is generally not supported in field studies (Ayars 1996b; Ayars et al. 1996; Christen and Skehan 1999; Christen and Skehan 2000), and indeed when consumptive use from a shallow water table is included in the design procedure, as was undertaken by Ayars and McWhorter (1985), the minimum depth to the water table occurs early in the season when rooting depth is shallow.

Quantitatively, little information is known about the effect of fluctuating water tables on soils and crops and few soundly based non-steady design criteria have been established. Indeed the large majority of research in developing drainage criteria in relation to crop responses has largely been undertaken with steady state approaches, (Smedema and Rycroft 1983).

It can largely be seen from the above that although drainage theories have been extremely well developed mathematically often there has not been sufficient information available on the drainage criteria to enable implementation for given situations commonly found in arid and semi-arid irrigated environments.

The focus of the above models has centred on drain discharge and water table characteristics of the system. None of the above design tools consider the salinity of the drain water and the main focus has centred on water table height, drain discharge relationships. Indeed the most common design tool being the Hooghoudt formula incorporates no aspects in relation to solute transport and the flow paths to the drains are highly simplified which offers no useful information on drain flow paths and subsequently solute transport and drainage salt loads.

Detailed information on the flow paths and solute transport can be gained from the Kirkham formula and this information can be used for investigating the solute transport and subsequent salt loads from the system, however generally this information is not incorporated into the design process.

2.5.4 Outcomes/Analysis/Problems of Existing Drainage Designs

Previously, subsurface drainage philosophies have generally been centred on the need to maintain a specified water table depth to protect the crop from waterlogging or salinisation. These critical depths have been used to design subsurface drainage systems using steady state or transient methodologies such as those presented in the previous sections. These methodologies have been very successful in preventing waterlogging damage to crops and also preventing land salinisation. However, the effectiveness of such systems agronomically has come at a great environmental cost due to the problems associated with the disposal of saline drainage waters.

In a review of subsurface drainage systems (Christen, Ayars and Hornbuckle 2001) in all major irrigation areas in Australia it was shown that in many cases the drainage salt loads are often 5-10 times greater than the irrigation water applied, indicating that such systems typically remove stored salt as well as that applied with the irrigation water even many years after rootzone reclamation has taken place, Figure 2-6. In many instances this salt is being mobilized from below the rootzone, and often from beyond the point where removal is needed for the health of the crop.

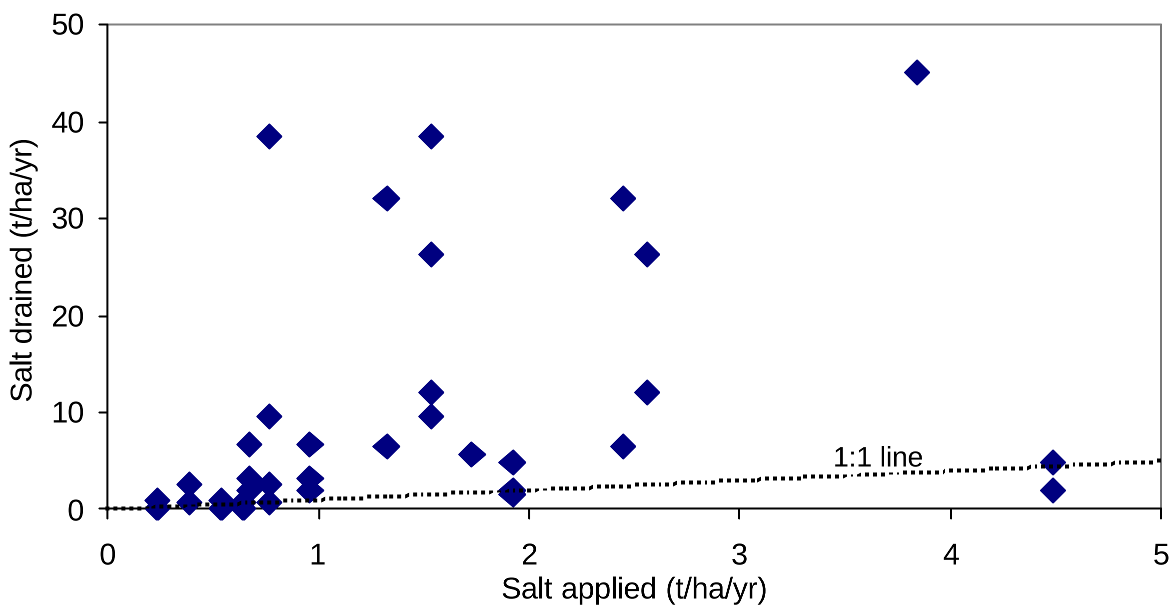


Figure 2-6. Salt applied and salt drained for different scenarios in ten irrigation areas of Australia, Christen, Ayars and Hornbuckle (2001)

Therefore, one of the major shortcomings of existing drainage design methodologies has been the lack of avenues to incorporate drain water salinity parameters into the drainage design process. Use of existing methodologies in subsurface drainage design has typically not considered water quality parameters and in many instances significant environmental problems have been associated with the disposal of saline drainage water, when designs have been based on these existing methodologies.

2.6 Research Tools for Subsurface Drainage Design

To deal with the problems and shortcomings with previous analytical drainage design methodologies a large emerging body of research has been undertaken using numerical methods, which allow a more complex flow domain and solute transport problems to be investigated.

More recently numerical procedures and routines have been developed for subsurface drainage design. Design criteria and experience using these methods have been very limited. However, when applied correctly they can yield valuable information for the drainage design process (Nieber and Feddes 1999). In recent times the role of drainage in problems relating to environmental water quality have become particularly important and off-site effects of drainage systems on external receiving water bodies has become a major issue. Numerical methods have allowed the expansion of drainage design to incorporate other more complex factors such as solute transport, which could not be considered using simple analytical based solutions due to the complex non-linear nature of the governing equations.

With the advent of the personal computer, and ample computational ability provided on most desktop computer systems, numerical methods have begun to dominate much of the current literature relating to drainage design. When non-ideal conditions apply and simplifying assumptions cannot adequately represent field conditions, numerical models can provide valuable insights into drainage design problems. Although analytical solutions can be found with relative ease for situations in which simple steady- state groundwater problems posed by a steady uniform flux across the water table flowing to drains occur, the analysis of non-steady state flow problems presented by changing conditions at the soil surface and at the drain are much more difficult, and analytical solutions giving water table heights and drain flows as a function of time are much less numerous (Youngs, 1999). It is in these situations, where simplifications cannot be made due to inadequate representation of the 'real' system, than numerical based solutions have significant advantages over analytical based methods.

More commonly numerical solutions to groundwater problems make use of the non-linear Richards's equation (Richards, 1931) for solving groundwater flow problems and incorporate both saturated and unsaturated zone components (Nieber and Feddes, 1999). The two-dimensional, isothermal Darcian flow of water in a variably saturated, rigid, porous medium is described using the following formulation of Richards' equation:

$$\frac{\partial q}{\partial T} = \frac{\partial}{\partial x_i}\left[k_{unsat}\left(k_{ij}^{A}\frac{\partial h_p}{\partial x_j} + k_{iz}^{A}\right)\right] - W$$

Equation 2-13

where q is the volumetric water content (m^3/m^3), h_p is the pressure head (m), W is a sink term for evapotranspiration (m^3/day), x_i (i = 1,2) are the spatial coordinates (m), T is time (days), k_{ij}^{A} and k_{iz}^{A} are components of a dimensionless anisotropy tensor k^A, and k_{unsat} is the unsaturated hydraulic conductivity function given by:

$$k_{unsat}(h_p,x,z) = k(x,z)\, k_r(h_p,x,z)$$

Equation 2-14

where k_r is the relative conductivity and k the saturated hydraulic conductivity (m/day). While the Richards equation (Equation 2-13) can be used to solve groundwater flow problems in both the saturated and unsaturated zones the simpler approximate equation known at the Boussinesq equation is often applied to the saturated zone, given by (Youngs, 1999):

$$Sy\frac{\partial H}{\partial T}+v \ = K_{unsat}\frac{\partial}{\partial x}\left(H\frac{\partial H}{\partial x}\right)+K_{unsat}\frac{\partial}{\partial y}\left(H\frac{\partial H}{\partial y}\right)$$

Equation 2-15

where Sy = Specific yield

K = Hydraulic conductivity

H = Water table elevation

v = Flux applied at soil surface

Solute transport is modeled using the Convective-Dispersion equation, which is presented below for the Fickian-based convection-dispersion equation for transient conditions (Simunek, Sejna & van Genuchten 1999):

$$\frac{\partial q_c}{\partial T}=\frac{\partial}{\partial x_i}\left(qD_{ij}\frac{\partial c}{\partial x_i}\right)-\frac{\partial q_i c}{\partial x_i}+m_w q_c+m_s S r_B+g_w q+g_s r_B-Sc_s$$

Equation 2-16

where θ = Volumetric water content

S = Sink term

x_i = Spatial coordinates

T = time

c = solution concentration

s = sorbed concentration

q_i = i^{th} component of volumetric flux

μ_w and μ_s = first order rate constants for solutes in the liquid and solid phases

γ_w and γ_s = zero order rate constants for solutes in the liquid and solid phases

ρ_B = soil bulk density

c_s = concentration of sink term

D_{ij} = dispersion coefficient tensor

A number of numerical methods have been used to solve Equations 2-13, 2-14 and 2-16 by numerous authors. These methods include classical finite difference methods, integrated finite difference methods, finite element methods and boundary element methods. The classical finite difference method and finite element method being the most commonly used for applications involving water flows and solute transport through soils (Nieber and Feddes, 1999). Of those applied specifically to drainage problems, Khan and Rushton (1996) used finite difference methods applied to a tile drainage problem to solve Equation 2-14 for specified boundary conditions representing a surcharged tile drainage system. Finite difference approximations were also used by Garcia, Manguerra and Gates (1995) for solving Equation 2-15 and Equation 2-16 related to drainage problems and by Ragab (2002). Finite element methods for solving Equation 2-14 and Equation 2-16 have been implemented by Pickens, Gillham and Cameron (1979) and Simunek, Sejna & van Genuchten (1999) for solving drainage problems based on Equation 2-14 and Equation 2-16.

Numerical solutions to Equation 2-13, Equation 2-15 and Equation 2-16 have been implemented in a number of computer based modeling programs, which aim to either aid in the design of subsurface drainage systems or simulate their operation. Examples of these include the Colorado State University Irrigation and Drainage Program (CSUID) developed by Garcia, Manguerra & Gates (1995) which uses a finite difference approach to solve the Richards equation for the unsaturated zone and the Boussinesq equation for the saturated zone. However, practical use of this model has been limited due to the fact it was created under a UNIX operating environment which does not see wide spread use. Similar models have also been developed (Kamra et al. 1991; Nour el-Din, King and Tanji 1987; Ragab 2002), however their use has not been widespread in drainage design.

Simunek, Sejna & van Genuchten (1999) created the SWMS_2D code which solves the Richards equation for ground water flows (Equation 2-13) and the Fickian based convection-dispersion (Equation 2-15) using a finite element technique. A user-interface to the code was developed known as Hydrus-2D and widespread comparisons of the model with field data collected for drainage situations have been made (Anderson and

Guitjens, 2000; Abbaspour et al. 2001; De Vos, Raats and Feddes (2002); Kohler et al. 2001; Rassam and Cook 2002). Use of the model for drainage design has also been referred to in Ayars, Grismer and Guitjens (1997), Guitjens et al. (1997) and Cook & Rassam (2002). The model can deal with a wide variety of boundary conditions, including seepage faces to simulate ditches and drain tubes as well as boundaries controlled by atmospheric conditions.

2.7 Advantages and Disadvantages of Analytical and Numerical Approaches

Problems relating to the use of numerical solutions to drainage problems stem largely from the large data requirement required by such methods. Accurate characterization of the initial and boundary conditions is needed along with detailed data on soil physical properties, particularly the soil water retention characteristics that are difficult to obtain (Youngs 1999; Skaggs n.d). Generally, when using numerical methods for drainage design most drainage criteria have simply been adopted from earlier criteria developed for the simpler analytical methods of analysis. More satisfactory design criteria, such as the moisture content of the rootzone (van Schilfgaarde, 1965) have not been used even though many of the above mentioned numerical models have this ability.

Although data input requirements are much more extensive than analytical models, detailed information of solute transport and hence water quality aspects of the subsurface drainage system can be investigated in the drainage design process.

In summary, although numerical models have the ability to investigate complex drainage domains and are capable of incorporating water quality aspects, they have the disadvantage of requiring considerable input data to characterise the problem and require skilled users. Analytical models require only minimal input data compared to numerical based models, but most lack an ability to provide detailed information on solute transport, however in some of the more complex analytical models this information can be inferred from the calculated flow paths.

2.8 Design Impacts on Drainage Water Salinity

A number of authors (Ayars, Grismer and Guitjens 1997; Grismer 1993; Guitjens et al. 1997; Manguerra and Garica 1997; Skaggs, Breve and Gilliam 1994) have investigated approaches that incorporate water quality parameters into subsurface drainage design in order to address adverse environmental impacts associated with subsurface drainage.

Guitjens et al. (1997) in an overview of drainage design for water quality highlights that historically drainage system design has dealt singularly with water table control for pre-determined rates of deep percolation and leaching fractions. Traditionally subsurface drainage system design has not considered any water quality aspects associated with a given drainage design.

In a soil with uniform soil salinity with depth the key parameters in drainage design for water quality aspects are the depth and spacing of the drains, which influence water flow paths to the drains and hence determine the water quality and quantity leaving the drainage system. The salt loads removed in drainage water also depend on the salinity of different soil layers.

2.8.1 Flow and Solute Movement to Subsurface Drains

Studies on water flow paths to subsurface drains have been undertaken by Jury (1975a,b). Theory of solute travel times based on the Kirkham (1949, 1958) steady state solution for pressure potential and streamline distribution was used to develop travel time estimates for flow of solutes to tile drains. Jury (1975a) found that travel times for water midway between subsurface drains may take 41 times longer than water entering at 0.1 of the drain spacing away from the drain. Figure 2-7 (Jury 1975a) shows streamlines followed by water flowing in a steady state to the tile line. It can be seen that as the distance from the subsurface drain increases, the travel time becomes longer and water path deeper. This has a large effect on the water quality leaving the subsurface drain as deeper flow paths tend to mobilize larger amounts of solutes due to increasing salt profile with soil depth found in most irrigated arid and semi-arid regions of the world (Guitjens et al. 1997).

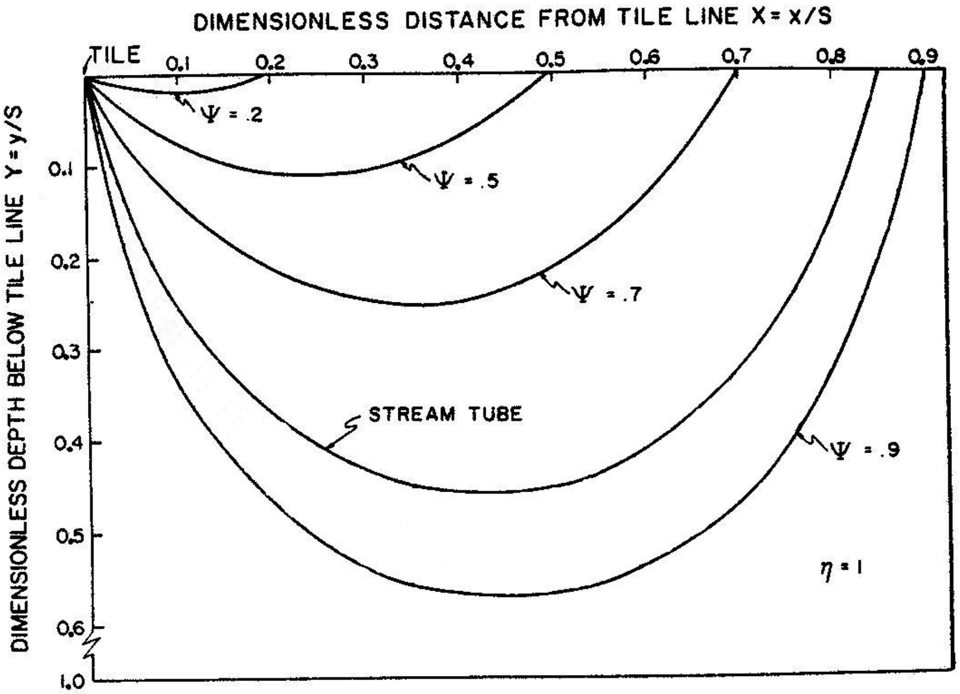


Figure 2-7. Streamlines followed by water flowing in steady state to tile line, where S is half drain spacing, x is distance from tile line, y is depth below tile line, and y is the stream function, after Jury (1975a)

Jury (1975a) was also able to show that water application and management practices had a substantial effect on the water and solute flow paths to subsurface drains. Figure 2-8 shows that for ponded and non-ponded situations (unsaturated zone above the drains) travel times to drains vary dramatically. In the ponded situation flow times increase as a power function with distance from the drain, whereas in the non-ponded case flow times increase linearly with distance from the drain. Therefore, irrigation management can have a significant effect on the quality of subsurface drainage water.

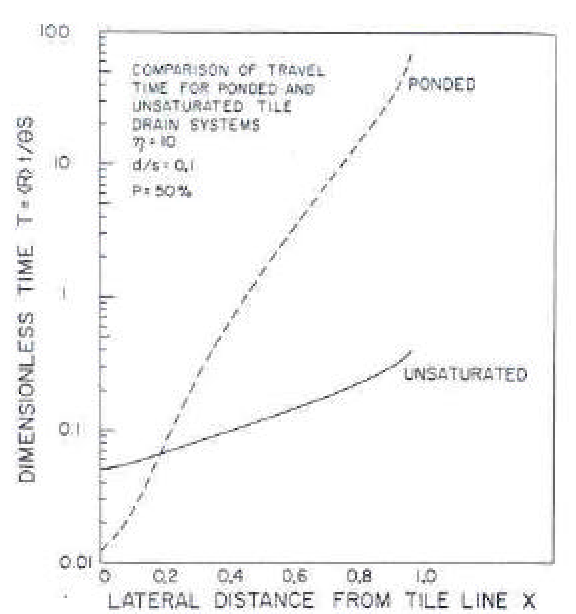


Figure 2-8. Dimensionless travel times for ponded and non-ponded (unsaturated) conditions, after Jury (1975a)

Similar results on flow paths and solute movement have also been reported by Deverel and Fio (1991), Fio (1994) and Fio and Leighton (1994) who evaluated the hydrological processes affecting the chemical and isotopic composition of subsurface drainage of agricultural fields in the western San Joaquin Valley, California. The field and modeling study investigated flow paths to subsurface drains at depths of 1.8 and 2.7m with spacings of 92 and 216m respectively. Results showed that flow paths for the 2.7m drain were 2 times greater and 5 times longer than the shallower 1.7m drain during non-irrigation periods. When irrigations were occurring the depth and length of flow lines were reduced but in non-irrigated periods the deeper drains discharged more water and also more saline water. Table 2-1 summarizes results based on modeling studies undertaken on the site.

Table 2-1. Flow depths, travel times and rates to drain laterals, after Fio and Deverel (1991)

Flow Factors	1.8m deep drain		2.7m deep drain	
	Irrigated Periods	Non-Irrigated Periods	Irrigated Periods	Non-Irrigated Periods
Maximum flow depth (m)	6	7	10	14
Maximum travel time (years)	5	7	22	34
Flow rate per unit drained area (m^3/m/yr)	0.293	0.043	0.292	0.213

The study also investigated the source of drain flow and found that deep groundwater (non-irrigation source) was 30% for the shallow drain and 60% for the deep drain, highlighting that deeper drains intercept more groundwater, usually of a high salinity level.

Fio and Deverel (1991) also reported on simulated flow paths to drains using a steady state model, which are shown in Figure 2-9 and Figure 2-10 for irrigated and non-irrigated conditions respectively. It can be seen from these figures that flow paths and hence solute paths to the drains are much deeper for the deeper drain, lateral 2, than drain lateral 1, both during irrigated and also non-irrigated conditions. Flow paths are also considerably deeper and much longer for the non-irrigated condition than the irrigated conditions. Considering these factors and results from the modeling and field studies undertaken by these authors it can seen that the source of solute and hence major contributor to drain water salinity, in many cases comes not from the removal of salt from the plant rootzone, but often from depths considerably deeper in the soil profile. It is also highlighted that the depth of drains has a large influence on water flow paths and hence solute transport, and these factors have a considerable influence on drain water salinity.

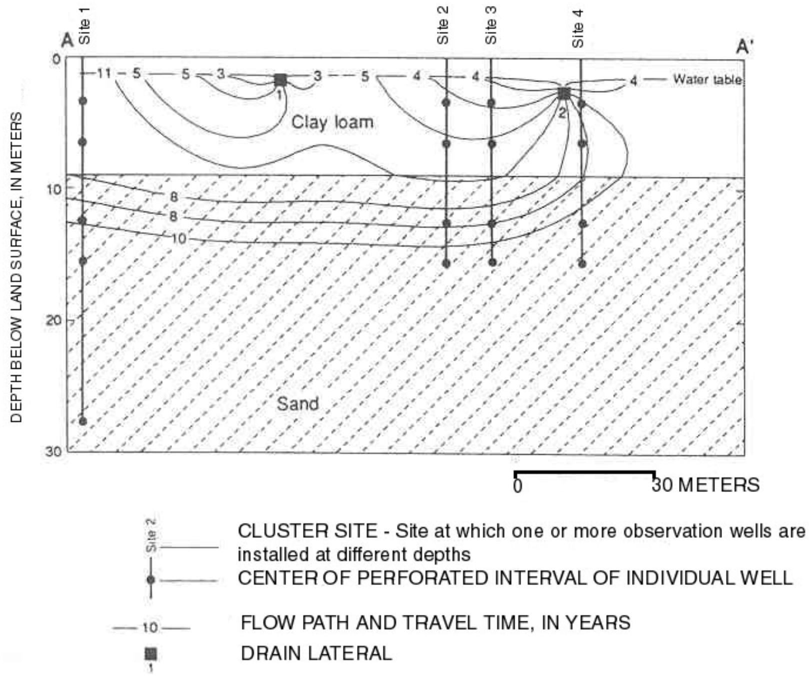


Figure 2-9. Simulated groundwater flow paths and estimated travel times for irrigated conditions. Simulated flow for drain lateral 1 is 27 m^3/yr/m and for drain lateral 2 is 63 m^3/yr/m, after Fio and Deverel (1991)

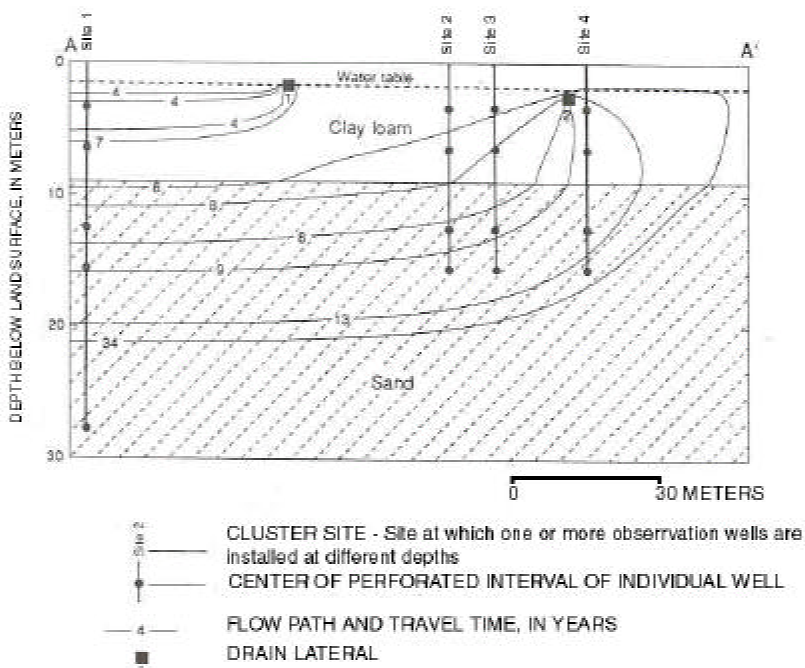


Figure 2-10. Simulated groundwater flow paths and estimated travel times for non-irrigated conditions. Simulated flow for drain lateral 1 is 4 m^3/yr/m and 46m^3/yr/m for drain lateral 2, after Fio and Deverel (1991)

Ayars, Grismer and Guitjens (1997) outline a number of drainage design factors, which contribute to water quality, associated with subsurface drainage systems. These are firstly, drain spacing and depth, which has considerable effects on the quality and quantity of drainage water. Table 2-2, reproduced from Ayars, Grismer and Guitjens (1997) shows for three different drainage configurations with different depths and spacings, the contribution of flow from sequential soil layers to total seasonal drain flow. Results were calculated using the SWMS-2D model developed by Simunek, Sejna and van Genuchten (1999).

Table 2-2. Percentage of flow to drains by layer for different drainage systems, after Ayars, Grismer and Guitjens (1996)

Layer (m)	System A[a]	System B[b]	System C[c]
0-0.3	18	23.9	21.7
0.3-0.6	16.2	20.7	20
0.6-0.9	14	15.1	15.6
0.9-1.2	13.2	10.3	14.4
1.2-1.5	14.6	8.8	15.5
1.5-1.8	15.8	10.2	10.6
1.8-2.1	8.3	9.4	2.1
2.1-2.4	0.01	1.4	0
2.4-2.7	-0.3	0.1	0
2.7-3.0	0	0	0
% Flow 0-1.2	**61.4**	**70.1**	**71.7**
% Flow 1.8-2.4	**8.4**	**10.8**	**2.1**

[a] Drain depth of 2.4m, midpoint water table depth of 1.2m, and lateral spacing of 299m with irrigation efficiency of 60%
[b] Drain depth of 1.5m, midpoint water table depth of 0.9m, and lateral spacing of 320m with irrigation efficiency of 80%
[c] Drain depth of 1.5m, midpoint water table depth of 0.9m, and lateral spacing of 160m with irrigation efficiency of 60%

It can be seen that as the drain depth is decreased then the percentage of flow to the drains for the 0-1.2m layer (the rootzone of most crops) is increased and the percentage of flow from the deeper layers (1.8-2.4m) reduced. More closely spaced drains also have the effect of reducing the percentage of flow from the deeper layers.

Drain water quality for the above drainage configurations was also investigated using an arbitrary salinity profile, which started at 0.5 dS/m at the surface and increased to 4.7 dS/m at a depth of 2.4m. The average electrical conductivity of each layer was then used with the flow from that layer to calculate the salt load from the layer. The drain salinity was then calculated as the sum of each of the layers. Average electrical conductivity during the growing season was found to be 1.7 dS/m for System A, 1.6 dS/m for System B and 1.5 dS/m for System C highlighting that as the drain depth becomes shallower and more closely spaced the electrical conductivity of the drainage water decreases. Total salt loads from each of the systems (a function of the drain flow and salinity) was highest with System A, followed by System C and lastly System B, showing that irrigation efficiency has a large effect on the total salt load leaving the drainage system. However, the simulation shows that reducing the drain depth will reduce the salt load even when irrigation efficiencies are not improved.

Recently De Vos, Raats and Feddes (2002) investigated the movement of chloride in soil profiles of a reclaimed Dutch polder during constant ponding. Modeling studies undertaken using Hydrus 2D were used to investigate water flow paths to drains. Figure 2-11 shows modeling results from steady state analysis of the drainage system with varying infiltration rates of 15 mm/day and 1mm/day. It can be seen that for the soil properties and boundary conditions used, as the water table depth increases the flow paths to the drains are larger in the shallower soil layers. Using the modeling and field studies De Vos, Raats and Feddes (2002) found that under dry conditions with a relatively deep water table, drainage water mainly occurred from soil zones close to drain depth. Under wet conditions, once the water table had risen to high levels (0-50cm) the majority of the drainage water originated from the topsoil. This had the effect of drainage water being of a lower salt concentration in periods when the water table was near the soil surface and higher in salt concentrations when the water table was lower, due to the flow paths to drains being shallower for a high water table situation and the soil profile increasing in salt content with depth.

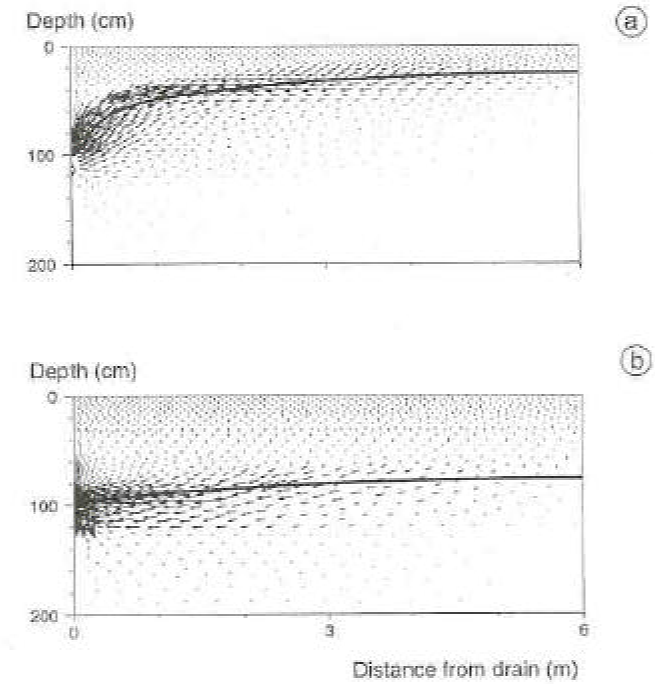


Figure 2-11. Distribution of the water flow for steady infiltration rates of (a) 15 mm/day and (b) 1 mm/day for a situation with an impermeable boundary at 200cm depth. The lengths of the arrows indicate the magnitude of the flow relative to the maximum. At the same arrow length, the absolute water flow is 20 times greater in (a) then (b). The Thick curves show the depth of the phreatic surface, after De Vos, Raats and Feddes (2002)

Figure 2-12 shows the relationship between water table height, drain discharge and the chloride concentration of the drainage water for a 120-day period. It can be seen that both the field and modelling studies show that drain water chloride concentrations are lowest when the flow paths to the drains are predominantly in the shallower soil layers, which occurs in high water table situations.

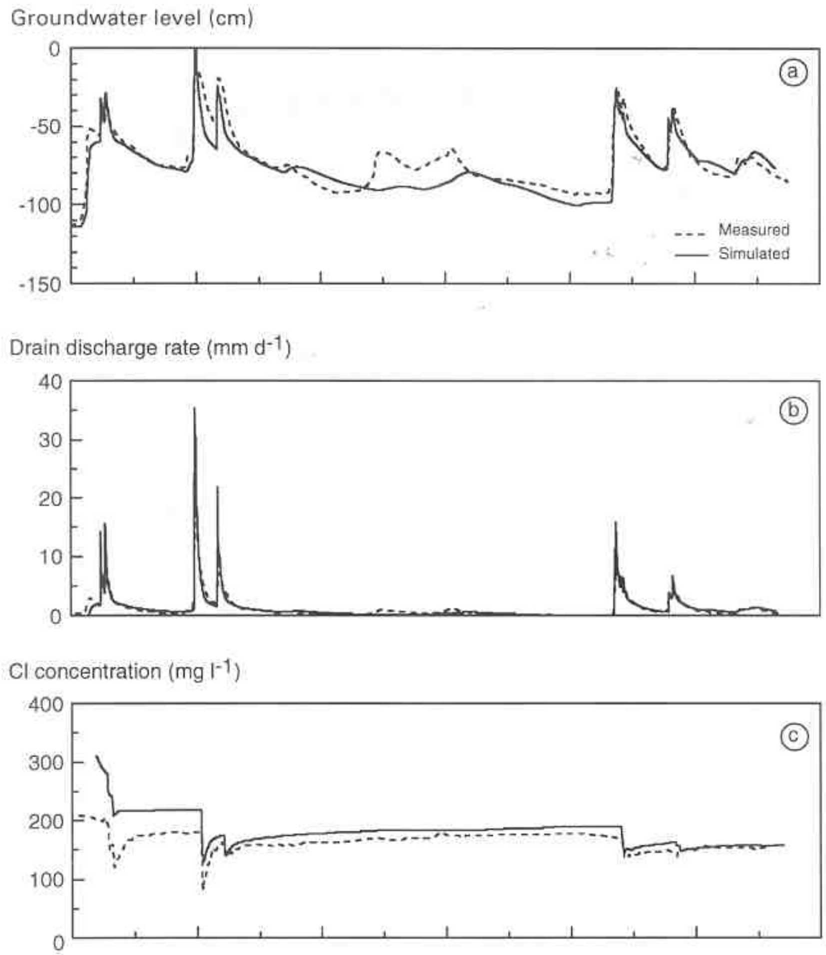


Figure 2-12. (a) Measured and simulated groundwater levels midway between the drains, (b) drain discharge rates, (c) Cl concentrations in the drainage water, after De Vos, Raats and Feddes (2002)

Rassam and Cook (2002) investigated the effect of different hydrological scenarios on the export of solutes from drainage systems in acid sulfate soils used to grow sugar cane in coastal flood plains of Australia. Field characteristics reported in Rassam, Cook and Gardner (2002) were used to construct a model using Hydrus 2D to investigate the effect of drain depth on solute concentration of drain water. Results of the modelling study found increasing the drain depth had a pronounced effect on drain water quality. Figure 2-13 shows clearly that as drain depth is increased the cumulative solute concentration is increased, with a four fold difference between drains at 0.5m depth and 2m depth.

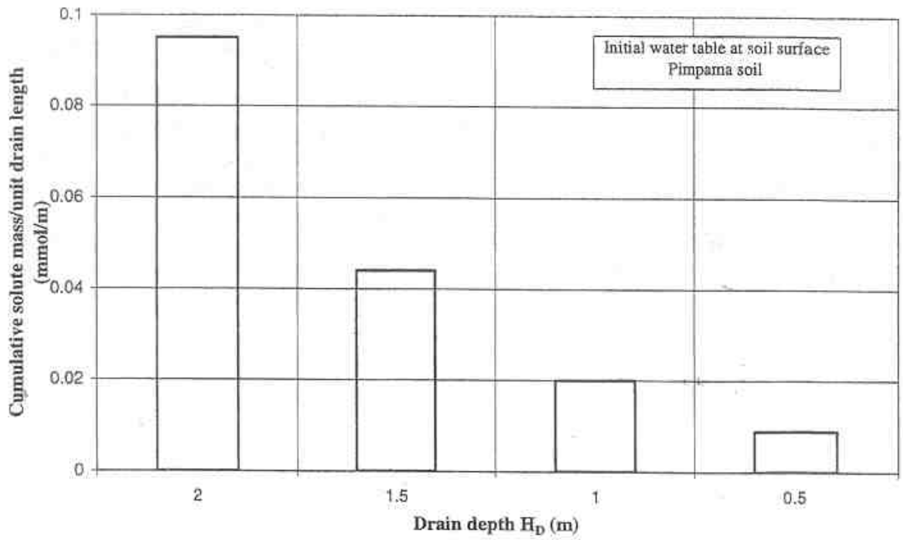


Figure 2-13. Effect of drain depth on cumulative solute mass export, after Rassam, Cook and Gardner (2002)

The authors also investigated the impact of varying the drain depth, drain spacing and evaporation rate on the cumulative solute seepage flux. It can be seen in Figure 2-14 that although the drain spacing had an effect on the solute load the depth of the drains had a more significant effect. Evaporation also played a major part in lowering the solute loads to drains with larger evaporation rates causing a decrease in the solute load.

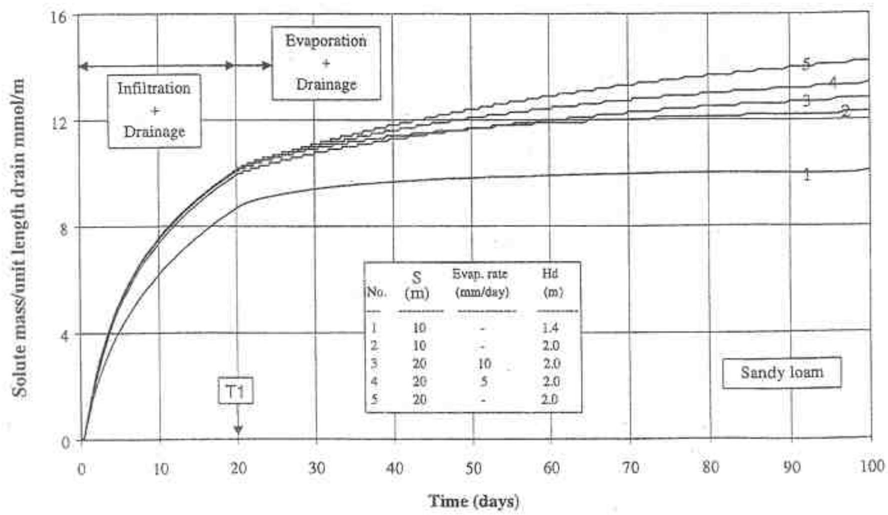


Figure 2-14. Effect of drain spacing, depth and evaporative potential on solute mass export to the drain, after Rassam and Cook (2002)

Grismer (1993) used a two-dimensional finite difference model to investigate the effects of drain spacings and depth on drain water salinity. Hydrogeological settings described by Fio and Deverel (1991) were used in the model, which consisted of a 9m thick clay loam layer overlying a 21m thick sand layer. The lateral boundaries were described as a constant flux condition, the base as a no flux boundary and the top as a free surface (water table) boundary condition. Groundwater salinity was assumed in the model to vary with depth and was assumed constant throughout the simulations at 5000 mg/L for the top layer and 10000 mg/L for the bottom layer. Drain water salinity was determined from the superposition of flow lines and the layered water salinity profile with depth. Four drain spacings and three drain depths were investigated for the effect each parameter had on the drain water salinity. Results from a steady state analysis with a constant recharge of 0.01m/day are shown in Figure 2-15.

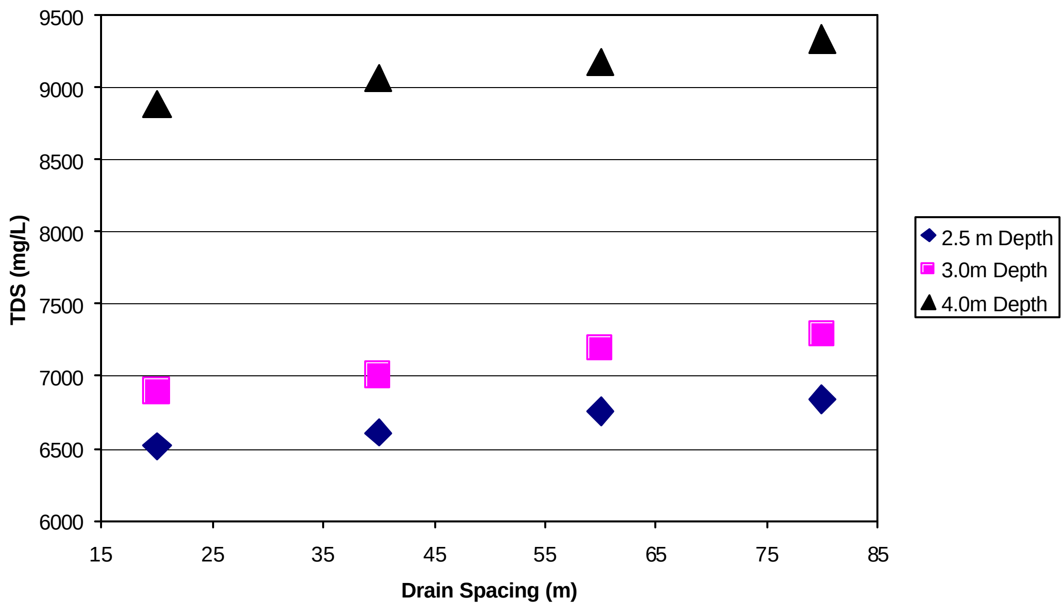


Figure 2-15. Drain water salinity as affected by drain depth and spacing under steady state flow conditions, after Grismer (1993)

It can be seen from Figure 2-15 that whilst both the depth and spacing of the drainage system affect the drain water salinity, drain depth has the greatest effect on drain water salinity. It can be seen that the effect of increasing the drain depth from 2.5m to 3.0m causes approximately the same increase in drain water salinity as increasing the drain spacing from 20 to 80m for a drain depth of 2.5m, for the hydrogeoloical settings modeled in this investigation.

Transient analysis showed a similar trend and salt load removed through the 20 and 80m spaced drains at varying depths over a two-day period are shown in Figure 2-16.

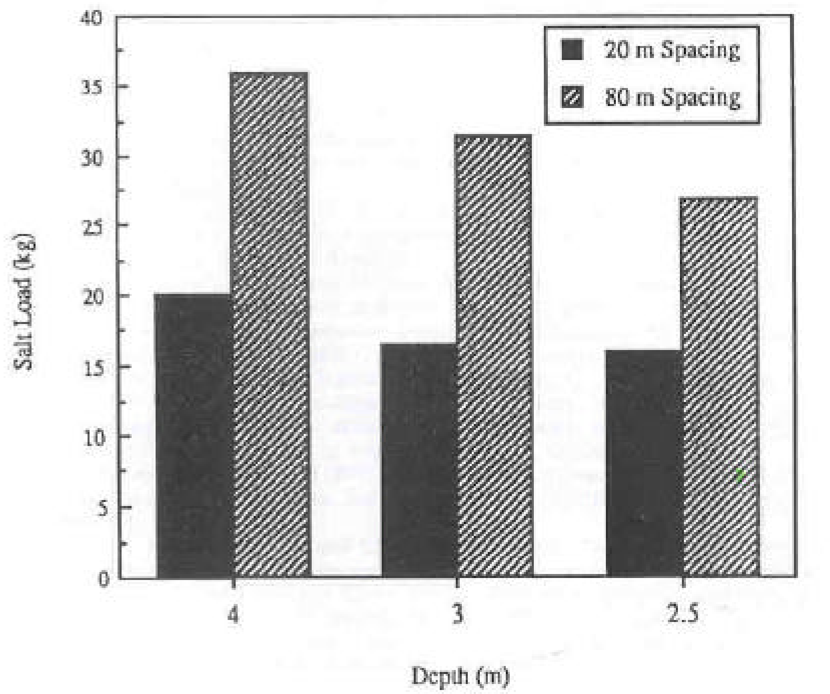


Figure 2-16. Cumulative salt load for drainage systems at spacings of 20 and 80m, after Grismer, (1993)

It can be seen that in all situations the 80m spaced drains removed a substantially greater mass of salt over all drain depths than the 20m spacing. These results show that when drain water salinity is a major consideration in the design process, consideration needs to be taken of the drain depth and spacing, as these largely determine the resulting drain water salinity, which ultimately needs to be disposed of appropriately.

Christen and Skehan (2000) reported on factors affecting drainage water quantity based on data collected from horticultural farms in the Murrumbidgee Irrigation Area. All farms were subsurface drained and drain spacing calculated using Equation 2-4, based on the method outlined by Maasland and Haskew (1958). Detailed studies of the relationship between soil salinity, water table depth and drain water salinity were investigated. A strong correlation between drain water salinity and water table depth was found, Figure 2-17.

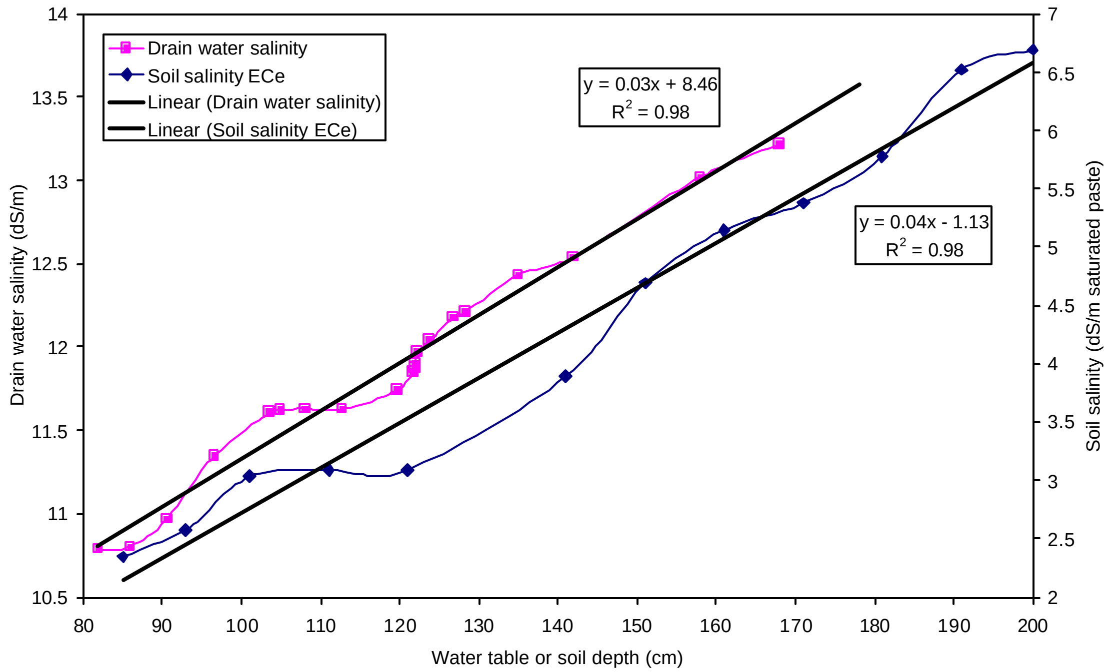


Figure 2-17. Drain water salinity and soil salinity with depth measured during a single irrigation event, after Christen and Skehan (2000)

The authors attributed the increasing drain water salinity with water table depth to changing depth of water flow paths to the drains. As the water table drops the water flow paths to the drain become deeper, and as the soil salinity increases with depth the salinity of the drain water increases.

It can be seen from these previous studies that flow path length, which is determined largely by the depth and spacing of the drains, is a critical component in determining the salt load from the drainage system. This has led to general recommendations of shallower more closely spaced drainage systems when water quality parameters relating to salt disposal are incorporated into the drainage design.

2.8.2 Effectiveness of Shallow Drain Configurations

Field studies investigating the effect of shallow drainage configurations on salt loads have been limited. Particularly studies, which have directly compared the performance of deep drain systems with shallow drain systems under identical conditions.

Muirhead et al. (1996) reported on the effectiveness of shallow subsurface drainage systems in an irrigated vertisol in the Murrumbidgee Irrigation Area for the control of waterlogging. Five drainage treatments were compared in the study consisting of an undrained control, mole drains (0.6m depth, 1.8m spacing), shallow pipe drains with (0.4m depth, 1.8m spacing) and deep drains (1.65m depth, 9.1m spacing). Average electrical conductivities from the experiment and salt loads for three consecutive crops are shown in Table 2-3.

Table 2-3. Average electrical conductivity of drain water and salt load for drainage treatments, after Muirhead *et al*. (1996)

	Mole	Shallow Pipe	Deep Pipe
Average EC (dS/m)	1	1	8.4
Salt load (t/ha) Tomatoes	1.9	-	11.2
Salt load (t/ha) Onions	1.4	1.7	12.2
Salt load (t/ha) Barley	0.2	0.2	3.9

It can be seen from Table 2-3 that the effect of increasing the drain depth and spacing had a significant effect on the drain water salinity, with an eight fold increase in average electrical conductivity of the drainage water from the shallow to deeper drainage systems. It was also found by the authors that the shallower drainage systems were much more effective in controlling waterlogging than the widely spaced, deeper drainage treatment, Table 2-4.

Table 2-4. Effect of drainage treatments on the number of days perched water table was above 400mm, after Muirhead et al. (1996)

Treatment	Days above 400mm
Control	47
Mole	17
Shallow Pipe	17
Deep Pipe	28

Shallow drainage systems using mole drains were also studied by Christen and Skehan (1999, 2000) who compared drainage treatments consisting of deep drains (1.8m depth, 20m spacing) and shallow drains (mole drains, 0.7m depth, 3.65m spacing).

The investigation showed the shallower mole drains produced a much lower volume of drain water (Figure 2-18), and lower drain water salinity (Figure 2-19) than the deep drain treatments. The authors attributed this reduction in drain water salinity to the lower depth of flow paths to the shallower drainage system and the soil salinity profile, which showed increasing salinity with depth. The shallower drainage system also removed a much lower volume of water compared to the deeper drains. Shallow drain flow typically only occurred for two days after an irrigation or rainfall event until the water table dropped below a depth of 0.7m (the depth of the moles). In most instances the flow from the deeper drainage system was continuous throughout the trial period. Total salt load from each of the treatments is given in Table 2-5 for the two-year period in which the experiment was carried out. It can be seen that both the deep drain treatments removed significantly more salt than was applied through the irrigation water. However, in the case of the shallow drain treatment there appeared to be signs that salt was accumulating in the soil profile, however there was no strong trends over the experimental period. Soil salinity changes over a three-year period for the drained treatments and an undrained treatment are shown in Figure 2-20 and Figure 2-21 for the 0-0.6m and 0-2.0m layer, respectively.

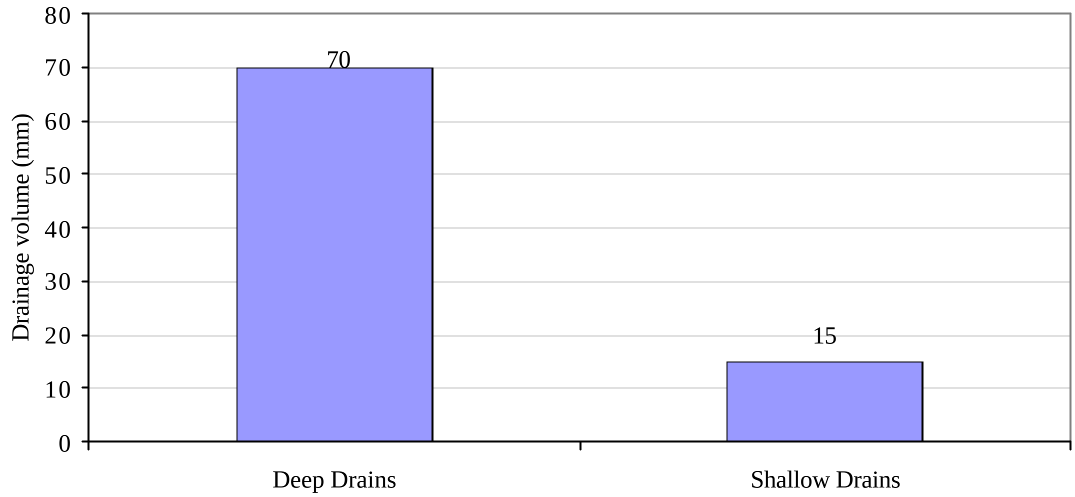


Figure 2-18. Measured drainage volumes for the 3 drainage treatments over 2 irrigation seasons, after Christen and Skehan (2000)

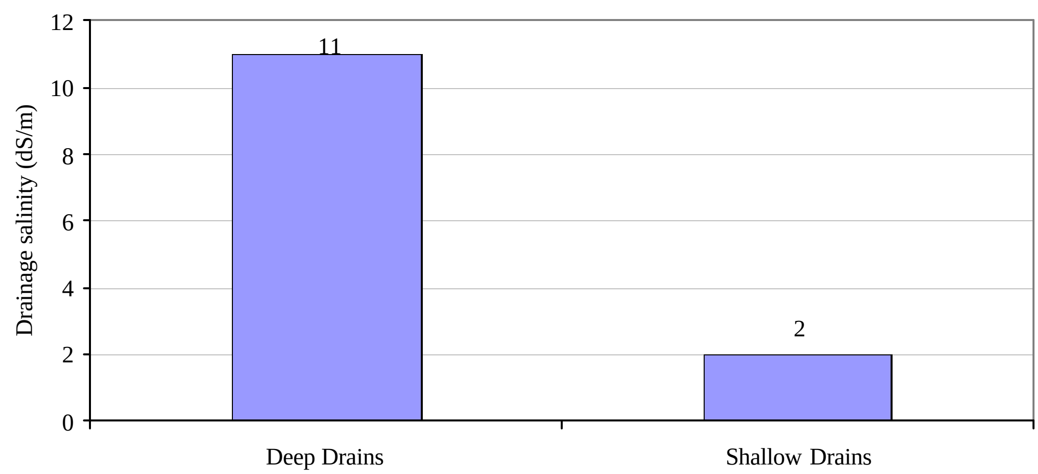


Figure 2-19. Average Drainage salinity for each treatment for an irrigation season, after Christen and Skehan (2000)

Table 2-5. Salt removed and applied for different management and drainage scenarios after Christen and Skehan (2000)

	Salt Applied (kg/ha)	Salt Removed (kg/ha)
Deep Drains	508	5867
Shallow Drains	508	319

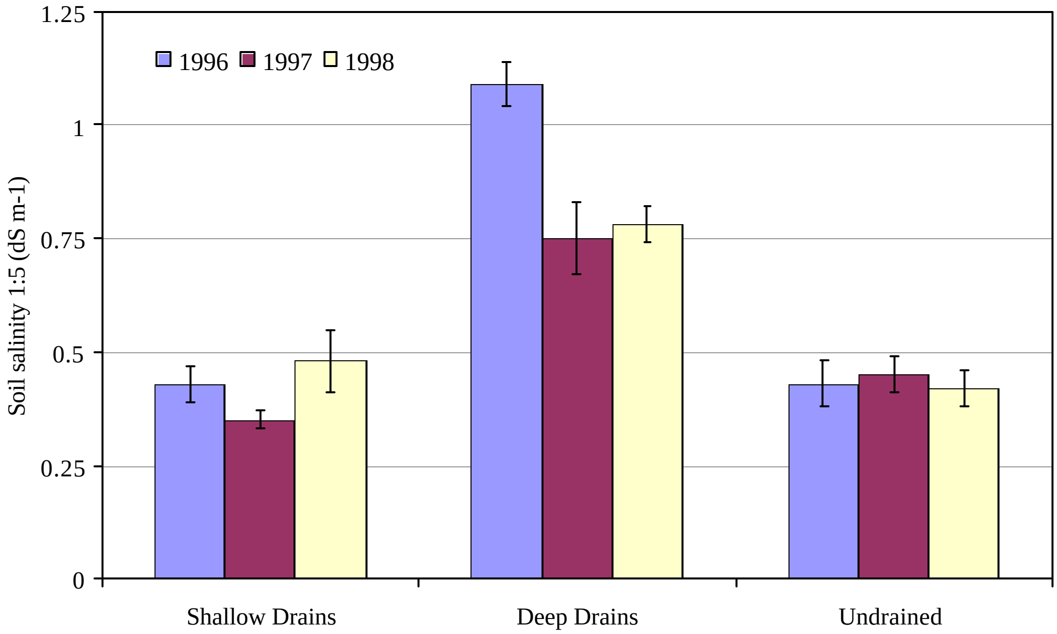


Figure 2-20. Change in soil salinity 0-0.6m, after Christen and Skehan (1999)

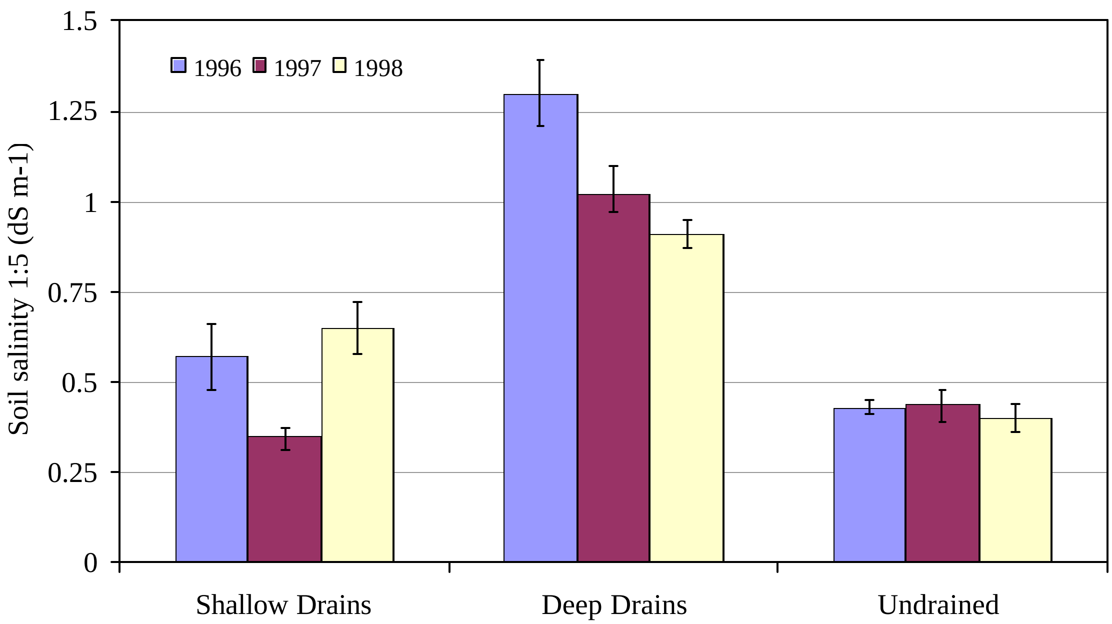


Figure 2-21. Change in soil salinity 0-2.0m, after Christen and Skehan (1999)

Thus, there may be limitations in the effectiveness of shallower drainage systems in preventing soil salinisation in the long term if the increasing soil salinity trend is maintained. However, there were no differences between yields of the treatments during the monitoring period.

In semi-arid regions Ghaemi and Willardson (1992) reported findings investigating the use of shallow plastic lined mole drains for controlling salinity in the Cache Valley, Utah. Three treatments were investigated with spacings of 6, 12, and 24m. All drains were installed at a depth of 0.75m. No dramatically different effects on either water table levels or salt removal were found between the treatments. The shallower plastic-lined mole drains were effective in reducing excess water in the upper level of the soil profile and provided adequate protection for the pasture grass grown on the experimental plots from salinisation. However, the success of the shallow drain system relied on the pasture grass lowering the water table to a significant depth below the shallow drains to prevent resalinisation.

Hermsmeier (1973) investigated the performance of shallow drains in a heavy clay soil in the Imperial Valley of California. Normal drainage design required drains at 1.2m depth to be spaced at a 6m spacing, however such a configuration was deemed to be unviable for economic reasons and instead drains were placed at 1.14m depth and 61m spacing. Results from the experiment found that the shallow drains were only marginally successful in providing protection from salinisation with only 42% of the net salt applied through irrigation water removed for a Barley crop (flood irrigated) and only 8% for a subsequent sugar beet crop. Measured soil salinities were found to only significantly decline in the top 0.3m of soil from 15 dS/m to 10 dS/m after the barley crop and later to 8.4 dS/m after the sugar beet crop. As there was no control in the experiment it was unclear, however, whether salinity in the top soil would have declined without the presence of the drains. Hermemeier (1973) concluded that the small amount of salt removed by the drains when combined with salt removed through natural drainage was sufficient to maintain a favorable salt balance.

It can be seen from the above studies, that the use of shallow drainage systems, may not provide adequate leaching of the soil rootzone. Reasons for this may be that with closely spaced shallow drainage systems the opportunity for preferential flow to occur is much greater than with deep wider spaced drains. Indeed, particularly with mole systems preferential flow through leg slot fissures is a major flow mechanism (Leeds-Harrison, Spoor and Godwin 1982; Christen and Spoor 1999) and this effectively reduces solute transport. Secondly, shallow drainage systems allow a build up of the water table to a shallow depth, which allows salinisation of the rootzone to occur through capillary rise. With shallow subsurface drainage systems installed at depths <1m from the soil surface salinisation potential through capillary upflow would be significant. Talsma (1963) in investigating the potential for salinisation of soils through capillary rise found that the potential for salinisation to occur was significantly increased when capillary rise was greater than 1mm/day and defined the concept of critical depth to the water table based on this capillary rise value. In soils investigated in both the Murrumbidgee Irrigation Area and also areas of California the critical depth to water table was found to be greater than 1m. Therefore, shallow drainage systems <1m have the potential to salinise from capillary upflux of salts if the water table stabilizes below drain depth.

Considering these factors one could hypothesise that an option that may allow the benefits of shallow drains to be incorporated into subsurface drainage designs for removing excess water whilst still ensuring protection against salinisation is through the use of complex drainage configurations that incorporate drains at different depths. Such systems could offer the potential benefits of shallow drains (decreased salt loads and increased waterlogging control) whilst maintaining a favourable salt balance in the rootzone through leaching from the deeper drains.

2.8.3 Complex Drainage Configurations

A number of investigations have been undertaken on non-traditional drainage configurations. Of these the most common configurations consist of bi-level drainage systems as reported by DeBoer and Chu (1975) and Chu and DeBoer (1976). In these studies mathematical treatment is given for the situation of Bi-level drains placed at alternating depths and these investigators focused on providing analytical solutions, based on Dupuit-Forchheimer assumptions, both steady state and transient, for the design of bi-level drainage systems.

The steady state analytical expression derived by the authors, for the case depicted in Figure 2-22 was

$$H_0^{\ 2} = \frac{va^2}{4k} + \frac{k\left(D_2^2 - D_1^2\right)^2}{4va^2} + \frac{\left(D_2^2 + D_1^2\right)}{2} \qquad \textbf{Equation 2-17}$$

which applies only when the maximum height of the water table is greater than D_2. The transient equation for a falling water table situation is given as:

$$\ln\left[\frac{1+\sqrt{\frac{A}{B}}H_0}{1-\sqrt{\frac{A}{B}}H_0}\frac{1-\sqrt{\frac{A}{B}}H}{1+\sqrt{\frac{A}{B}}H}\right] = \frac{-2\sqrt{AB}T}{Cf} \qquad \textbf{Equation 2-18}$$

where

$A = 4k/a^2$

$B = 2k(D_1^2 + D_2^2)/a^2$

H_0, H, D_1, D_2 and a = dimensions of the systems shown in Figure 2-22

k = Hydraulic conductivity in cm/day

T = time in days

C = Water table shape factor proposed

f = Drainable porosity

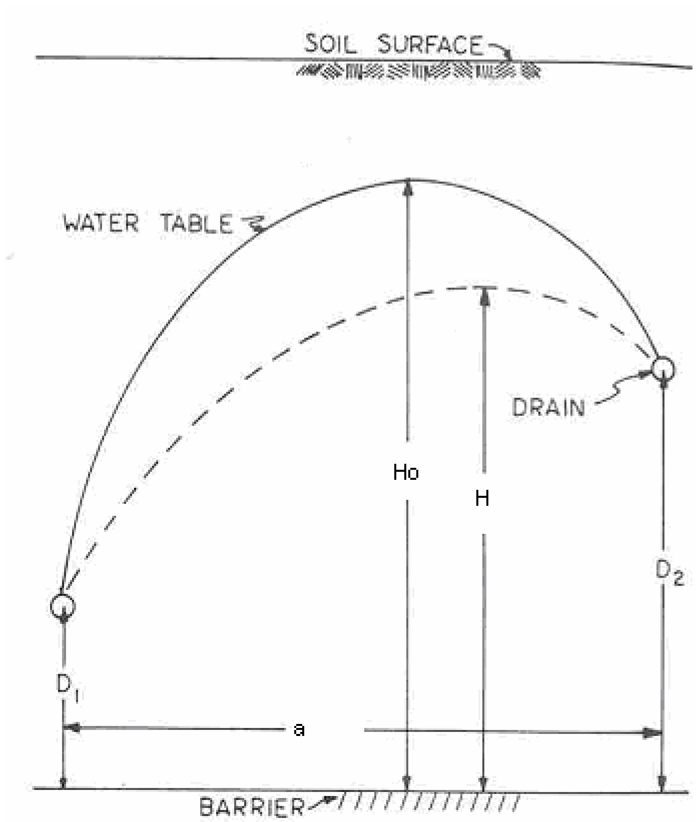


Figure 2-22. Geometry of bi-level drainage system, after Chu and DeBoer (1975)

Verma et al. (1998) later used the linearised Boussinesq equation to formulate a boundary value problem for a bi-level drainage system and obtained expressions for the head and discharge of a bi-level drain system given below:

$$H = H_0\left[1+\sum_{n=1}^{\infty}(-1)^n erfc\frac{(na-X)}{2\sqrt{ET}}+\sum_{n=0}^{\infty}(-1)^{n+1}erfc\frac{(na+X)}{2\sqrt{ET}}\right] + H_1\left[\sum_{n=0}^{\infty}\left\{erfc\,\frac{(2n+1)a-X}{2\sqrt{ET}}-erfc\,\frac{(2n+1)a+X}{2\sqrt{ET}}\right\}\right]$$

Equation 2-19

$$Q_d = -\frac{kD_a}{\sqrt{ET}}\left[2H_1 e^{-\frac{a^2}{4A^2}} + H_0(1-2e^{-\frac{a^2}{4A^2}}\right]$$

Equation 2-20

$$Qs = -\frac{kD_a}{\sqrt{ET}}\left[H_1 + H_0(2e^{-\frac{a^2}{4A^2}} - 1)\right]$$

Equation 2-21

Where:

H_0 = Initial watertable elevation above deep drains

H_1 = Watertable elevation at time T

E = Aquifer diffusivity

D_a = Average depth of ground water flow

k = Hydraulic conductivity

Q_s and Q_d = Discharge of shallow and deep drains respectively

Comparisons of Equation 2-18 of Chu and DeBoer (1976) and Equation 2-19 of Verma *et al.* (1998) with field observations of Chu and DeBoer (1976) are shown in Figure 2-23.

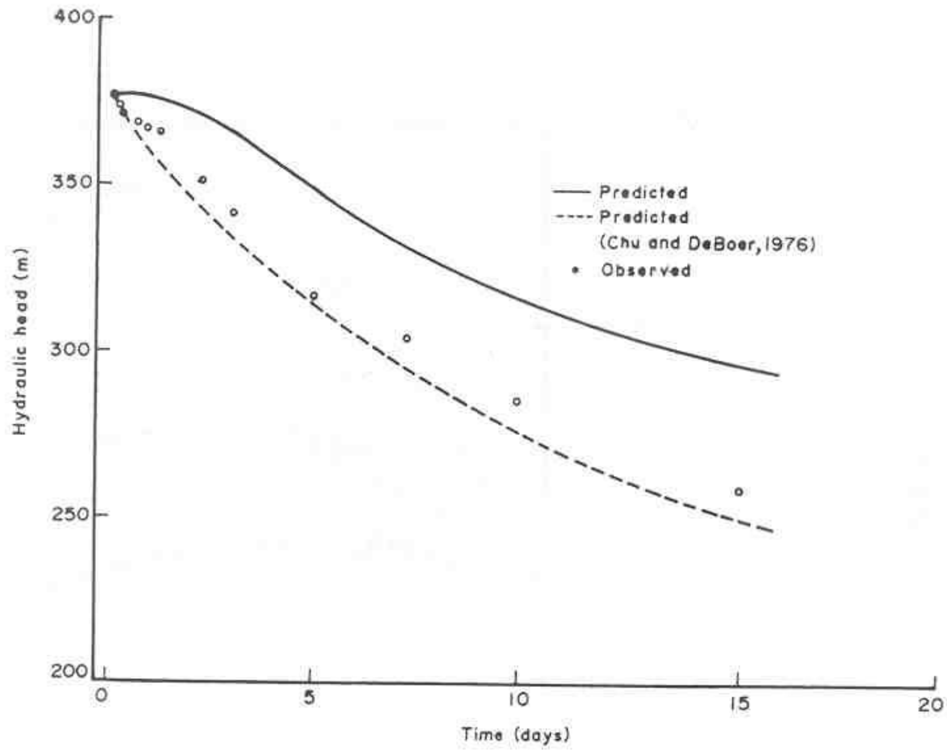


Figure 2-23. Comparison of the predicted and observed hydraulic heads for a bi-level drainage system, after Verma et al. (1998)

Figure 2-23 shows that the solution of Chu and DeBoer (1976) predicted lower hydraulic heads, which were closer to field observed data than that of Verma *et al.* (1998). Reasons stated for this were that the assumption of an initial parabolic water table shape was used by Chu and DeBoer (1976), whereas Verma et al. (1998) assumed an initially flat water table. The field data collected tended to meet the criteria of a parabolic water table shape hence the better agreement with the solution presented by Chu and DeBoer, (1976).

Numerical analysis undertaken by Verma et al. (1998) comparing Bi-level and single – level drainage configurations showed that through the use of bi-level drainage systems benefits in reduced drain water salinity may be achieved. Figure 2-24 shows the variation in hydraulic head mid-way between two drains for a theoretical bi-level drainage system (alternate drains at 1.8m and 1.2m depth) and conventional single level drainage system (1.8m depth), both with a 50m spacing between drains.

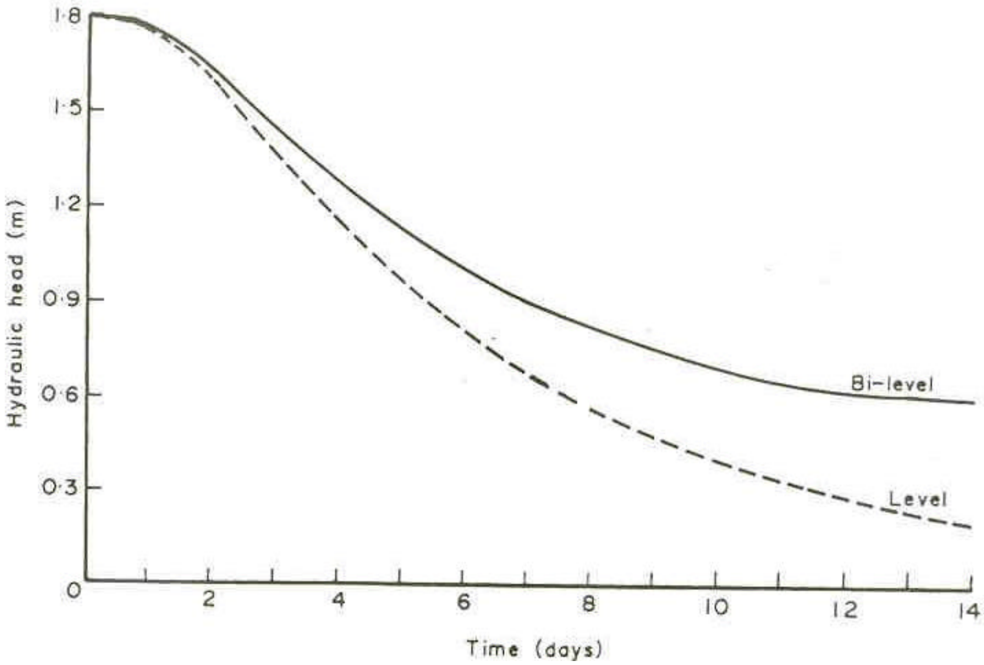


Figure 2-24. Temporal variation in maximum hydraulic head in the case of a bi-level and level drainage system, after Verma et al. (1998)

It can seen that hydraulic head decreases continuously at a lower rate for the bi-level drainage system than for the single-level drains. However, for the first 3 days, when waterlogging problems occur, differences between the two systems are small. This results in a lower drainage rate (Table 2-6) once the water table drops below the depth of the shallow drain and was believed by the authors to be beneficial in arid and semi-arid irrigation regions where too much drainage should be avoided due to disposal problems. The lower drainage rate after longer periods of time is due to the bi-level drainage system reverting to a single level drainage system with double the spacing once the water table drops below the depth of the shallow drains. Therefore, the depth of the shallow drains play an important role in controlling the drainage rate.

Table 2-6. Comparison of discharge rate for deep drain in a bi-level and a conventional single level system, after Verma et al. (1998)

	Spacing (m)	Discharge per unit length (h_0 = 1.8m and h_1 = 0.6m)
Bi-level	50	0.14
Conventional	50	0.23
Single Level	100	0.12

Kirkham, van de Ploeg and Horton (1997) extended existing potential flow theory for single-depth drainage systems to investigate bi-level drainage systems. The authors used complex variables and the method of multiple drain images to derive equations for the hydraulic head, the velocity potential, the stream function and the drain discharge. The focus of the work was on investigating the effects of adding additional drains between existing drains for increasing the drain discharge and performance of the drainage system. The authors found that with the addition of a single drain mid-way between two existing drains increased the performance of the drainage system significantly even when drain depths of the additional drain were only half the depth of the original system. For example, the addition of a 0.6m deep drain between existing drains 1.2m deep and spaced 25m apart saw a 160% increase in drain discharge. Therefore, it can be seen that the addition of shallow drains has a significant effect on the performance of drainage systems and by incorporating the increased discharge into the drainage design then spacing of the deeper drains may be increased.

Hathoot (1998) outlined theory, again using complex potentials and multiple drain images, of a drainage system consisting of regularly spaced drains with a series of mole drains laid between the drains for addressing the problem of draining heavy soils in which traditional drainage designs prove costly due to the narrow spacing needed to drain such soils. An equation for the unsteady vertical movement of the water table was developed from which an approximate implicit spacing formula was derived as shown:

$$a = \frac{pkET}{FB\ln\left[\dfrac{d+\dfrac{J}{E}}{h_m+\dfrac{J}{E}}\right]}$$

Equation 2-22

where:

T = specified time period required for lowering water table from h_0 to h above mole drains

a = spacing between pipe drains

h_m = water table height above mole drains midway between two mole drains

δ = depth of mole drains

F = drainable porosity of the soil

k = hydraulic conductivity of the soil

B = GH-FI

E = 2(G-I) + m(H-F)

$$J = \frac{d_1}{2}(2G - mF) - (D_1 - \frac{r}{2})(2I - mH)$$

where:

$$F = \ln\left[\frac{Cosh\ \frac{p}{a}(D_1 + h_m)\cosh\ \frac{p}{a}(2D + D_1 + h_m)}{\sinh\ \frac{pr}{2a}\sinh\ \frac{p}{a}(2D + \frac{r}{2})}\right]$$

$$G = \ln\left[\frac{\cosh\ \frac{pmh_m}{a}\cosh\ \frac{pm}{a}(2D + 2D_1 + h_m)}{\cosh\ \frac{pm}{a}\left(\frac{r}{2} - D_1\right)\cosh\ \frac{pm}{a}\left(2D + D_1 + \frac{r}{2}\right)}\right]$$

$$H = \ln\left[\left\{\frac{\cosh\frac{p}{L}(D_1 + h)\cosh\frac{p}{L}(2D + D_1 + h_m)}{\left[\cos^2\frac{p}{2m} + \sinh^2\frac{p}{a}\left(D_1 - \frac{d_1}{2}\right)\right]\left[\cos^2\frac{p}{2m} + \sinh^2\frac{p}{a}\left(2D + D_1 - \frac{d_1}{2}\right)\right]}\right\}^{\frac{1}{2}}\right]$$

$$I = \ln\left[\frac{\cosh\frac{pmh_m}{a}\cosh\frac{pm}{a}(2D + 2D_1 + h_m)}{\sinh\frac{pmd_1}{2a}\sinh\frac{pm}{a}\left(2D + 2D_1 - \frac{d_1}{2}\right)}\right]$$

where

m = number of mole drains installed between pipe drains

r = pipe drain diameter

D = thickness of soil layer between pipe drains and impermeable layer

D_1 = thickness of soil layer between pipe and mole drains

d_1 = mole drain diameter

a = spacing between pipe drains

Hathoot (1998) was able to show that by introducing mole drains the spacing of pipe drains could be increased several times. However, no validation of the mathematical expressions was undertaken with field data. In a subsequent discussion by Kacimov (1999) on the above analysis a number of problems regarding the analysis and subsequent assumptions were pointed out. These included the expression for the complex potential which only occurs in cases of an infinitely high depth of the saturated layer located far above drain arrays, which is unlikely to occur in practice. These assumptions limit the applicability of the analysis when true field conditions of drainage systems are considered.

Unfortunately, no field-based research has been reported for such drainage configurations, and hence possible benefits from a water disposal and irrigation water use efficiency point of view cannot be made. Benefits of such systems to water quality aspects can be assumed based on previous research where shallower drainage systems improved water quality aspects of drainage water in relation to salinity aspects, however no quantification of the benefits of improved water quality from the above mentioned systems has been made.

2.8.4 Summary

Considering the benefits of shallow drainage systems in the reduction in drain water salinity then incorporation of such a system into drainage design is beneficial. Due to the possible problems in relation to the effectiveness of shallow drainage systems, associated with problems of capillary rise of saline water, then the use of a combined shallow and deep drainage system could offer potential benefits and overcome many of the shortcomings associated with the individual systems. The proposed system investigated in this research is shown in Figure 2-25 and consists of a series of shallow drains underlaid by deeper drains. The conceptualisation of the system is that the shallow drains will provide significant protection to the crop from waterlogging and provide rapid removal of water from the rootzone and have low salinity of drainage waters. The deeper drains, which can be spaced at greater distances than in a single-level system, provide protection from salinisation due to capillary rise by lowering the water table to a safe depth. With such a system it is hypothesized that there will be an overall reduction in drainage salt load due to the shallow drains removing a significant portion of the water. Such a system should also provide better waterlogging protection and also allow a much greater degree of control over the drainage system, with the option of operating only the shallow or deep drains at different times depending on drainage water disposal restrictions. Costs of the system may also be lower due to the increased spacing of the deep drains and the reduction in installation costs of the shallower system. The drainage configuration, termed a ‘Multi-level Subsurface Drainage System’ (MLD) for this research is shown in Figure 2-25. The MLD system was investigated in this research for reducing salt loads from subsurface drainage systems.

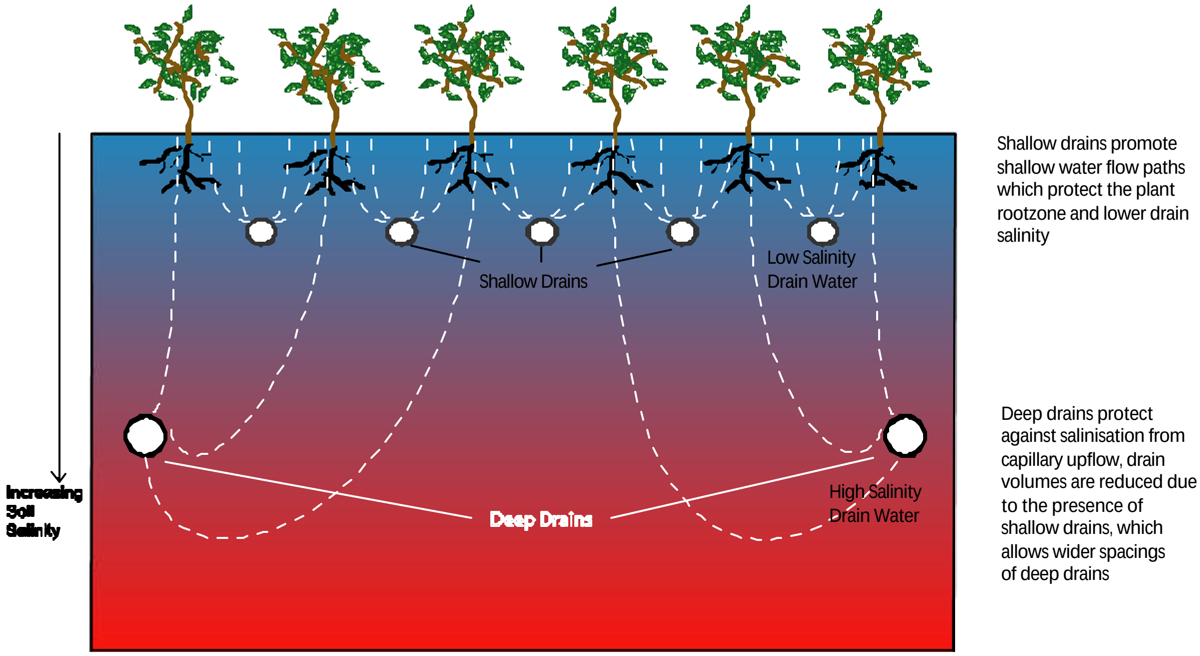


Figure 2-25. Multi-level subsurface drainage system, white dotted lines indicate idealised water flow paths

2.9 Controlled Drainage

Traditional management of irrigation and drainage systems in arid and semi-arid areas has been undertaken without considering the impacts associated with disposal of saline drainage water. Recently, it has become apparent that in many instances subsurface drainage systems may 'over drain', i.e. remove more water than is needed to maintain a productive rootzone. This may be due to a number of factors such as draining in non-critical periods, drainage of regional sources of water, preferential flow to drains and draining below the rootzone depth. Controlled drainage is a practice that aims to minimize the volume of saline drainage water and hence reduce the disposal problem relating to drainage water. Figure 2-26 shows diagrammatically conventional drainage, shallower drainage and controlled drainage. Controlled drainage involves the installation of water control structures to a drainage system, which allows the water table level within the field to be manipulated through active management of the drainage system. This may involve controlling the water table depth to maximize plant water use from a shallow water table or controlling the depth to minimise drainage flow rates.

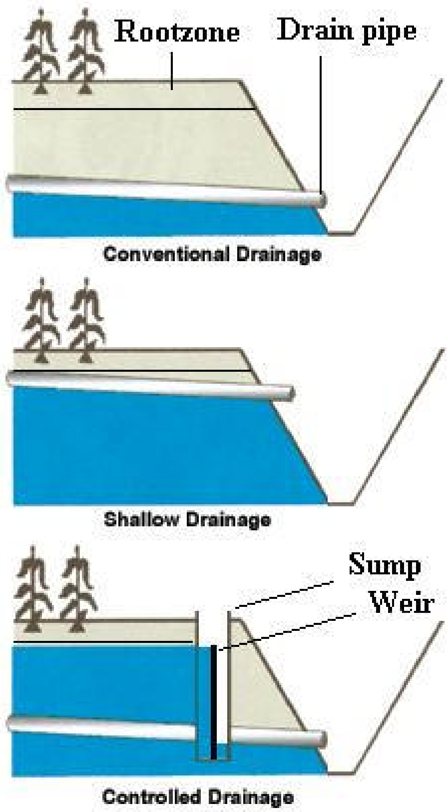


Figure 2-26. Conventional, shallow and controlled drainage.

2.9.1 Crop Water Use from a Shallow Saline Water Table

Recently, investigations have begun into the potential benefits of shallow groundwater availability for meeting crop water requirements in arid and semi-arid irrigation areas. Research has demonstrated crops can use saline groundwater, which means that in some situations there is the opportunity for crops to utilise water from a shallow saline groundwater source (Ayars, Grismer and Guitjens 1997).

Van Schilfgaarde (1974) believed that plants could use significantly higher saline water than previously reported based on thresholds for plant salt tolerances, which are generally reported. Maas (1986) demonstrated that plants tend to be more salt sensitive during the earlier growth stages than in later growth stages, allowing use of more saline water after crop establishment.

2.9.1.1 Lysimeter Based Studies

A number of researchers (Hutmacher et al. 1996; Kruse, Young & Champion 1985; Meyer, White & Smith 1996; Namken, Weigand & Brown 1969) have shown in lysimeter based studies that annual crops such as wheat, lucerne, sunflower, corn and cotton have the potential to extract significant amounts water from a shallow saline water table in carefully managed systems. A summary of findings from the above mentioned studies is given in Table 2-7.

Table 2-7. Water table contribution to evapotranspiration

Study	Crop Type	Depth to Water Table (m)	Water Table Salinity (dS/m)	Water Table Contribution to ET (%)
Meyer, White & Smith 1996	Lucerne	0.6	1.6	22-55
Meyer, White & Smith 1996	Lucerne	0.6	16	13-25
Kruse, Young & Champion 1985	Corn	0.6	6	55
Namken, Weigand & Brown 1969	Cotton	0.9	1.6	60
Hutmacher et al. 1996	Cotton	1.2	<20	30-42
Hutmacher et al. 1996	Cotton	1.2	20-30	14-19

It can be seen that the potential for shallow saline groundwater use is a function of a number of variables. From these studies the most limiting factors were the depth to the water table and the salinity of the water table. Kruse, Young and Champion (1985) reported that increasing the depth to water table had a larger effect on crop water use than did increasing the groundwater salinity.

Studies undertaken on perennial crops have been much more limited. Borland et al. (1996) investigated the effects of saline and non-saline water on peach tree water use in lysimeters. The effect of salinity and shallow water tables (1.4m depth) used in combination with Regulated Deficit Irrigation (RDI) on peach trees was studied over a 2-year period. Results are presented in Table 2-8 and show that for the non-saline treatment the potential for crop water use from the shallow water table was as high as 30% of total tree water use during RDI irrigation periods. This dropped to between 7-11% during non RDI irrigation periods. The saline treatment had a much lower use of the saline groundwater, 6.5-15% during RDI irrigation periods and 3-4.5% during non RDI periods.

Table 2-8. Water use from water table as a percentage of total tree water use, after Borland et al. (1996)

	Year 1		Year 2		
Treatments	**RDI Period**	**Post RDI Period**	**RDI Period**	**Post RDI Period**	**Yield (kg/Tree) 1st Year**
Non-Saline RDI + WT	27.9	6.8	28	11	22.6
Saline RDI + WT	15.1	2.9	6.5	4.5	19.1
Control	-	-	-	-	25.8

* WT = Watertable

Peach trees (Prunus Persica), however, are extremely sensitive to salinity (Maas, 1986). Water table salinities for the treatments over the 2 year period are shown in Figure 2-27 and it can be seen that during the second year a large increase in the water table salinity of the saline RDI treatment was observed, which would account for the drop from 15% to 6.5% of water use from the water table in this treatment. Yields declined in both the non-saline and saline RDI treatments compared to the control treatment with no water table and no RDI (Table 2-8) with a decline of 15% and 25% respectively for the two treatments.

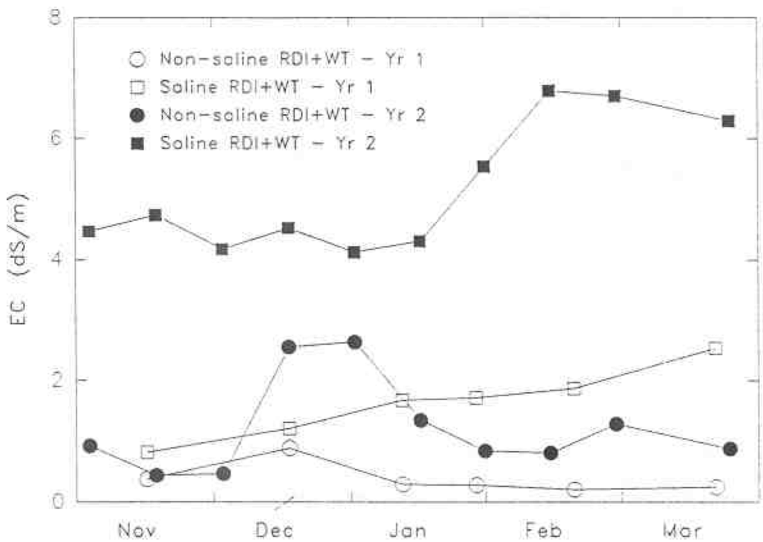


Figure 2-27. Effect of water table treatment on the EC (dS/m NaCl) of the water table (EC_w) calculated from measured Na and Cl, after Borland et al. (1996)

2.9.1.2 Field Studies

Field studies investigating controlled drainage in semi-arid and arid irrigation areas have been very limited. A large body of work has been carried out in humid areas using controlled drainage to minimize nitrate and phosphate in drainage water through the use of controlled drainage. Evans, Gilliam and Skaggs (1991) and Evans, Skaggs and Gilliam (1995) present a summary of controlled drainage effects on water quality in humid areas and show that as much as 30% of nitrogen and 50% of phosphorus loads can be reduced through controlled drainage as compared to conventional drainage. This occurs through the large reduction in drainage volumes due to control mechanisms to minimise drainage quantities. Whilst the same principle of reducing drainage volumes and hence salt loads in semi-arid irrigated areas applies, controlled drainage has not been widely practiced in these areas due to the potential for soil salinisation that accompanies high water tables.

Field based research investigating crop water use from shallow groundwater sources has been undertaken in the arid and semi-arid regions of California and in some field studies controlled drainage has been used beneficially to minimize drainage water volumes and hence disposal problems.

Ayars (1996a,b) and Ayars et al. (1996,1999) report findings of a case study undertaken on the West side of the San Joaquin Valley of California to investigate the effects of drainage system management on a tomato crop. Control structures were installed on subsurface drainage laterals on a 65 ha field to raise the water table and investigate the potential for shallow saline groundwater use by the tomato crop. The field was then divided into three areas based on water table heights, which are reproduced in Table 2-9.

Table 2-9. Water table depth areas and start and end of season water table heights, after Ayars (1996a)

	Water Table Depth (m)	
Area	Start Season	End Season
Shallow (S)	1.5	2.2
Medium (M)	1.8	2.6
Deep (D)	2.2	2.6

The EC of the shallow groundwater ranged from 3 to 8 dS/m. Leaf Water Potential (LWP) measurements were undertaken in each of the variable water table areas and are shown in Figure 2-28.

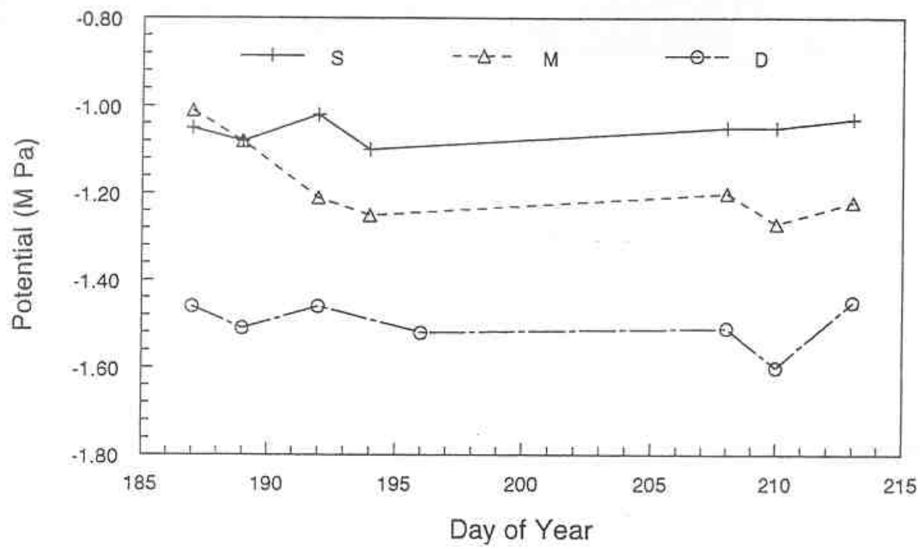


Figure 2-28. Tomato leaf water potential in shallow (S), medium (M) and deep (D) groundwater areas, after Ayars (1996a)

LWP of –0.9 to –1.1 MPa is considered a minimal stress level in tomato plants. It can be seen from Figure 2-28 that the area with the deep water table increased LWP and was well above recommended levels for all of the growing season. This had a large effect on the yields from each of the treatments, which are shown in Figure 2-29. It can be seen that as depth to water table decreased yields were increased supporting the view that the tomato crop was using shallow ground water.

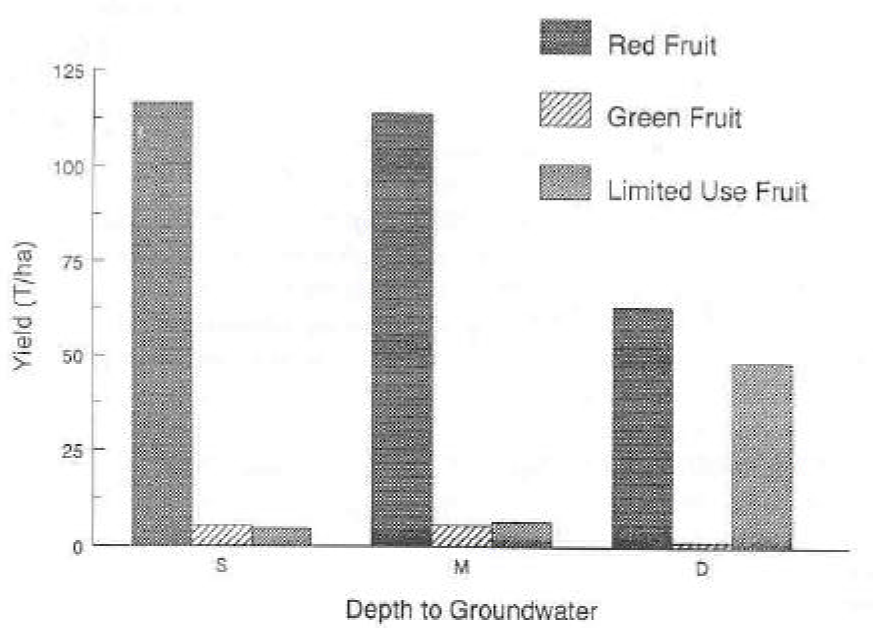


Figure 2-29. Distribution of tomato fruit yield (T/ha) components in the shallow (S), medium (M) and deep (D) groundwater areas, after Ayars (1996)

Using controlled drainage and in-situ use of groundwater reduced the irrigation requirement by 141mm compared to an adjacent field, which was irrigated and managed in the same way without controlled drainage.

Unfortunately, no investigation of drainage volumes was reported in the study. However, considering the lower water application and the in situ use of shallow ground water the drainage volumes could be assumed to be greatly reduced compared to an unmanaged drainage system.

Ayars and Soppe (2001) report on a three-year study investigating the integrated management of irrigation and shallow ground water in the presence of drains. The study used both lysimeter and field based studies to assess controlled drainage practices in the San Joaquin Valley California. The study objectives were to investigate if yields were maintained in controlled drainage situations, whether the salt balance of the rootzone was favorable and if any drainage water reduction was possible. Discharge data for the study period showed that controlled drainage practices helped reduce the total drainage flow compared to unmanaged drainage systems and a favorable salt balance was maintained in the rootzone. However, the controlled drainage practices required careful management to ensure that this was the case, and salinisation was a threat unless careful management was applied. The authors found that generally winter rainfall and pre-plant irrigation allowed significant leaching to maintain a favorable rootzone salt balance. Yields under controlled drainage situations were difficult to assess due to the large variations year to year and problems with stand establishment and poor soil condition. Within a given year, however, plant sizes varied little between treatments. It was concluded from the study that managing shallow groundwater was an effective way of reducing total drainage water even in saline conditions. Rootzone salinity would be controlled provided a careful integrated approach to managing irrigation and drainage was applied.

2.9.2 Reduction in Drainage Rate

Controlled drainage practices have also been implemented in semi-arid and arid irrigation areas with the aim of reducing drainage rates simply by reducing the drainage criteria to that needed to maintain a salt balance in the rootzone. These research efforts have focused not on crop water use from the water table but rather on reducing the drainage rate to a lower rate than originally intended. Reasons for such reductions may be actual field drainage rates being much higher than design rates and system changes, which affect drainage requirements such as a change in irrigation method or cropping.

Day, Gartung and Lord (1988) compared controlled drainage against conventional drainage systems in the Firebaugh district of California on silty clay loam soils using furrow irrigation. Three fields were investigated, two without controlled drainage and one with controlled drainage practices. The controlled drainage treatment consisted of installing weirs on drainage sumps 0.76m above the drain line. Comparisons between the fields were made based on a Net annual Deep Percolation (NDP) principle defined as:

$$NDP = AAI + RF - ET$$

Equation 2-23

Where NDP = Net annual deep percolation

AAI = Sum average amount infiltrated from irrigation

RF = Annual infiltrated rainfall

ET = Annual evapotranspiration

The minimum NDP (NDP_{min}) defined as the minimum deep percolation that maintained a salt balance in the rootzone was then used to compare measured subsurface drainage flow values with NDP_{min} values calculated based on a 5 % leaching requirement and 92 % distribution uniformity. Table 2-10 shows excess drainage above NDP_{min} for the three field experimental sites.

Table 2-10. Computed excess drainage from three field sites, after Day, Gartung and Lord (1988)

Site	Excess Drainage (mm)
P-1 (Controlled Drainage)	15
P-2	280
B10-2	51

It can be seen that the controlled drainage site, P-1, had only 1.5cm of excess drainage above that required to maintain an adequate salt balance of the rootzone. For the two uncontrolled sites, P-2 and B10-2, drainage was much higher. Day, Gartung and Lord (1988) concluded that reductions in subsurface drainage water could be achieved with careful management of the drainage system using controlled drainage practices. No details were reported in the study on the effect controlled drainage had on the productivity of the cropping systems used at the experimental. Also, no direct comparisons could be made on water table behaviour, due to the installation of the control drainage structures, as no data was reported from uncontrolled periods of operation, hence no comparisons or effects of controlled drainage on soil salinities was reported.

Christen and Skehan (1999) reported on findings undertaken using controlled drainage to reduce drainage volumes from subsurface drainage systems in the Murrumbidgee Irrigation Area of Australia. Subsurface drains at the experimental site were 1.8m deep and at a 20m spacing. The controlled drainage management consisted of installing risers on drain outlets to maintain a target water table depth of 1.2m below the soil surface. The main aims of the controlled drains were to prevent preferential trench flow during irrigation and drainage of the soil profile below the rootzone. There was also and un-managed drainage treatment. The trial was conducted over a 2-year period and drainage volumes in the controlled treatment were reduced by 33 %. There was also a reduction in the average salinity of the subsurface drainage water of 36 % compared to the un-managed drainage treatment.

It can be seen that the controlled drains reduced the drain volumes, salinity of the drain water and hence the salt load compared with uncontrolled drains installed at the same depth and spacing. Soil salinity of the rootzone in the two treatments was also comparable with little difference between the two treatments.

2.9.3 Summary

Based on previous research it can be clearly seen that annual crops have the potential to use significant volumes of saline water from a water table. This has been proven in both field and lysimeter studies undertaken under a number of irrigation and drainage management conditions throughout various parts of the world. Less well understood and researched is the potential for perennial crops to use water from a saline water table. Only one study undertaken on peaches in lysimeters has investigated the contribution of the water table to meet evapotranspiration (Borland et al. 1996) and the results were promising. However, no field based studies investigating the use of saline groundwater in perennial crops under irrigated conditions have been undertaken. Considering the potential benefits associated with the increased use of saline water from a water table, investigation of the use of controlled drainage in such systems is important. Controlled drainage offers benefits of reduced drainage volumes and subsequently reduced salt loads, hence if irrigated perennial crops can utilize significant amounts of water from the water table then there is a large potential to reduce drainage volumes and subsequent salt loads.

Therefore, a component of this research aims to investigate the effects of implementing controlled drainage management on drainage salt loads and investigate the potential for crop water use from a saline water table in irrigated perennial horticulture when using controlled drainage management.

2.10 Conclusions

From the literature review it can be seen that two options for reducing salt loads from subsurface drainage systems have been identified that need further research. These being firstly, changes in drainage design which incorporate drainage salinity aspects, and secondly, active management of drainage systems through controlled drainage. In considering both options it can be seen that changes in drainage system design can only be easily implemented with new systems, hence opportunities for reductions in drainage salt loads are limited.

Therefore, the proposed research work has two components. Firstly, investigating a multi-level subsurface drainage system for reducing salt loads, (incorporating water salinity aspects into drainage design) and secondly, assessing the potential to modify existing drainage systems with controlled drainage to reduce drainage salt loads and promote crop water use from a shallow water table. Both options have the same ultimate aim of reducing drainage salt loads. Each option is also suitable for the soil and groundwater conditions present. Newly installed drainage systems are generally in very saline areas, hence the potential for crop water use from these sources is limited, whereas existing drainage systems tend to have less saline water tables and leached soil profiles, which provide greater potential for benefits from controlled drainage management.

3 Experimental Setting

3.1 Location

The Murrumbidgee Irrigation Area (MIA) lies between latitudes 34^0-35^0 S and longitudes 145^0-147^0 E and lies to the north of the Murrumbidgee River (Figure 3-3). The MIA is irrigated from water diverted from the Murrumbidgee River, supplied by large catchment dams located in the Snowy Mountains. The off-take for the MIA occurs at Bemembed weir located East of Narrandera. A locality map is shown in Figure 3-1, which shows the main canal distribution systems for the MIA. The Mirrool Creek and Little Mirrool Creek are used for drainage disposal within the MIA to nearby Barren Box Swamp where water is stored for later re-use in the Wah Wah Irrigation Area.

The MIA has a total farm area of 480 000 ha. Initially production from irrigation centered on horticulture, dairying and other pasture enterprises. Rice was grown experimentally in 1912 and since then has become the MIA's major annual crop farm commodity. The MIA is an important farming area and accounts for 32% of rice, 50% of citrus and 40% of grape production in New South Wales.

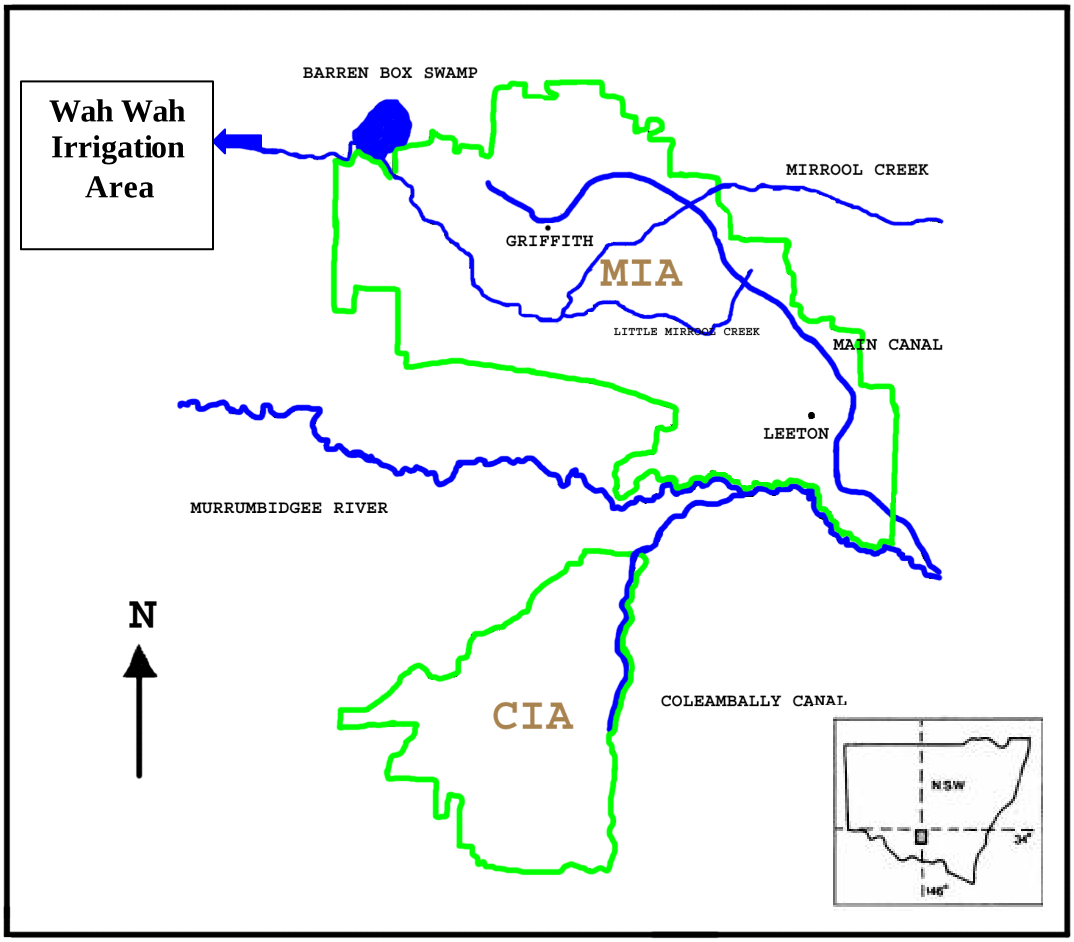


Figure 3-1. Location of the Murrumbidgee Irrigation Area

3.2 Climate

Average annual rainfall is 406mm, with a high variation ranging from 256mm (10 percentile year) to 609 mm (90 percentile year). Rainfall is fairly evenly distributed throughout the year. Mean monthly Class A pan evaporation peaks at 294mm (9.5mm/day) in January dropping to 43mm (1.5mm/day) in June. Mean total evaporation is 1869 mm or 18.69 ML/ha. (MIA and Districts Community Land and Water Management Plan, 1998)

3.3 Land Use and Irrigation Management

About 18 000 ha of the lighter textured soils are used for horticultural plantings within the MIA. Vines and citrus are the dominant crops, however other horticultural crops such as peaches and prunes are grown to a lesser extent. Irrigation management on the lighter soil types has traditionally been with furrow irrigation. Of the 600 commercially sized farms about 100 have converted to drip systems, particularly grape enterprises in the newer developments, (van der Lely 2001, pers. comm.) Water distribution systems to the horticultural areas of the MIA are generally through a concrete lined distribution system. In recent times horticultural expansion has seen horticultural crops extend into the heavier soil areas due to a lack of readily available lighter textured soils. These recent horticultural plantings tend to be predominately irrigated by drip irrigation.

The relationship between dominant crop type and geomorphic units and soil associations can be seen in Figure 3-2, taken from Pels and Stannard (1977). The figure indicates the relative proportions of soil types within the MIA. Due to the expansion of horticulture within the MIA, a shortage of more traditional horticultural areas shown in Figure 3-2 as area D and hillslope soils, has seen movement onto less suitable areas such as B and C areas in Figure 3-2.

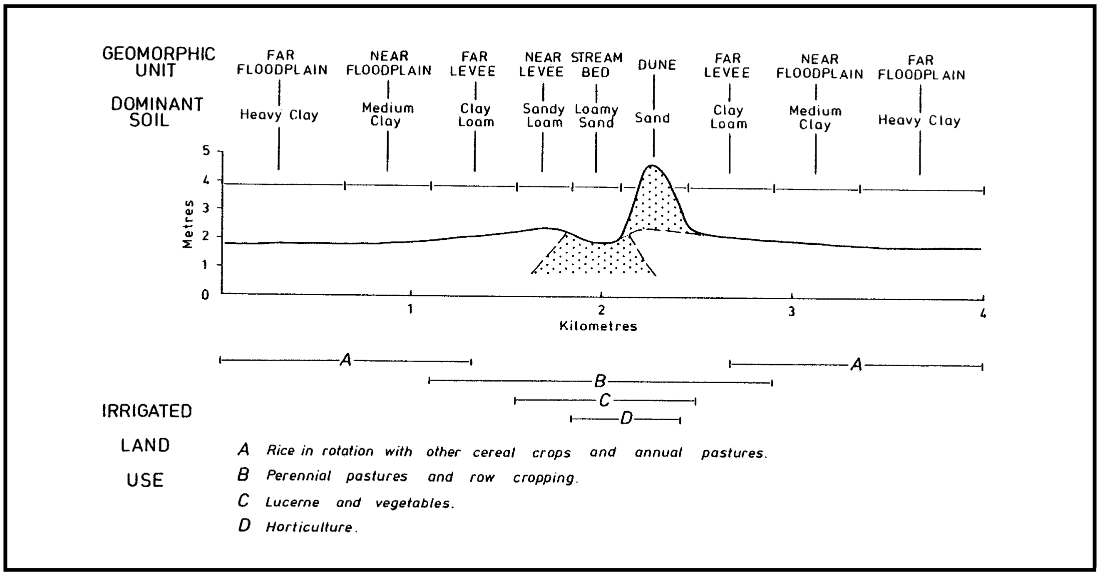


Figure 3-2. Diagrammatic cross-section of prior stream illustrating inter-relationship of geomorphic units, soils and land use, (Pels and Stannard, 1977)

Currently, 12000 ha of horticulture occur on the traditional horticultural soil types – areas D in Figure 3-2 and hillslope soils. Farm units are typically 10-20 ha. The conversion of the less suitable soil types (B and C of Figure 3-2) currently account for around 6000 ha of horticultural land (van der Lely 2001, pers. comm.). These newer farm areas range from 50-600 ha in size and are considerably larger than the more traditional horticultural plantings.

3.4 Geology

The MIA lies on the Riverine plain of the Murray Basin. The eastern boundary of the plain is formed by outcropping of bedrock as it forms the foothills of the eastern highlands. The Murrumbidgee alluvial fan forms a large part of the lower Murrumbidgee region. The apex of this fan is situated near Narrandera and sediments increase in thickness in a westerly direction from the eastern flank of the basin. The location of the Riverine Plain is shown in Figure 3-3.

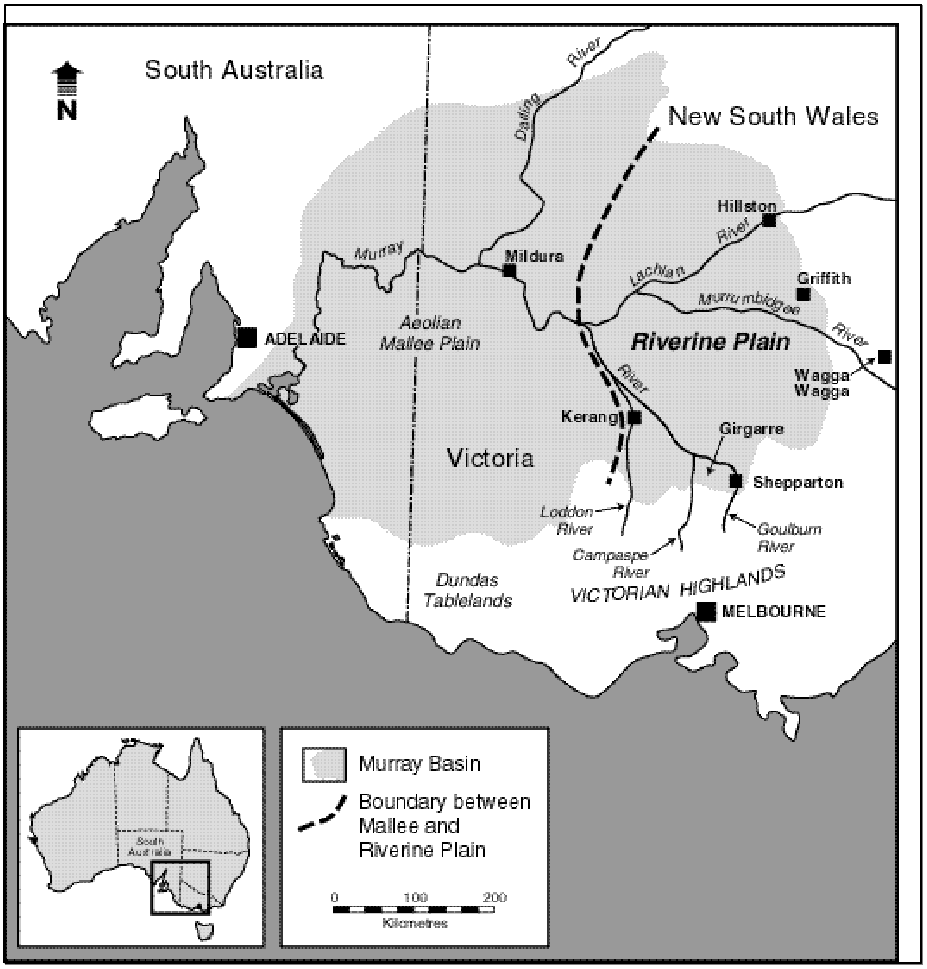


Figure 3-3. The Riverine Plain on which the Murrumbidgee Irrigation Area lies Herczeg et al. (2001)

Sediments of the riverine plain were deposited by fluvial lacustrine processes and form a blanket over the basin bedrock. The sediments from the plain have been categorised based on age and type of deposition into three distinct units by Brown and Stephenson (1991). These units are the Renmark Group, the Calivil Formation and the Shepparton Formation. In total around 230m of unconsolidated sediments are present.

A description of the stratigraphy units depicted by Brown and Stephenson (1991) are given below:

3.4.1 Renmark Group (136-178m)

The oldest stratigraphic unit within the basin is the Renmark Group, which directly overlies the pre-Cainozoic bedrock. The Renmark Group is also the most extensive of the three startigraphic units and forms a near continuous layer over the bedrock of the basin. It was deposited between Palaeocene to Middle Miocene ages and consists of light brown or quartz sand, with the upper sequence containing a higher proportion of argillaceous and carbonaceous sediments.

3.4.2 Calivil Formation (76-136m)

The Calivil Formation comprises of mostly pale grey coarse to granular quartz sand, with lenses of kaolin and carbonaceous clay. Deposition occurred during the late Miocene to Pliocene ages.

3.4.3 Shepparton Formation (0-76m)

The Shepparton formation forms part of the present day land surface and stems from the Pliocene age. This formation consists of clay, silt and silty clay, with lenses of coarse to fine sand and gravel.

The Shepparton formation is usually discontinuous in lateral extent and transmissivity is generally low. Flow within this aquifer is related to prior stream activity. Groundwater loss may be due to leakage to the lower Shepparton layer, capillary rise and through lateral movement through prior stream channels.

3.5 Physiography

The MIA lies on the north eastern section of the Riverine Plain across which the Lachlan, Murrumbidgee, and Murray rivers flow. This plain is due largely to the fluviate activity by streams of varying ages and magnitude. These sedimentary deposits are interbedded with wind blown clay deposits known as parna (Butler and Hutton 1956).

Butler and Hutton (1956) indicated the occurrence of three periods of parna deposition, within the Upper Shepparton formation, which forms the present day ground surface, each being followed by a period of soil development. Between each parna deposition there was a sporadic deposition of riverine materials associated with erosion, but lack of soil development on these indicated that the riverine phases were followed closely by the next parna deposition. The lowest and hence oldest deposition and soil forming phase is called the Cocoparra (van Dijk 1958). The next deposition of parna and its associated riverine material is called Barellan. The final deposition forms the greater part of the present day land surface and are called the Widgelli parna and its related riverine material is called Hanwood. Within the MIA a characteristic phase of the Widgelli parna occurs, known as the Tabbita phase.

Highly differentiated soils occur on the parna layer and these include brown solodized soils in the dune zones, red-brown earths on the hills, and red-brown earths and grey and brown soils of heavy texture on the riverine plains. The variation in soil types is caused by belts of riverine alluvium of varying width traversing the parna, variations in depth of the Widgelli parna sheet, fuluviatile-colluvial modifications of varying degree, differences in age of fluviatile deposits and drainage conditions which determine the main characteristics of the landscape and its soils, van Dijk (1961). A schematic diagram of the characteristic sequence of soils due to prior stream activity is shown in Figure 3-4.

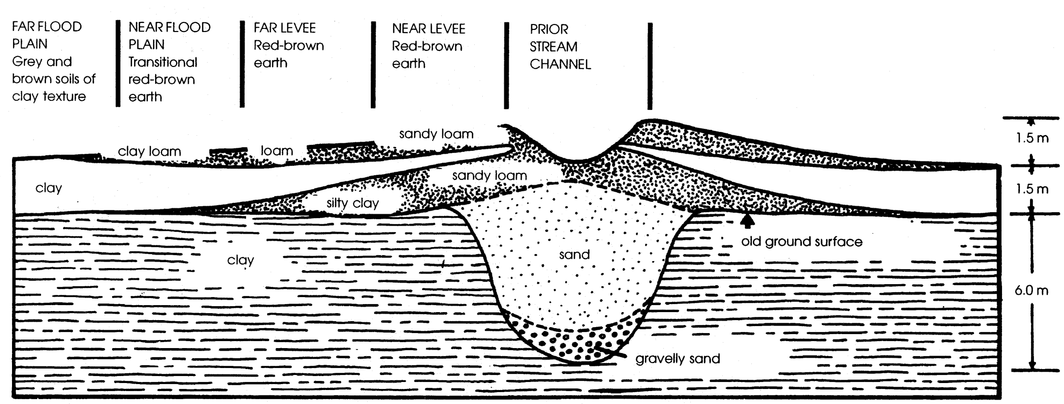


Figure 3-4. Relationship between prior stream and soil type, (Stannard 1976)

3.6 Description of the Soils

Investigation of the geomorphology of the area and review of the soil surveys (Stannard 1970; Taylor and Hooper 1938; van Dijk 1958 and van Dijk 1961) revealed that although there were at least 94 different soil types mapped within the MIA, the soils could be grouped together based on morphological similarity and recurrent patterns of associations. The soils of the area fit into the following five broad soil groups, taken from Hornbuckle and Christen (1999):

1. Clays (Both self-mulching and hard setting)
2. Red Brown Earths
3. Transitional Red Brown Earths
4. Sands over Clay (Solodized Solonetz)
5. Deep Sands

For a further description of the soils in there relation to drainage problems the reader is referred to Hornbuckle and Christen (1999).

3.7 Origin of Dissolved Salts

Numerous hypotheses relating to the development of salinity in the Australian landscape have been developed to describe the source of high salinity in shallow groundwaters and soils. Evaporation was investigated by Bonython (1956), remnant sea water entrapped in sedimentary basins at the time of their deposition (Johnson 1979; Wopfner and Twidale 1967), airbourne oceanic aerosols (cyclic salts) transported inland into basins by rainfall (Jack 1921; Mazor and George 1992) or a combination of rock weathering and marine aerosol accession (Chivas et al. 1991; Herczeg and Lyons 1991).

Recently, Herczeg, Dogramaci & Leaney (2001) used isotopic analysis to investigate four hypotheses regarding the source of solutes in the Murray basin. These four hypotheses were (1) mixing between meteoric water connate fluids trapped within the pores from the time of deposition of the sediments, (2) dissolution of evaporates left behind after the last sea-water retreat, (3) weathering of aquifer minerals, and (4) accumulation of solutes through accession of solutes dissolved in rain over thousands to millions of years. The stable isotope analysis provides compelling evidence that the source of solutes found in the basin are derived from rainfall, and that none of the groundwaters or pore fluids are remnant sea water.

Recently Ladanay-Bell and Acworth (2002) presented hypotheses on the salinisation processes in the Coleambally Irrigation of south eastern Australia. Hydrogeochemical data suggested that salinisation of the groundwater system is associated with solubilisation of very significant salt stores within the upper Shepparton formation. The authors attributed the source of the salts to Quaternary dust transport processes, Aeolian deposition and re-working of salt laden parna sourced from saline lakes and playas of the Mallee Plain. Using salt balance modeling and investigating time frames associated with salinisation the most likely method of salinisation has been through salt laden aeolin dust input. This hypotheses contends that within wind-blown dusts there were large amounts of salts transported during the Quaternary through wind-blown aeolin dusts. These layers remained relatively undisturbed within the unsaturated zone until the commencement of irrigation whereupon enhanced leaching due to removal of native vegetation and associated rising water tables led to solubilisation of these ‘dry’ salt stores.

3.8 Quantity and Profile Distribution of Stored Salts

Van Dijk (1961) reported on soil salinity profile distributions for the irrigated soils in the MIA. Generally soil salinity increased with depth in the soil profile to a 2-2.5m depth. Lighter textured soils had a maximum salt concentration generally occurring at a 1-1.5m depth, whereas in the heavier textured soils salinity increased more linearly with depth. Figure 3-5, taken from van Dijk (1961) shows that for both the red-brown earths and heavy textured soils found in the MIA the upper surface soil layers are generally much less saline than those deeper in the soil profile.

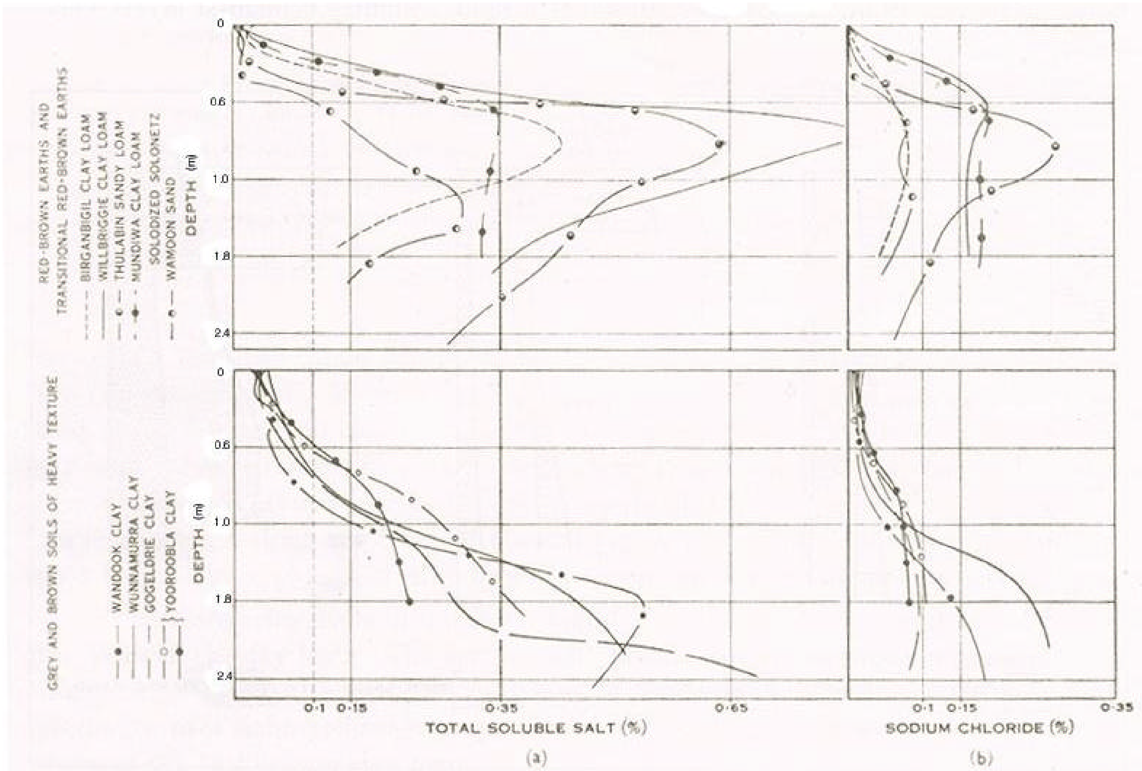


Figure 3-5. Salt profile distributions with depth for soils of the MIA, after van Dijk (1961)

This was also supported by Hornbuckle and Christen (1999) who reviewed previous research undertaken on salinity of irrigated soils in the MIA. Figure 3-6 shows a typical soil salinity profile for red brown earths found in the MIA. This was constructed based on average soil salinity profiles of a number of studies undertaken in the MIA by previous researchers.

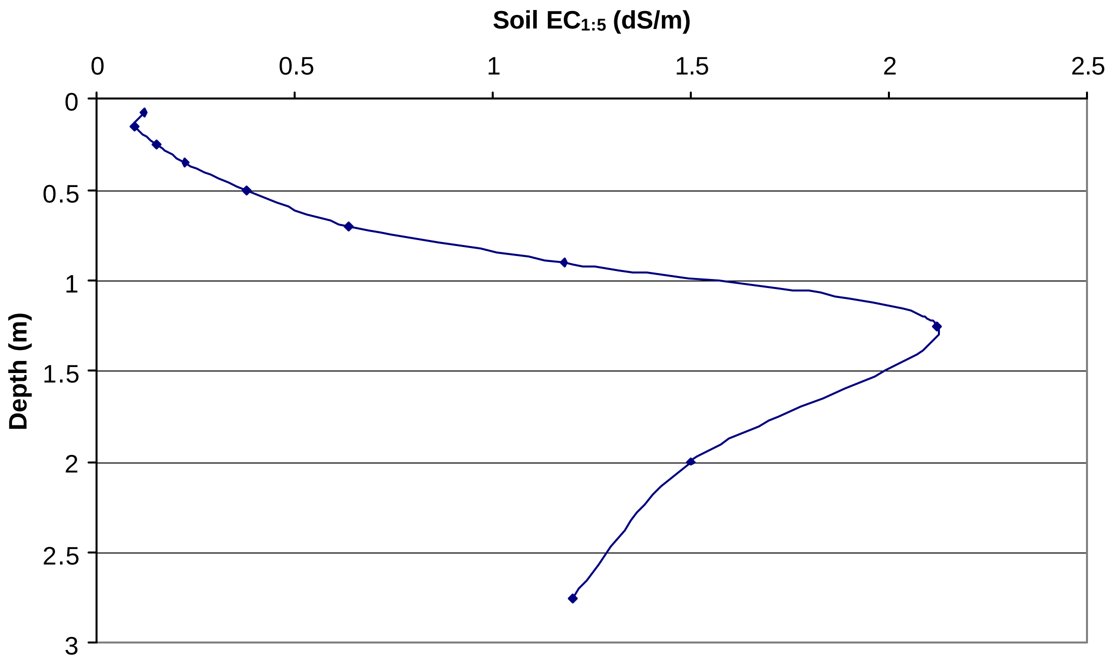


Figure 3-6. Typical soil salinity profile taken from Hornbuckle and Christen (1999) for irrigated red-brown earths of the MIA

What can be seen from the above soil salinity profiles is that generally within the MIA there is considerably less stored salt in the upper soil layers than at deeper soil depths. For the soil profile shown in Figure 3-6 the approximate amount of salt stored in the upper soil profile (0-1m) and lower soil profile (1-2m) is 25 and 91 t/ha, hence it can be seen that at depths greater than 1m there is considerably more natural stores of soil salts than at shallower depths, with nearly a four-fold increase in salt at a 1-2m depth compared to the surface 0-1m depth.

4 Experimentation

The experimentation was divided into two components. These being, a theoretical investigation into multi-level subsurface drainage and two field experiments investigating the use multi-level subsurface drainage systems and controlled drainage management.

4.1 Theoretical Investigation

The theoretical investigation involved the development of an analytical solution for multi-level subsurface drainage. Development of the analytical solution was undertaken using potential theory first used in drainage investigations by Kirkham (1949). The programming environment of Mathematica (Wolfram 1991) was used to investigate parameter interactions and develop an understanding of the interaction of parameters and their effect on flow paths to drains and drainage discharge rates.

4.1.1 Aims and Objectives of the Theoretical Investigation

The specific aims of the theoretical investigation into multi-level subsurface drainage was to:

1. Develop an analytical solution for multi-level subsurface drainage systems

2. Determine flow paths to drains in a multi-level drainage system through investigation of streamlines

3. Determine whether spacing of deep drains could be increased with the addition of shallow drains

4.2 Field Experimentation

The experimental field sites selected in the MIA represent typical horticultural farms within the region. Both experimental studies were conducted in co-operation with commercial farm operators to ensure that practices undertaken were representative of typical farming situations and could be incorporated into the farming system by farm managers.

The sites represented two different phases in relation to a subsurface drainage situation. The first experimental site referred to as the **M**ulti-**L**evel **D**rainage (**MLD**) site was extremely saline in nature and in a reclamation phase. This site investigated the use of a multi-level drainage system. The second site known as the **C**ontrolled **W**ater table **M**anagement (**CWM**) site was located on an established vineyard that had problems due to a regional high water table that was of variable salinity. At this site controlled drainage management practices were investigated.

4.2.1 MLD Site

This site was on the outskirts of Bilbul village approximately 7 km from Griffith. The site is typical of a traditional horticultural farming enterprise. An aerial photograph taken in 1957 is shown in Figure 4-1 and the experimental area is indicated. Although the site was originally developed for irrigation (circa 1930) it had not previously been irrigated until this trial.

Rain fed native pasture and native wattle as shown in the aerial photograph (Figure 4-1) remained until May 1999 when the land was cleared and laser leveled in preparation for installation of a subsurface drainage system, furrow irrigation system and establishment of a vineyard. The *vitis vinifera* cultivar Semillon on its on rootstock was planted on the site.

Figure 4-1. Aerial View of MLD Experimental site

Surrounding farming areas were drained in 1968 due to extensive salinisation, which can been seen visually in Figure 4-1, with clay tiles laid at a nominal depth of 1.8m and 20m spacing. Design was based on recommendations for subsurface drainage systems developed for the region by Talsma and Haskew (1959).

Vegetable production was practiced on the surrounding farming areas until ~1970 when wine grapes were established and remain to the present day.

4.2.1.1 Soil Type

Analysis of the soil at the study site leads to the classification of the soil as a Red – Brown Earth of the Great Soil Groups outlined by Stace et al. (1968). Local classification of the soil by Taylor and Hooper (1938) mapped the site as a Bilbul loam. The surface soil is shallow and passes quickly through a clay loam to a light clay. A grey subsoil occurs below a depth of 0.75m and continues to a depth of 7m becoming heavier with depth. Soft and hard carbonates are found at depths below 0.5m. A profile sketch is shown in Figure 4-2 along with soil physical properties from the experimental site.

Layer	Bulk Density (kg/m^3)	CS%	FS%	Si%	Cl%
0-0.15m	1.510	3.0	39.8	15.5	41.7
0.15-0.3m	1.456	1.3	30.5	14.1	54.1
0.3-0.6m	1.490	0.9	18.3	21.2	59.7
0.6-1.2m	1.520	26.6	1.4	21.3	50.8
1.2-2.0m	1.550	28.4	1.6	21.4	48.6
2.0-3.0m	1.500	26.2	1.0	22.6	50.2

Figure 4-2. Profile description of Bilbul loam found at the MLD site

The soil salinity at the MLD site was very saline. Figure 4-3 shows the average electrical conductivity based on 22 cores taken at the site.

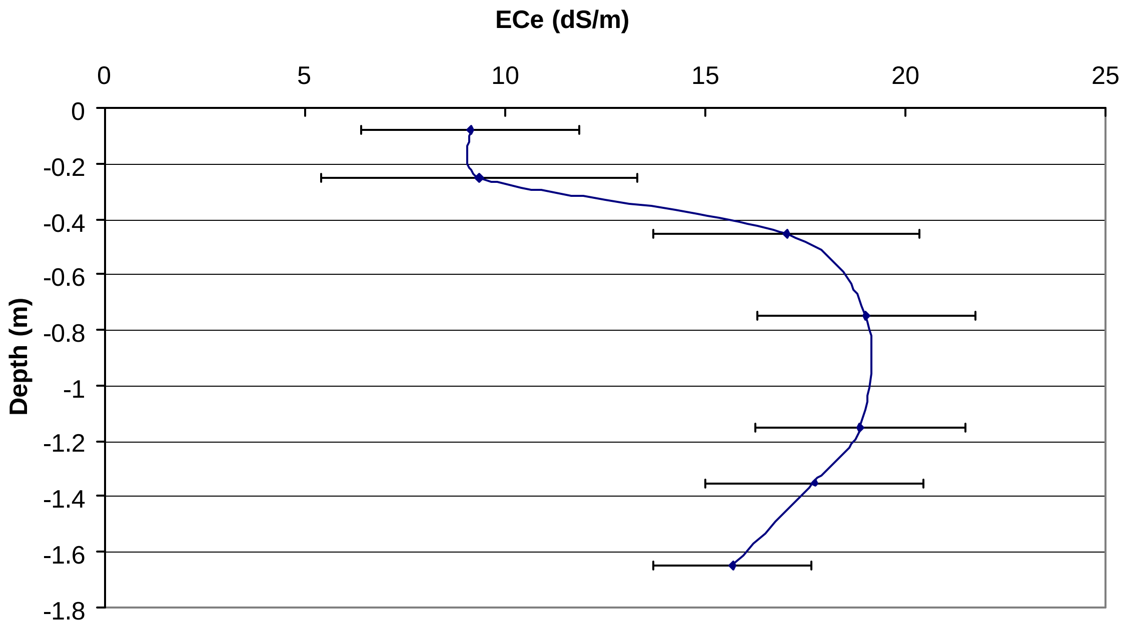


Figure 4-3. Average soil salinity at the MLD experimental site, based on 22 cores. Horizontal bars show standard deviation

It can be seen that the site was saline in nature and well above recommended salinity levels for grapes. ECe threshold for no yield loss for grapes is 1.5 dS/m (Rhoades and Loveday, 1990). It was also apparent that the salt content of the deeper soil layers was higher than the shallower surface layers (0-.05m).

Variability of soil salinity was also high at the site as can be seen from the standard deviation values in Figure 4-3. EM 38 ground conductivity mapping also highlighted the variability of soil salinity at the experimental site, Figure 4-4.

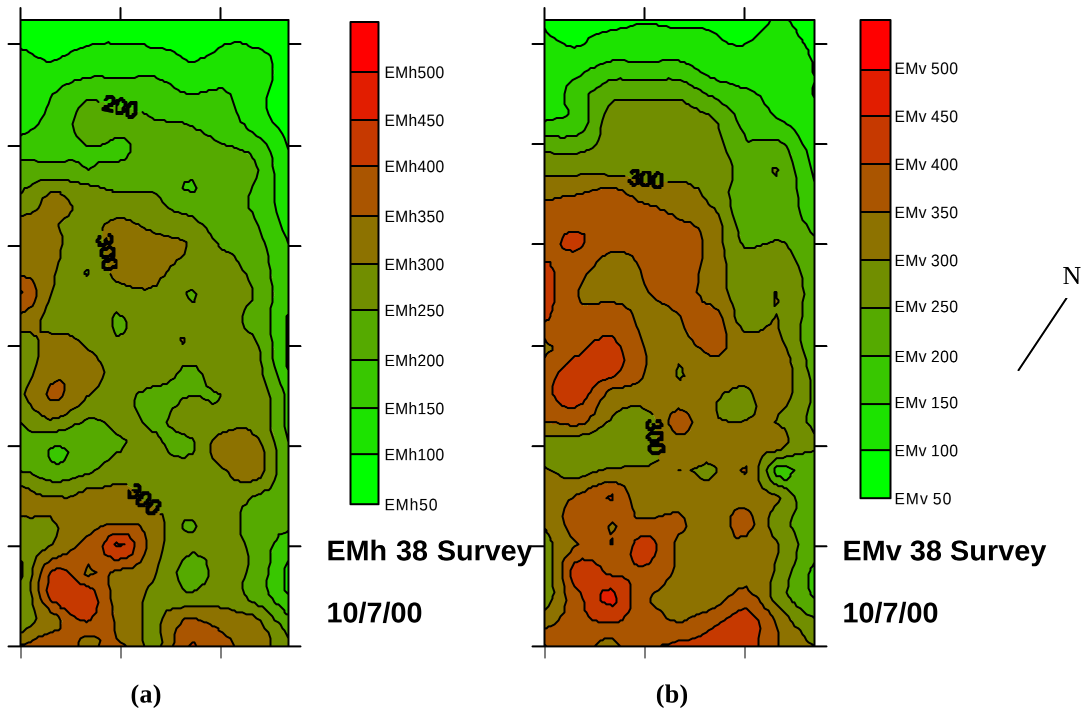


Figure 4-4. EM 38 ground electrical conductivity survey from the MLD site

It can be seen from Figure 4-4 that the left side of the experimental area was more saline than the right. Both in the upper soil surface layers shown by the EMh readings (a) and particularly in the deeper soil profile shown by the EMv readings (b).

4.2.2 Aims and Objectives of the MLD Field Experiment

The specific aim of the MLD experiment was to compare Single-Level and Multi-Level drainage systems in a field situation. The objectives were to:

1. Compare drainage volumes and subsequent salt loads from single-level and multi-level drainage systems

2. Compare effectiveness of salt leaching between single-level and multi-level drainage systems in relation to root zone removal of salts

3. Determine the effectiveness of water table and waterlogging control between single-level and multi-level systems

4.2.3 Experimental Layout

In order to achieve these objectives two treatments were installed at the site. These being a **M**ulti-**L**evel (**ML**) subsurface drainage treatment and a **S**ingle-**L**evel (**SL**) subsurface drainage treatment. Due to the experiment being conducted in a commercial vineyard spacing of the deep drains on the multi-level drainage system was set at 20m. This allowed a direct comparison to be made between the systems, with any effects on the salt load of the system being directly attributed to the presence of the shallow drainage system. The ML treatment was placed in the higher salinity area of the field. This was done to provide a thorough assessment of the MLD system in highly saline conditions.

Subsurface drainage was installed at the site from 17/07/2000 to the 20/07/2000 by Aussie Drain Pty Ltd. All drains were installed using a Mastenbroek 30/20 trenching machine fitted with a Spectra physics precision laser for gradient control. Further details on the installation machinery can be found at www.aussiedrain.com.au.

Drain spacings of the deeper drains were calculated from the methodologies developed by Talsma and Haskew (1959), which led to a design spacing of 20m. Shallow drains were spaced at 3.3m to align with the center of each vine row. Deep drains were laid at a 0.2% gradient and the shallower drains at a 0.1% gradient. Starting and finishing depths are indicated in Figure 4-5.

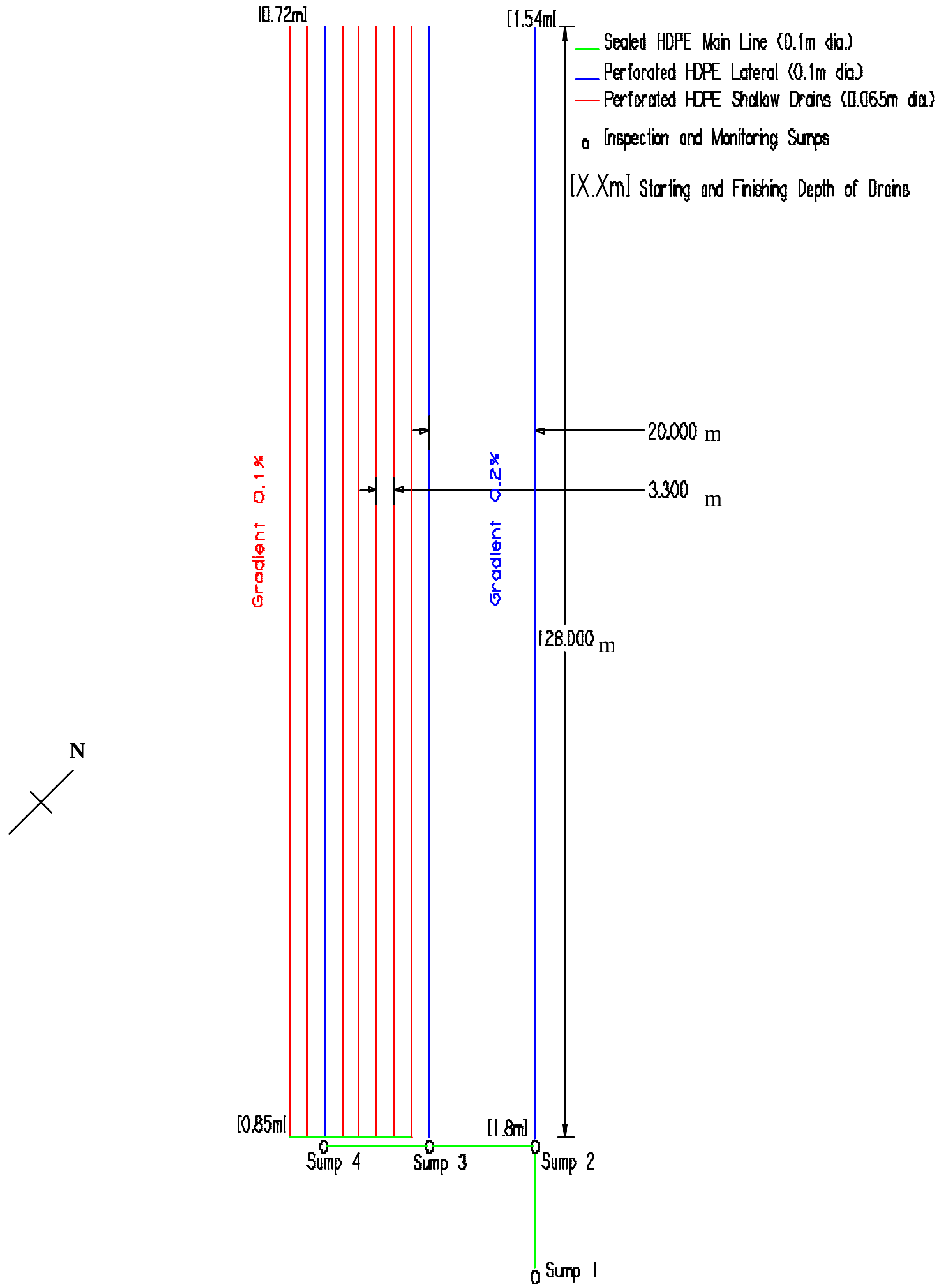


Figure 4-5. Plan view of subsurface drainage system installed at the MLD site.

High Density Polyethylene (HDPE) drainage pipe was used with 0.1m diameter for the deeper drains and 0.065m diameter for the shallow drains. All main lines were sealed.

Deep drainage laterals were installed (Figure 4-6) with a gravel envelope with dimensions shown in Figure 4-7. The shallower drainage system was installed without an envelope surrounding the drain. Inspection and monitoring sumps were installed at junctions and consisted of 0.9m internal diameter concrete sumps with sealed bottom. Sump locations and numbering are given in Figure 4-5.

Figure 4-6. Drainage laterals being installed with a gravel envelope surrounding the drain

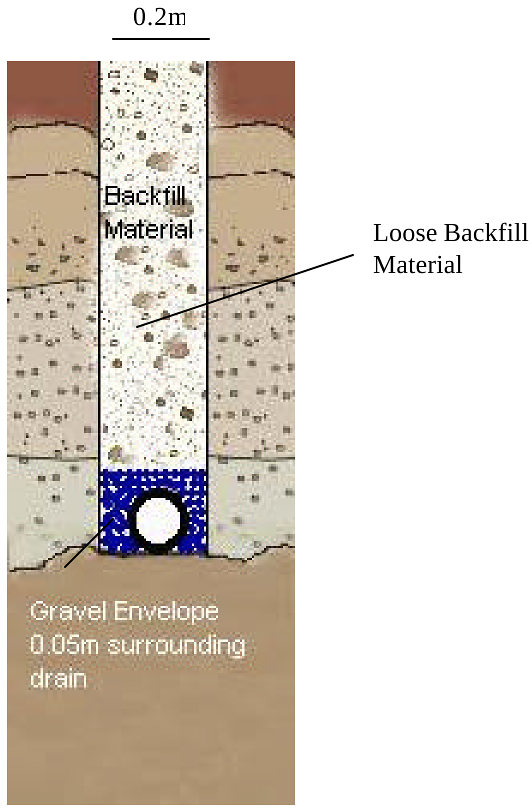


Figure 4-7. Diagramatic representation of subsurface drainage installation showing gravel envelope and dimensions

With this configuration the two treatments could be investigated and comparisons between the systems investigated. A cross-sectional representation of the SL and ML drainage treatments is shown in Figure 4-8 and Figure 4-9 respectively.

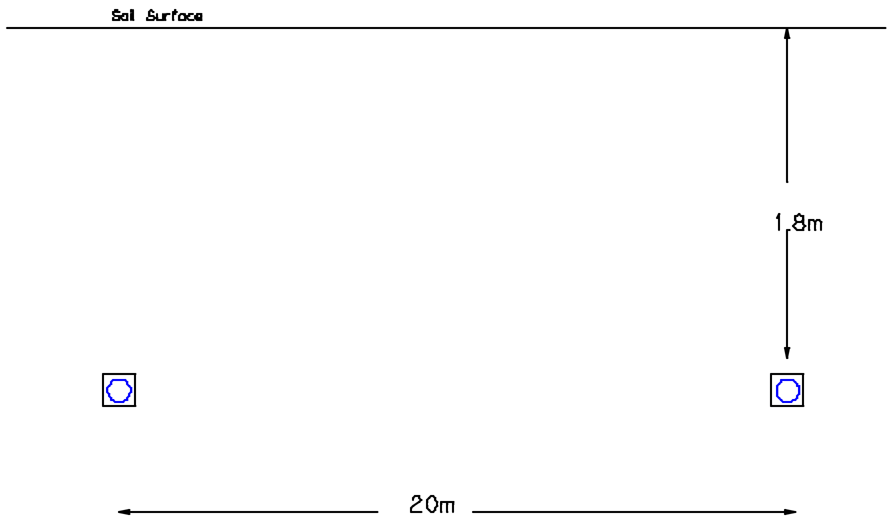


Figure 4-8. Cross section of SL treatment

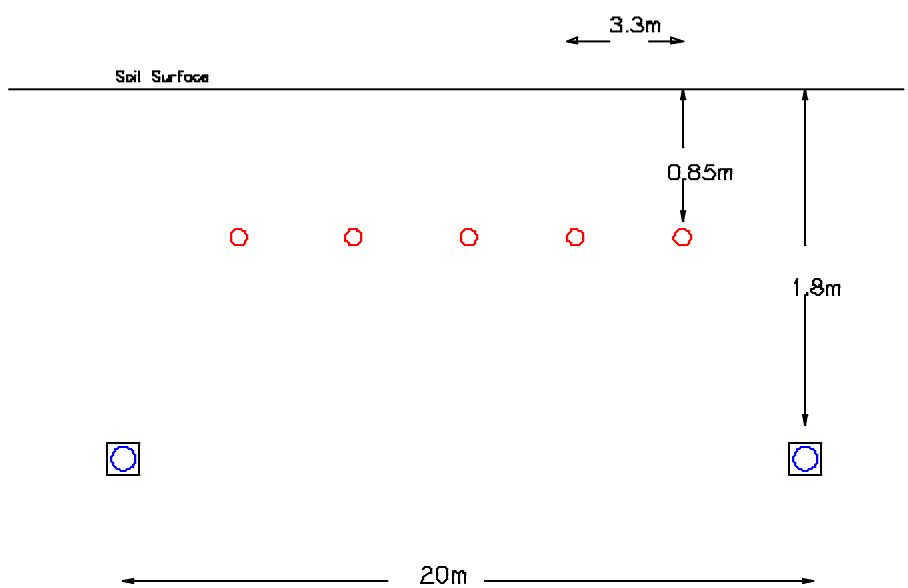


Figure 4-9. Cross section of ML treatment

In order to achieve the specific objectives outlined then each treatment was extensively monitored for saturated and unsaturated water movement, drainage flows, salt loads and water application to the field.

Positioning of testwells, piezometers, flow meters, EC sensors, flumes, tensionmeters, rain gauges and Environscan probes is shown in Figure 4-10. Instruments were positioned to adequately represent the treatments in a three dimensional manner. Three cross-sections of each drainage treatment were monitored at positions located at distances ¼ , ½ and ¾ from the supply end to the runoff end of the treatments. The cross sections at the center of the field were the most intensively monitored.

Details on installation and monitoring of the equipment is given in Chapter 5.

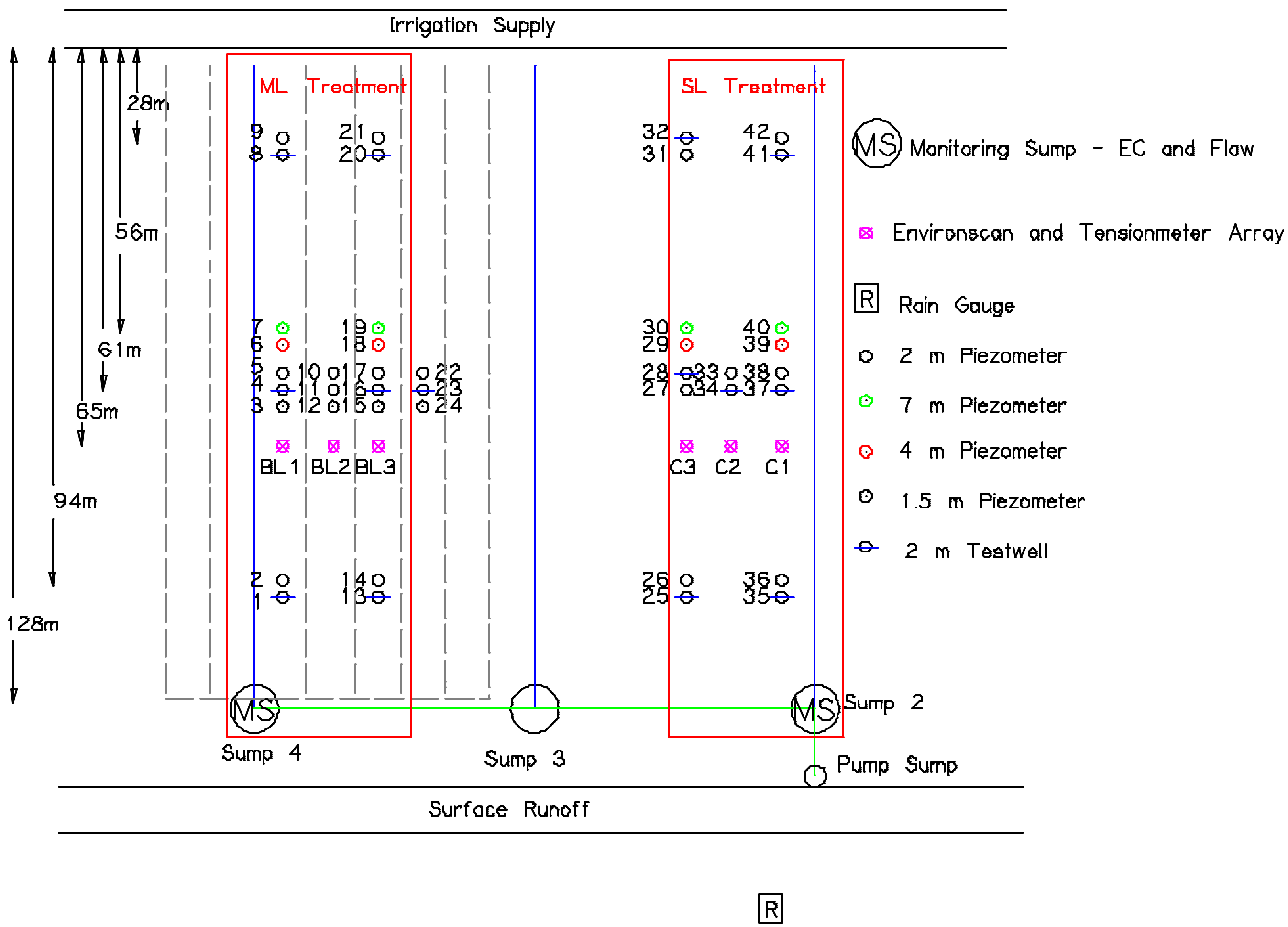


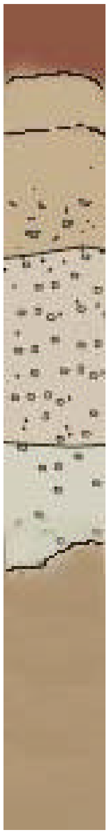
Figure 4-10. Layout of MLD site showing monitoring equipment and treatments

4.2.4 CWM Site

This site is situated in Hanwood approximately 5 km from Griffith. The site was previously used for rice production and is now used for wine grape production. The vineyard had been planted 7 years prior to the installation of a subsurface drainage system in November 2000 for the control of a regionally high water table. The grapevines consisted of a mixture of (*Vitis vinifera*) cultivars Cabernet Sauvignon (a red grape variety) and Semillon (a white grape variety). All vines were grafted onto Ramsey rootstocks. Surrounding areas are planted to a mixture of horticulture, rice and pastures all of which are irrigated.

4.2.4.1 Soil Type

Analysis identified the soil as a Red – Brown Earth of the Great Soil Groups outlined by Stace (1968). Although the soil was not mapped by Taylor and Hooper (1938) pit investigations show it to fit into the local soil type known as a Jondaryan loam. The surface soil is shallow (0.1 – 0.3m) and passes into a clay loam at a depth of 0.6m. The deeper subsoil varies from a dark brown to red-brown in color and is associated with alternating sandy and clayey layers. Both soft and hard carbonates are present. A profile description is given in Figure 4-11 along with physical soil properties from the site.



Layer	Bulk Density (kg/m^3)	CS%	FS%	Si%	Cl%
0-0.1m	1.146	6.7	36.3	12.3	44.7
0.1-0.45m	1.318	3.2	20.6	10.0	66.3
0.45-0.75m	1.338	2.7	18.3	11.8	67.2
0.75-1.0m	1.398	3.9	27.5	16.6	52.0
1.0-1.2m	1.420	4.7	33.9	17.5	43.9
1.2-3.0m	1.450	2.0	40.2	17.8	39.9

Figure 4-11. Profile description of Jondaryan loam found at the CWM experimental site

4.2.4.2 Drainage System Layout

Subsurface drainage was installed at the site from the 08/11/2000 to the 10/11/2000 by Aussie drain Pty Ltd. Installation and machinery used was identical to that used at the MLD site.

Drain spacings were calculated using the design procedures outlined by Talsma and Haskew (1959), which led to a design spacing of 36m. Perforated HDPE pipe (0.1m dia.) was used for laterals and all mains were sealed (0.15m dia.) HDPE pipe. A gravel envelope was used on all laterals.

A plan view of the experimental site showing gradients, lengths and inspection and monitoring sumps is provided in Figure 4-12.

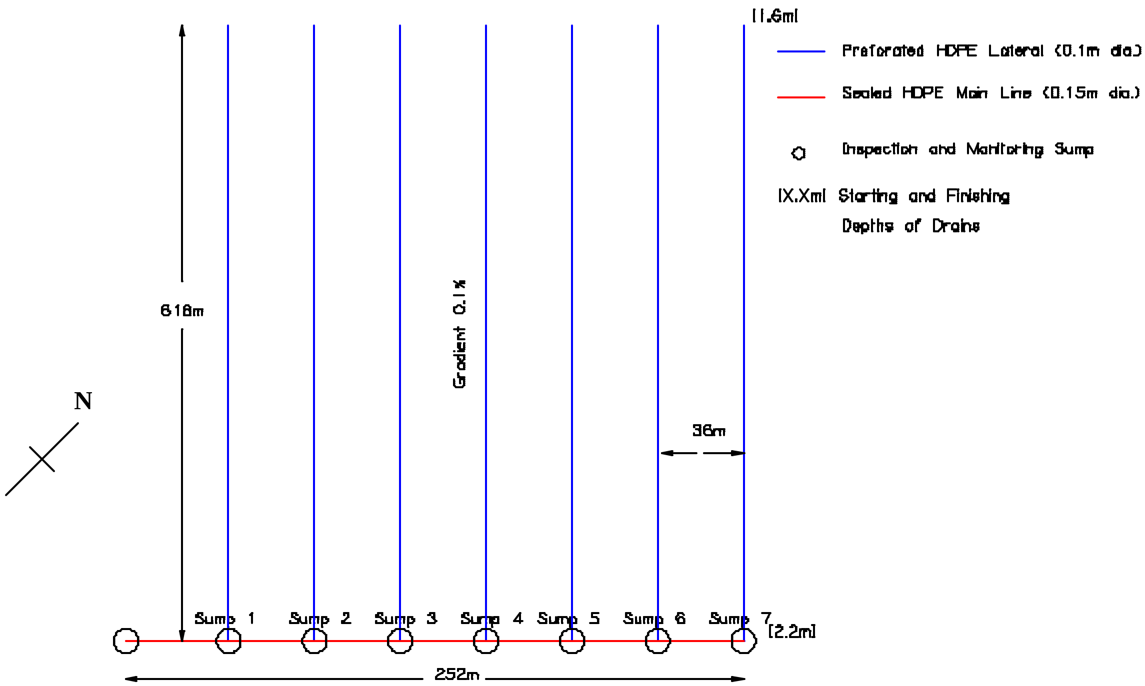


Figure 4-12. Plan view of subsurface drainage system installed at the CWM site

Soil pits and hand auguring for the determination of water table depth and electrical conductivity of the water table, using a Corning 316 electrical conductivity meter, were undertaken in August 2000 and are shown in Figure 4-13 and Figure 4-14 respectively.

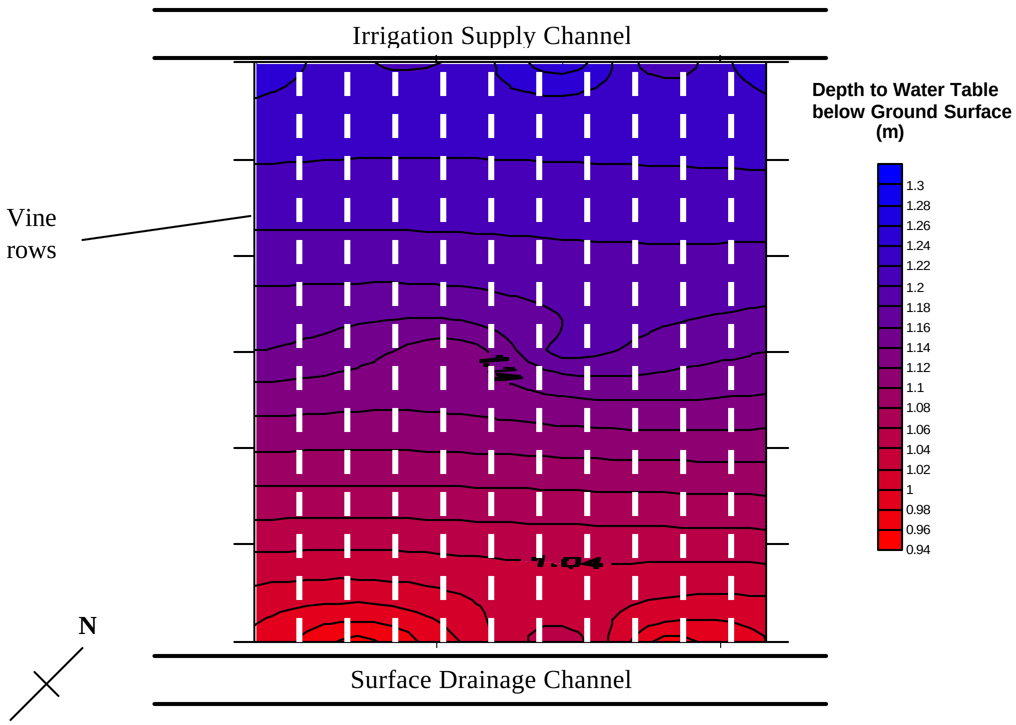


Figure 4-13. Water table depth below ground surface, August 2000

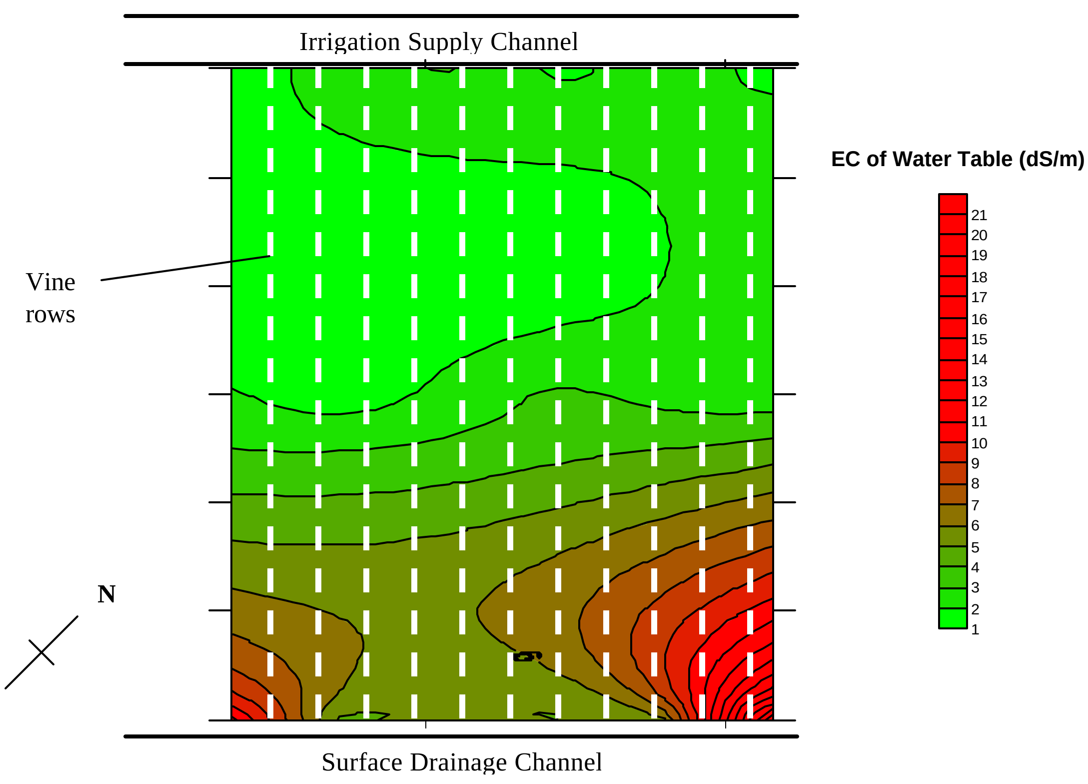


Figure 4-14. Electrical conductivity of water table, August 2000

4.2.5 Aims and Objectives of the CWM Field Experiment

The specific aim of the CWM experiment was to compare managed and un-managed drainage systems in a field situation. The objectives were to:

1. Investigate the effects of controlled drainage management on water table regimes

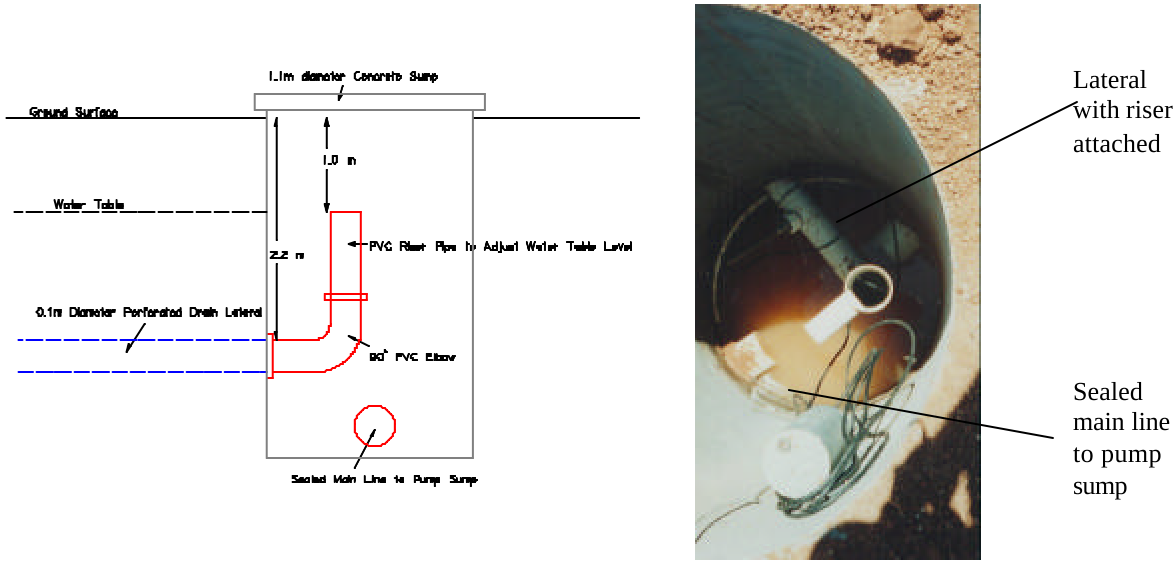
2. Compare the effect of controlled drainage management on drainage volumes and salt loads

3. Investigate the potential for grapevines (*Vitis vinifera*) to use shallow saline groundwater

4. Investigate the effects of controlled drainage management on root zone salinity

4.2.6 Experimental Layout

In order to achieve the stated objectives a controlled and uncontrolled drainage area was implemented at the site. Uncontrolled areas were situated over drainage laterals 1-3 (Figure 4-12) where the Cabernet Sauvignon variety was grown and the controlled areas were situated over drainage laterals 4-7 (Figure 4-12) where the Semillon variety was grown. The selection of these areas was based on the vine variety. Red grape varieties such as Cabernet Sauvignon typically require periods of water stress to improve grape quality, hence too high a water table may cause loss in yield quality. White varieties, such as Semillon, do not require any periods of water stress and hence this area was chosen for the controlled drainage implementation. Implementation of controlled drainage was undertaken using PVC risers on the laterals at the point where the laterals entered sumps 4 to 7, Figure 4-15.



a b

Figure 4-15. Schematic (a) and photograph (b) of PVC pipe riser used for controlling subsurface drainage flow at the CWM site

This essentially gave two drainage treatments, which were further divided based on the natural salinity gradient of the water table at the site into three areas in each treatment, consisting of areas with low, moderate and high salinity water tables (Figure 4-14).

This treatment configuration allowed a comparison between, firstly, the controlled and uncontrolled drainage systems at short periods (irrigation intervals and applications rates were not always identical due to differing water requirements of the varieties), and secondly, the effect of water table salinity and depth on groundwater contribution to crop evapotranspiration for both the Cabernet Sauvignon and Semillon varieties.

Positioning of testwells, flow meters, flumes, rain gauges, tensionmeters, watermark sensors, neutron probe tubes and DREAM ET instrumentation is shown in Figure 4-16. Four existing piezometers installed by the Department of Land and Water Conversation were in close (< 1km) proximity to the experimental site and were also monitored to track changes in regional water table levels.

Positioning of instruments was undertaken to investigate salinity and water table responses in controlled and uncontrolled drainage treatments. All components of the water balance were measured in order to determine the contribution of capillary rise from a shallow water to meet crop evapotranspiration requirements.

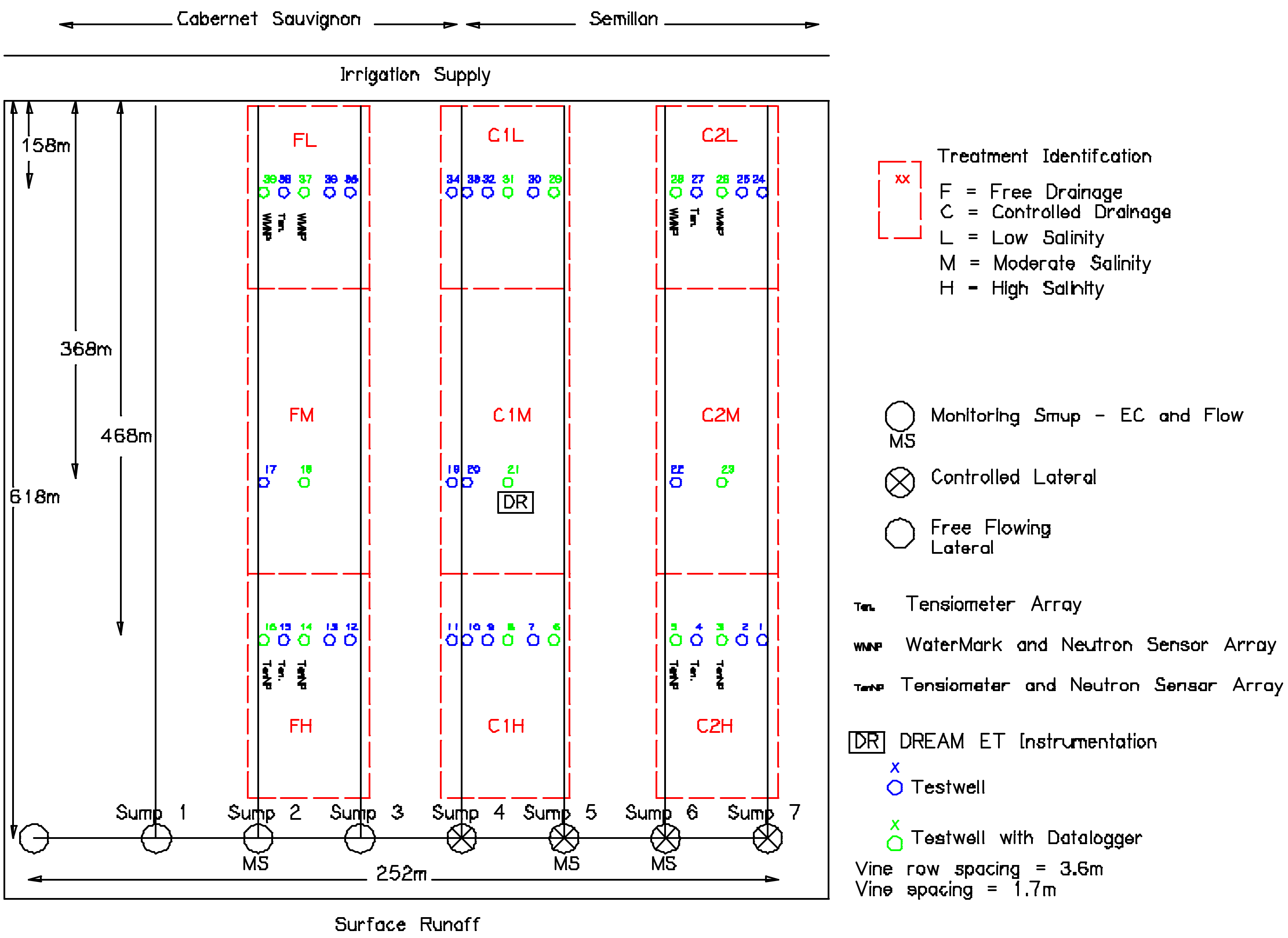


Figure 4-16. Layout of CWM site showing monitoring equipment and treatments

5 Experimental Methods

In order to investigate the potential reduction in drainage salt loads, adequate characterization of water and salt movement is needed. Monitoring techniques undertaken at both experimental sites were similar and are outlined in the following sections. Treatment layouts and positioning of monitoring equipment for each site have been given in Chapter 4.

5.1 Watertable and Piezometer Levels

5.1.1 Construction and Installation Methods

Testwells and piezometers used in the experimental sites were constructed of PVC piping of 0.09m diameter for testwells and piezometers installed shallower than 2m. Smaller 0.032m diameter piping was used for piezometers installed at depths greater than 2m. Slots were uniformly distributed over the length of the slotted area at a 0.02m spacing, 0.05m length and 0.005m width on both sides of the PVC. The slotted area was then covered with a fine filter material to limit entry of soil. Piezometers were slotted 0.3m above the bottom of the PVC pipe and testwells were slotted to 0.3m below the soil surface, Figure 5-1.

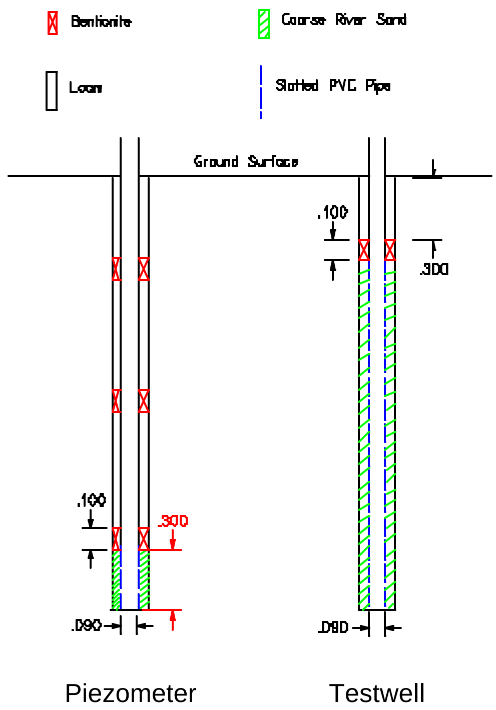


Figure 5-1. Diagramatic representation of piezometers and testwells installed at the experimental sites

Installation of testwells and piezometers was undertaken with an Adcom portable drilling rig and followed the general procedure outlined by Cassel and Klute (1986). Wells above 2m below the ground surface were installed with a 0.12m diameter auger and those below 2m with a 0.05m auger. Slotted areas were then surrounded with a fine river sand of high hydraulic conductivity of known properties. A series of loam and bentonite plugs were then installed to prevent preferential flow of water down the sides of the wells, Figure 5-1.

In the case of the deeper piezometers installed below a depth of 2m it was sometimes necessary to first purge the ground water, which had entered the hole, with a sludge pump to allow the proper seating and installation of the piezometer and to ensure an adequate backfill that prevented preferential flow down the sides of the piezometer casing. This was particularly the case at the MLD site where piezometers were installed to a depth of 7m.

5.1.2 Monitoring

Water levels in both piezometers and testwells were measured using the procedure outlined by Reeve (1986). Depth to water table was measured with a tape with a plopper attached to the end. Accuracy using such a method was within ±0.01m.

Continuous monitoring was also undertaken in the majority of wells using automated water level loggers. Both pressure transducer and capacitance sensors were used along with single channel loggers to monitor analogue outputs from the sensors. Monitoring frequency was at 2hr intervals during the duration of the experimental period. A mixture of Dataflow 392 (Dataflow System Pty Ltd) and GPSE 301 loggers and sensors (Harris Pty Ltd) were used. Quoted resolution of the Dataloggers and sensor combinations was ±0.0025 m for the Dataflow units and ±0.0015 m for the GPSE units.

All water table depths are reported as depths below the average ground surface for the field.

5.2 Subsurface Drain Flows

Subsurface drainage water flows were recorded using a combination of manual and automated sampling procedures. Manual measurements involved measuring a collected volume for a set time period. This was done with a bucket and stopwatch with volumes being recorded with a graduated measuring cylinder with 5ml increments.

Water samples were collected using two different methodologies depending upon the flow volume to be measured. For the smaller flow rates at the MLD experimental site tipping buckets were used to measure flow rate. Accuracy of the buckets was ±100ml. A small magnet was mounted to the tipping buckets that tripped a reed switch, which was logged with a GPSE 301 600 12 bit multi channel datalogger.

At the CWM site a dual flow measuring system was used in the uncontrolled drains consisting of a tipping bucket for lower flow rates and a Mace Agriflow Ultrasonic Doppler meter (Measuring and Control Equipment Pty Ltd) to monitor higher flow rates. Outlets to the sump were modified to ensure a full pipe was flowing at all times to aid in the use of the ultrasonic Doppler meter. This method was found to be successful and has been reported by Replogle (n.d). Accuracy of the system was found to be ± 2 % for flows below 1 L/s and ± 5 % for flows above 1 L/s when compared to manual measurements. For controlled drains circular flumes (Hager 1988; Kohler & Hager 1997; Samani, Jorat & Yousaf 1991) of 0.1m diameter PVC pipe were constructed.

5.3 Subsurface Drainage Water Quality

Subsurface drainage water quality was monitored using a combination of automated and manual procedures. Manual samples were collected at regular intervals for determination of electrical conductivities. Samples were collected in 400ml bottles and stored in an insulated container. In the laboratory they were measured for electrical conductivity using a Corning 316 Electrical Conductivity Meter. Automatic temperature compensation was enabled on the unit.

Manual samples were taken for ICP analysis and this procedure involved taking 400ml samples and freezing within 1 hr of sample collection. Samples were then analysed after appropriate dilution for high concentrations of Ca, Mg, Na, and S, using Inductively Coupled Plasma Optical Emission Spectroscopy (ICPOES). The method followed was Method 3120 of Standard Methods for the Examination of Water and Wastewater (1992).

Automated samples were collected using two sampling methodologies depending upon the use of the samples. If a sample was needed to be collected for further laboratory analysis then Gamet Autowater samplers (Gamet Equipment Pty Ltd) were used. These were sampling units, which could take 24 individual samples at specified time intervals. Sampling intervals varied between ½ to 2 hours depending upon drainage flow rate.

Continuous monitoring of drainage water electrical conductivity was undertaken using TPS electrical conductivity sensors and microCHEM transmitters (TPS Pty Ltd) which provided a standard 0-5V output which was logged with either Hobo 8 bit multi-channel loggers (Onset Computer Corporation) or GPSE 301 600 12 bit multi channel dataloggers (Harris Pty Ltd). Resolution of these units was 0.4 dS/m using the Hobo dataloggers and 0.04 dS/m using the GPSE dataloggers. Sensor ranges were set to 0-20 dS/m at the CWM site and 0-200 dS/m at the MLD site. Units were powered using 12 watt solar panels and 7 amp hour 12 volt batteries. Modification of the drainage outlet to ensure that the sensors were continually submersed was undertaken as outlined by Replogle (n.d).

5.4 Water Application

5.4.1 Flow Rates to Furrows

Water application was measured to individual furrows using a modified version of the circular flume, (Hager 1988; Kohler & Hager 1997; Samani, Jorat & Yousaf 1991). Flumes were constructed at the CSIRO workshop using 0.15m diameter PVC pipe and a flat PVC sheeting (0.2 x 0.6m) was welded on the front of the flumes to stop preferential flow around the flumes. Flumes were placed in furrows during each irrigation and leveled using a spirit level. Location and placement of the flumes is shown in Figure 5-2 and Figure 5-3 (Note hydraulic jump shown in Figure 5-3). Upstream water level depth was measured using a small manometer tube that was placed inside the smaller restricting PVC pipe. The manometer tubing was then removed and water level read off the graduated scale. Accuracy of the measurement was within 0.001m. A regression equation relating upstream water level depth to flow rate was then used to determine the flow rate (Samani, Jorat & Yousaf, 1991).

Figure 5-2. Front view of modified circular flume showing cut-off barrier used to prevent preferential flow around the sides of the flume

Figure 5-3. Rear view of circular flume showing positioning of flume in furrow and hydraulic jump during an irrigation event

5.4.2 Irrigation Advance

Irrigation advance rates were measured using a colour coded peg placed at intervals down the furrow during irrigation events. Distance to each peg was then measured after the irrigation event using either a 100m tape measure at the MLD site, or in the case of the CWM site a hand held GPS unit (GARMIN eTrex Personal navigator) was used to mark positions then downloaded and distances calculated using the GPS Utility software package (Murphy, 2001). Using the tape methodology accuracy was within 0.05m and with the GPS unit was 3m.

5.4.3 Rainfall

Rainfall at the experimental sites was measured using a tipping bucket rain gauge to measure rainfall intensity and duration. Logging intervals were set to ½ hourly intervals. A manual rain gauge was also installed next to each automated rain gauge and used as a 'back-up'.

5.5 Soil Moisture

Soil moisture regimes were measured using a combination of methods utilising soil tension measurements and also volumetric water content measurements. At monitoring sites a combination of both soil tension and volumetric water content were used.

5.5.1 Soil Tension

5.5.1.1 Tensiometers

Construction

Tensiometers were all constructed using porous ceramic cups purchased from Cooinda Ceramics Pty Ltd. Cups were then glued onto PVC electrical conduit using epoxy cement and a 0.1m length of acrylic transparent tubing glued to the other end of the conduit to aid in monitoring water levels within the tensiometer, to ensure they did not dry out and were maintained at a constant head.

Installation

Prior to installation tensiometer tubes were filled with distilled water and placed in a bucket of distilled water for three days. Tensiometers were then removed and with a hand vacuum pump, a 60 kPa suction was applied for 60 seconds to the tensiometers to removed air bubbles from the porous cup. Tensiometers were then placed in a glass house and tested for leaks. Response times of tensiometers were then checked by placing the dry tensiometer into a bucket of water and using the 5 minute response test as outlined by Cassel and Klute, (1986).

Installation was done approximately three days after an irrigation event. Holes 0.05m in diameter were augured to the desired depth. Tensiometers were inserted into the holes and a back fill of fine loam material was placed around the tensiometer ceramic cup to ensure good contact was made with the surrounding soil. A 0.02 m layer of bentonite was then placed above the loam to prevent preferential water flow and a bentonite/soil 50:50 mixture was then used to fill the hole. Previous investigations using this methodology have found this installation method to give the best results on soil types found in the region, (Christen, 1994, Muirhead et al. 1996). The acrylic transparent tubing, which remained above ground, was then covered with 0.05m thick foam to minimize temperature effects on measured tensions and prevent deterioration of the rubber septum.

Monitoring

Soil tensions were measured with a Soilspec portable tensiometer reader, which used a pressure transducer and needle apparatus as outlined by Cresswell (1993). Readings were taken over a 2 minute interval to allow the equilibration of the pressure transducer. The tensiometers were refilled regularly with de-aired water to maintain a constant head of water in the tensiometer as indicated by Cassel and Klute (1986). The rubber septums were also monitored closely and replaced when signs of damage were noted.

5.5.1.2 Watermark Granulated Matrix Sensors

Watermark granulated matrix sensors (Soil Moisture Corp.) were used to continuously monitor soil moisture tensions at the CWM site. Installation procedures were carried out using the same methodology as the tensiometer installations. Sensor excitation and logging of output from the Watermarks were recorded with a Campbell 21x datalogger (Campbell Scientific Inc). For full details on wiring diagrams used and excitation measurement see Campbell Manual. A soil temperature sensor was also installed at the sites and the relationship developed by Thompson and Armstrong (1987), shown in Equation 5-1, was used to calculate soil water potential.

$$SWP = \frac{Rs}{0.01306[1.062(34.21 - Ts + 0.01060Ts^2) - Rs]}$$

Equation 5-1

where:

Rs – Resistance of watermark sensor (Ohms)

Ts – Temperature of soil (^{0}C)

SWP - Soil Water Potential (kPa) (Thompson and Armstrong 1987)

Soil tensions using this methodology were recorded at ½ hour intervals.

5.5.2 Volumetric Water Contents

5.5.2.1 Neutron Moisture Meter (NMM)

NMM access tubes were installed using a hand coring device and slide hammer apparatus. The extracted soil cores were used for bulk density and volumetric water content determinations in order to provide a calibration equation for use with the NMM. Subsequent analysis showed the soil properties and measured calibration points to be very similar to the soil intensively investigated by Meyer (1992) and was classified as the same soil type. The calibration equations developed in lysimeters at the Griffith CSIRO Laboratory (Meyer 1992) were used in this experiment to convert raw neutron probe measurements to volumetric water contents due to the fact that only one calibration point was recorded. This was considered to adequately represent water contents at the field site due to the soil type measured by Meyer being very similar to that at the experimental site. These are given in Equation 5-2.

For depths less than 0.1m

$$q = -0.0642 + 0.7684 \frac{C_{np}}{C_{npw}}$$

Equation 5-2

For depths greater than 0.2m

$$q = -0.1881 + 0.9365 \frac{C_{np}}{C_{npw}}$$

Equation 5-3

where:

θ = Volumetric water content (m^3/m^3)
C_{np} = Raw count of neutron probe
C_{npw} = Raw Count of neutron probe in water (Meyer 1992)

A 32 second count was used on all readings.

5.5.2.2 EnviroScan Capacitance Sensors

EnviroScan Capacitance Sensors (Sentek, Pty Ltd) were used at the MLD site for continuously monitoring volumetric water content. Six probes each with 5 sensors were used. Installation of the access tubes was undertaken using a hydraulically mounted coring machine, which cored a 0.056m diameter hole to a depth of 1.1m (Figure 5-4). The EnviroScan access tubes were then pushed down the hole to ensure a tight fit and good contact with the surrounding soil. This methodology was used previously by Smith

(Pers. Comm.) for similar soils in the area and prevents problems associated with preferential flow down the sides of the access tubes during irrigation events. Sensors were logged at ½ hour intervals during the duration of the experiment.

Figure 5-4. Hydraulic coring machine used to install EnviroScan installation tubes and take soil cores

5.5.3 Positioning of Soil Moisture Sensors

At the MLD site a combination of tensiometers and EnvironScan probes were used at each monitoring location. At the CWM site a combination of Tensiometers and Neutron probes and Watermark granular matrix sensors and neutron probes were used at each monitoring location.

Sensors were positioned approximately 0.2m from the vines and in a row parallel to the vine rows as shown in Figure 5-5. Installation depths of the sensors at each site are given in Table 5-1. No soil tension measurements were made at either site in the 0.1m depth. At all other depths a volumetric water content sensor and soil tension sensor were placed at the same depth in the soil profile.

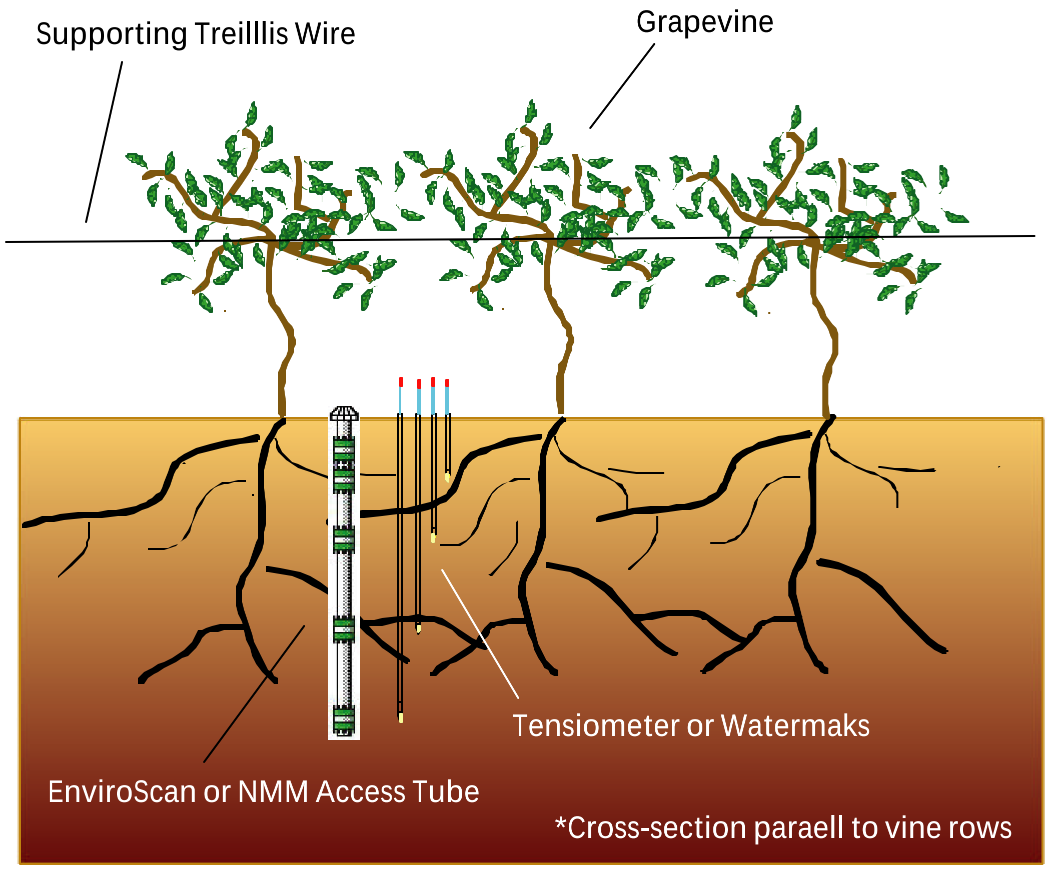


Figure 5-5. Positioning of soil moisture monitoring devices in relation to vine

Table 5-1. Soil moisture sensor depths for the experimental sites

	Depths of Soil Moisture and Potential Sensors
MLD Site	0.1, 0.2, 0.4, 0.7 and 1.0
CWM Site	0.1, 0.3, 0.6, 0.9 and 1.1

5.6 Soil Physical Properties

5.6.1 Salinity

Soil cores were taken using a hydraulic coring rig mounted to a tractor. Cores were divided into 0.1m increments and bagged. Samples were then dried in a glass house and ground using an automated grinding unit to pass a 2mm sieve. Care was taken during grinding of the samples not to over grind the samples and not grind hard carbonates present in some samples.

5.6.1.1 1:5 Electrical Conductivities and Chlorides

The method used to determine 1:5 electrical conductivities was that outlined by Tucker and Beatty (1974). 20g of air-dried ground soil were added to 100ml of distilled water in a 200ml suspension bottle. Samples were then placed on a shaker table for 1-hour duration and removed and left to settle for 30 minutes. 5ml of suspension was then decanted off for chloride analysis for segmented flow analysis using an ALPCHEM Flow Solution IV segmented flow analyzer.

The remaining suspension was then used to determine the electrical conductivity. A TPS conductivity cell was used and electrodes washed with distilled water between samples. Calibration of the conductivity cell was undertaken using standards of 0.141, 0.282, 0.564, 1.41, 2.82, 5.64, 8.46, 11.28, 14.1 and 28.2 dS/m, depending on the EC of the sample.

5.6.1.2 Saturated Paste Electrical Conductivity

Saturated pastes were obtained by adding distilled water to a 20g sample using a pressurized ceramic plate. Oven dried soil samples were placed on the ceramic plate and allowed to saturate under capillary flow. Extracts were then separated from the saturated soil by use of a centrifuge and electrical conductivities of the extract determined using the same equipment and methodology as for 1:5 electrical conductivities.

Relationship between $EC_{1:5}$ and EC_{SAT}

1:5 electrical conductivities were undertaken on all soil samples and a regression equation developed between $EC_{1:5}$ and EC_{SAT} to convert $EC_{1:5}$ to EC_{SAT}. The regression relation was developed on 50 soils sampled from the two sites. The regression relationship is shown in Figure 5-6.

All future samples taken in the experiment were then converted to EC_{SAT} by use of the following regression:

$$EC_{SAT} = EC_{1:5} \times 7.6118$$

Equation 5-4

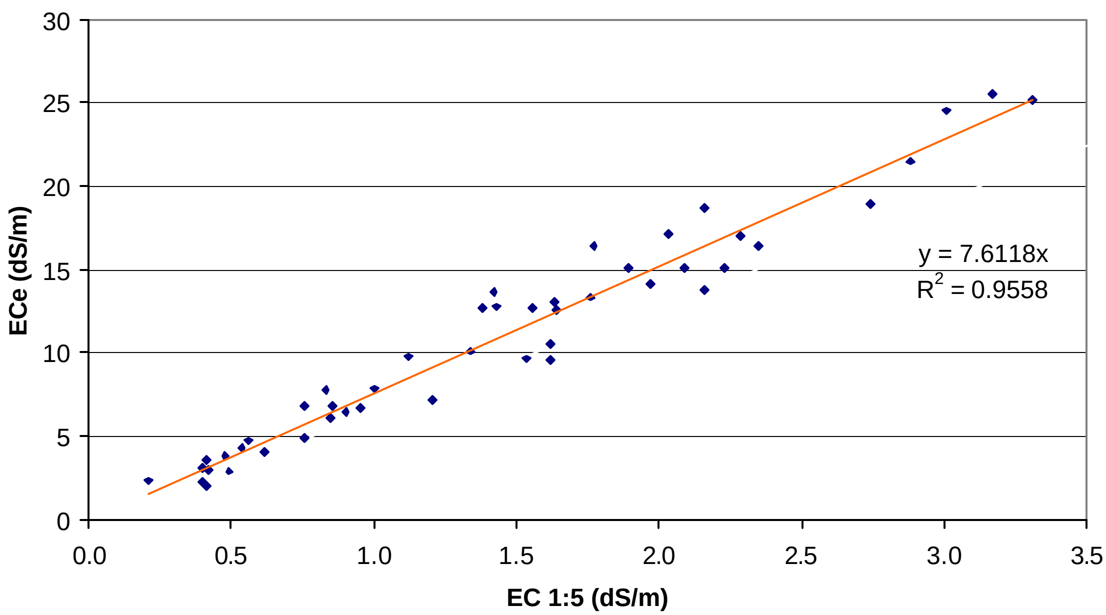


Figure 5-6. Regression between $EC_{1:5}$ to EC_{SAT}

5.6.1.3 Apparent Electrical Conductivity

In order to assess the in-field spatial variability of soil salinity of the field sites and temporal variations over the duration of the experiment, undisturbed soil electrical conductivities were determined using an EM38^{TM} Geonics meter (McNeil, 1986). Previous studies have shown this methodology to be useful in assessing spatial variability of soil salinity (Lesch, Herrero & Rhoades 1998; Rhoades, Chanduvi & Lesch 1999; Slavich 1990).

Measurements were undertaken on a grid spacing of 6 x 6m on the MLD site and 20 x 20m on the CWM site. Both vertical and horizontal dipole measurements were taken at each point. The general procedure used was that outlined by Slavich (n.d) for initial nulling of the instrument and collection of raw readings.

EM38 surveys were undertaken at each soil sampling event before and after the irrigation seasons of 2000/2001 and 2001/2002. This allowed calibration of the EM38 readings which have been shown to be sensitive to soil type, moisture content and temperature (Hanson & Kaita 1997; Rhoades, Chanduvi & Lesch 1999; Slavich 1990). The ESAP (**E**C_e **S**ampling, **A**ssessment and **P**rediction) software (Lesch, Rhoades & Corwin 2000) was used to convert the raw EC_a readings to depth calibrated EC_e readings.

5.6.2 Bulk Density

Bulk density measurements were taken on 0.1m diameter cores taken with a hydraulic coring rig (Figure 5-4). The cores were cut into 0.1m lengths and bulk densities determined by the method for non-expansive soils given by M^{c}Intyre and Loveday (1974a).

5.6.3 Particle Size Analysis

Particle size analysis measurements were carried out using the methodology described by M^{c}Intyre and Loveday (1974b). Silt and clay fractions were determined using the modified form of the hydrometer method and sand fractions with sieves. Particle sizes were taken as Clay (<2μm), silt (2-20μm), fine sand (20-200μm) and coarse sand (200-2000μm).

5.6.4 Hydraulic Conductivity

Saturated hydraulic conductivities were measured using the auger hole method (Boast & Kirkham 1971; Maasland & Haskew 1958; van Beers 1958). Hydraulic conductivity measurements were undertaken on wells in the experimental sites using the methodology described by Maasland and Haskew (1958). Automated water level loggers were used to record well recoveries.

5.7 Soil Cations and Anions

Saturated paste extracts prepared as outlined in section 5.6.1.2 were analysed, after appropriate dilution for concentrations of Ca, Mg, Na and S, using Inductively Coupled Plasma Optical Emission Spectroscopy (ICPOES). Method 3120 of the Standard Methods for the Examination of Water and Wastewater (1992) was used.

5.8 Evapotranspiration

Actual evapotranspiration was measured at the CWM site using the energy balance methodology described by Faulkner (1992). The energy balance method is calculated using:

$$E_T = \frac{R_N - G}{L(1+b)}$$

Equation 5-5

where E_T = Evapotranspiration (mm/day)

R_N = Net Radiation (MJ/m^2)

G = Heat Flux into Earth (MJ/m^2)

L = Latent Heat of vaporisation (MJ/m^2)

β = Bowen Ratio (dimensionless) (Bowen 1926)

The Bowen Ratio can be calculated from the temperature and vapour gradients above a crop as:

$$b = \frac{g\,(T_1 - T_2)}{(e_{v1} - e_{v2})}$$

Equation 5-6

where

γ = Psychometric constant (kPa/^{0}C)

T_1 = Temperature in ^{0}C at the height above crop canopy

T_2 = Temperature in ^{0}C at the crop canopy

e_{v1} = Vapour pressure in kPa above the crop canopy

e_{v2} = Vapour pressure in kPa at the crop canopy

(Bowen 1926)

A suite of instruments developed by Faulkner (1992) known as DREAM (**D**irect **R**eading **E**vapotranspiration **A**ssessment **M**onitor) was used to collect parameters for input into the above equations and ET calculated. Sensors were set to read every minute and record average readings at ½ hour intervals. This provided a continuous dataset of ET readings at ½ hourly intervals. Positioning of the DREAM instrument in relation to the vines is shown in Figure 5-7.

Figure 5-7. DREAM instrumentation used to measure evapotranspiration at the CWM site

Reference crop evapotranspiration data was taken from the CSIRO weather station located at the CSIRO experimental research station Griffith, approximately 6 km from both of the experimental sites.

5.9 *Plant Analysis*

5.9.1 Leaf Water Potential

Leaf water potentials were measured using the pressure chamber method and methodology outlined by Slavik (1974). Fully developed leaves were selected from the vines on the northern facing side and carefully removed with a sharp razor blade. Leaves were then covered in silver foil and placed in an insulated container and transported to a portable laboratory containing the pressure chamber apparatus. All leaf sampling was undertaken between 12:00pm and 2:00pm as an initial experiment found this time to correspond to the maximum water stress period, see Figure 5-8.

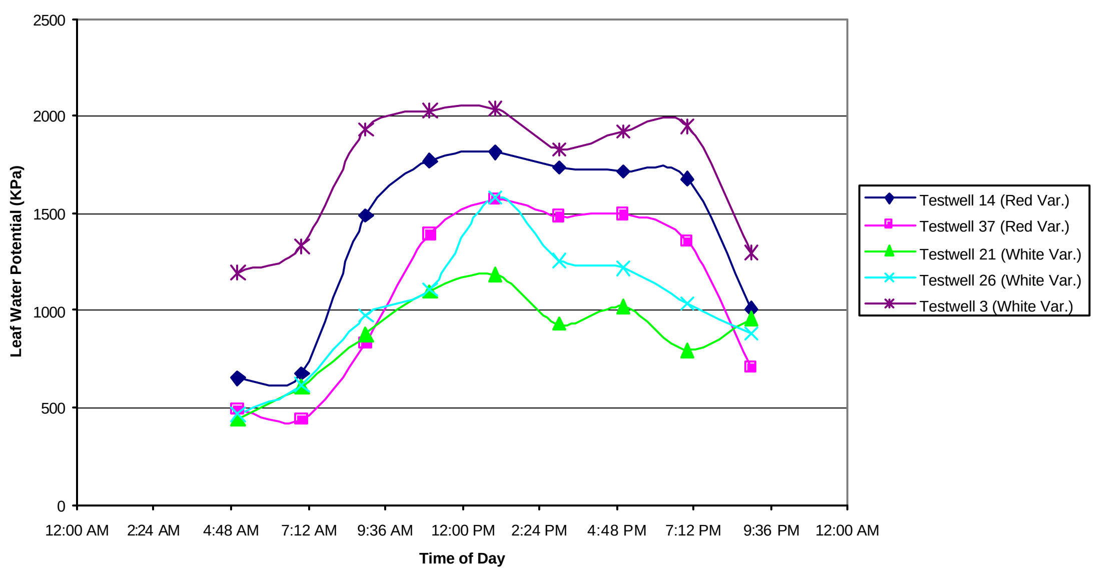


Figure 5-8. Leaf water potential changes over a one-day period for the CWM site

Leaf water potentials were recorded when small sap droplets appeared at the xylem vessels on the cut stem of the leaf. Three replicate leaves were taken from each sampling site and average leaf water potential values recorded. Leaf water potential data was used to calibrate the airborne infrared CWSI data described in Section 5.9.2.

5.9.2 Crop Water Stress Index

Crop water stress index (CWSI) was determined using airborne infrared thermal emission scanning equipment. The equipment was mounted in a light aircraft and linked to a DGPS system. Details of the system are described in Meron, Tsipris and Charitt (2003). This procedure was used to develop CWSI maps at three stages at the CWM site during January of 2002.

5.9.3 Yield and Leaf Chlorides

Yield monitoring was undertaken at the CWM site and consisted of hand picking grapes located directly above the testwells positioned in the treatments. All grapes were hand picked between two vines and weight recorded using a field balance accurate to within ±0.05 kg. 50 berries were then selected at random and taken back to the laboratory to determine average berry weight.

Samples were also collected from these positions for leaf chloride analysis and involved selecting 15 mature leaves from each sampling site. The leaves were then weighed and oven dried at 75^0C for 24 hours and reweighed. The samples were then ground and a 1:5 extract prepared. Chloride concentrations were analysed using segmented flow analysis procedures with an ALPCHEM Flow Solution IV segmented flow analyser.

6 Theoretical Investigations into Multi-level Drainage

6.1 Introduction

In order to investigate the potential benefits and effects of a multi-level drainage system an extension of potential theory developed by Kirkham (1949) was undertaken to extend the theory to incorporate a series of drains at different depths in the soil profile representing a multi-level drainage system. Previously, potential theory has only been applied to bi-level drainage situations by Kirkham, van der Ploeg and Horton 1997. Although Hahoot (1997) presented theory for a multi-level drainage configuration a number of assumptions undertaken by the author have been pointed out to be incorrect. These errors have been shown by Kacimov (1998) in subsequent discussions and relate to the complex potential corresponding to a case in which there is a finite depth of the saturated layer above the subsurface drains, which occurs in practice. In situations in which the assumption that a finite depth of saturated layer occurs above the drain depth, then use of the Kirkham infinite series (Kirkham, 1957) needs to be applied.

The analytical solution developed below is an extension of potential theory to incorporate a multi-level drainage configuration using infinite series presented by Kirkham (Kirkham, 1957) to represent subsurface drains. The analytical solutions presented allow detailed information on the hydraulic head, velocity potential of the stream function, and discharge rates for the both levels of drains in conditions in which water is ponded on the soil surface. The model assumes a homogenous, fully saturated soil profile underlain by an impervious barrier. While this situation would not occur at all times during the operation of the drainage system, the ponded water case does represent the most extreme case in terms of the volume of subsurface drainage generated and can be assumed to occur immediately following surface irrigation when the system is often represented as a quasi steady state. This period hence corresponds with periods of high leaching due to the increased drainage hence its importance when analyzing the potential benefits and effects of a multi-level drainage system.

Parameters in the analytical solution developed are all related to physical aspects of the drainage system, such as drain depths, impervious layer depth, ponded water depth, drain spacings and drain radius. The only field measured parameter required is the saturated hydraulic conductivity. Hence, the analytical solutions provide a great deal of information and do not require extensive field measured parameters, yet they provide valuable information on the flow paths to drains and drain discharge rates. Allowing an initial comparison between drainage configurations to be undertaken. The analytical solution presented also can be reduced to the Kirkham, van der Ploeg and Horton (1997) bi-level drainage solution in the case where only one shallow drain is placed between two deeper drains and to Kirkham's (1949) single-level drainage solution when no shallow drains are used. Where possible all previous notation used by Kirkham, van der Ploeg and Horton (1997) has been applied to the following analysis.

6.2 Analysis of Multi-level Subsurface Drainage System

The following assumptions have been made in analysis of the problem:

1. The problem is represented two dimensionally, and an (x,y) system of coordinates used.
2. The soil is homogeneous and isotopic in nature.
3. Darcy's Law is applies.

Considering these assumptions then Laplaces's equation applies and the hydraulic head (ϕ) is given by:

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} = 0$$

Equation 6-1

In order to determine the hydraulic head then appropriate boundary conditions must be known. Figure 6-1 shows a diagrammatic representation of the problem with general geometry shown on the left hand side and boundary conditions on the right. One of the fictitious infinite array of drain tubes is shown in Figure 6-1, which are used in the analysis.

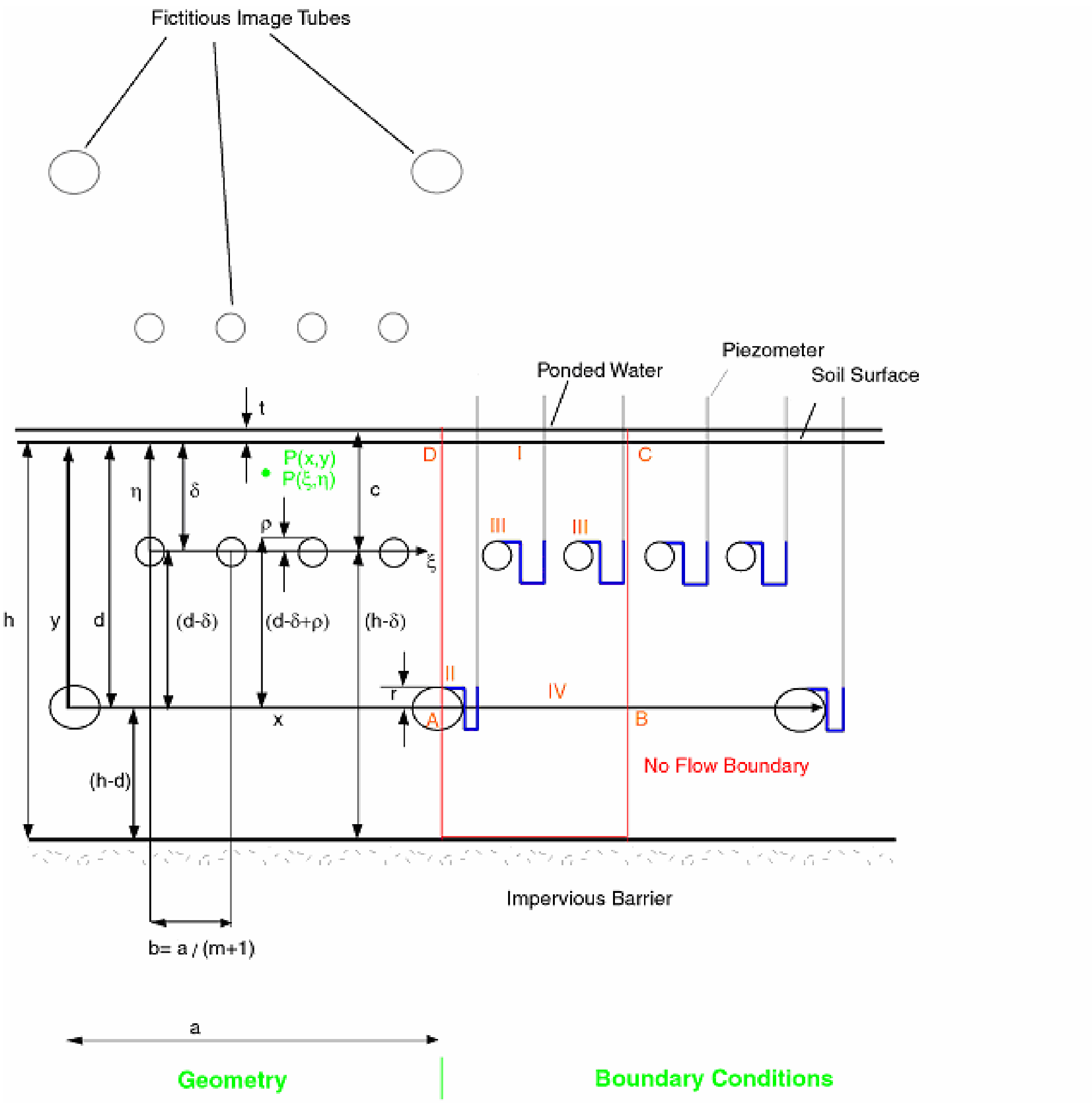


Figure 6-1. Geometry of the ponded multi-level drainage system with one of the infinite number of fictitious image tubes shown.

In Figure 6-1 deep drain tubes are represented by the larger circles, with radius r, at depth d and the shallow drain tubes by the smaller circles with radius ρ at depth δ. In Figure 6-1 four shallow drain tubes are shown between each deep tube, however the theory developed below can be used to analyze any number (m) of shallower tubes between the deeper tubes. The horizontal distance between two deep tubes is given by a and the spacing between shallow tubes is assumed to be equally spaced between deep drains and given by b, where:

$$b = a/(m+1)$$

Equation 6-2

The origin of the (x,y) coordinates is taken as the center of the left deep drain tube and the reference level taken as the center level of the deep drain tubes. A (ξ,η) system of coordinates is used for the shallow drain system with its origin at the center of the left most shallow drain tube. Ranges for specific parameters including m (number of shallow drains) are as presented below:

$\infty > (a/2) > (r+\rho)$

$d > \delta > \rho > 0$

$\infty > h > d > d + r > d > r \geq \rho > 0$

$t \geq 0$

$c \geq d$

$m \geq 0$

$x^2 + y^2 = r^2$ for $r \rightarrow 0$

$\xi^2 + \eta^2 = \rho^2$ for $\rho \rightarrow 0$

Boundary conditions for the problem are shown in the right hand side of Figure 6-1. No flow boundary conditions are shown in red and occur along the plane marked AB, BC and AD in Figure 6-1.

Boundary conditions can be summarized as follows with Roman numerals denoting specific boundary conditions shown in Figure 6-1.

Boundary Condition I: for the region $0 \leq x \leq a/2$, at $y=d$, then a constant hydraulic head equal to the sum of the depth of the saturated layer and ponded water depth applies:

$$\phi_{MLS} = d + t$$

Equation 6-3

The subscript MLS refers to the Multi-Level drainage system, incorporating both shallow and deep drains.

Boundary Condition II: for the region $x^2 + y^2 = r^2$ for $r \to 0$, At the deep drain we can assume an ideal drain:

$$\phi_{MLS} = r$$

Equation 6-4

Boundary Condition III: for the region $\xi^2 + \eta^2 = \rho^2$ for $\rho \to 0$ a similar boundary condition will apply to each of the shallow drains:

$$\phi_{MLS} = d - \delta + \rho$$

Equation 6-5

Boundary Condition IV: No flow boundary conditions are shown in red in Figure 6-1.

$$\partial \phi_{MLS} / \partial n = 0$$

Equation 6-6

6.2.1 Determination of Hydraulic Head

From Kirkham (1949) an expression for the hydraulic head, in the case of only the deep drains, is given by:

$$\phi_{DD} = q_{DD} W_{DD}$$

Equation 6-7

where the subscript DD refers the deep drains and q_{DD} is the hydraulic head coefficient of the deep drains given latter. W_{DD} is given by:

$$W_{DD} = \sum_{n=-\infty}^{\infty} (-1)^n \ln \frac{\cosh \frac{2p\,(y-2nh)}{a} - \cos \frac{2px}{a}}{\cosh \frac{2p\,(y-2d-2nh)}{a} - \cos \frac{2px}{a}} + C_{DD}$$

Equation 6-8

Where the origin of the (x,y) coordinate system is taken at the center of the deep drain tube and C_{DD} is a constant.

Now an expression for the hydraulic head due to the shallow system of drains can be expressed by:

$$\phi_{SD} = q_{SD} W_{SD}$$

Equation 6-9

Where the subscript SD refers to the shallow drains and q_{SD} is the hydraulic head coefficient of the shallow drains (given later). W_{SD} is given by:

$$W_{SD} = \sum_{n=-\infty}^{\infty} (-1)^n \ln \frac{\cosh \frac{2p\,(h-2nh)}{a} - \cos \frac{2px}{a}}{\cosh \frac{2p\,(h-2d-2nh)}{a} - \cos \frac{2px}{a}} + C_{SD}$$

Equation 6-10

(Note: In Equation 6-10 the spacing parameter a is used, not b, as spacing between similar shallow drains in relation to the deep drains occurs at a spacing of a in our imaginary fictitious array of drain tubes)

C_{SD} is a constant. Equation 6-10 is a general expression for each shallow drain in the system, hence potentials of shallow drains are added to gain the total hydraulic head due to the influence of the shallow drains:

$$\phi_{SDTotal} = q_{SD1}W_{SD1} + q_{SD2}W_{SD2} + \_\_\_\_\_ + q_{SDm}W_{SDm}$$

Equation 6-11

where m is the total number of shallow drains.

In order to add the potentials from the deep drain and shallow drain system, then the shallow drain system coordinates need to be mapped to that of the deep drain coordinates, namely (x,y). In considering the point P shown in green in Figure 6-1 the following relationships between the coordinates are found:

$$\eta = y - (d - \delta)$$

Equation 6-12

All shallow drains are at the same depth.

$$x_{1\to m} = \frac{x - an}{m+1} \text{ for n=1 to m}$$

Equation 6-13

which results in m expressions of x for each drain spacing.

Substitution of Equation 6-12 and Equation 6-13 into Equation 6-10 and then combining the result with Equation 6-7 yields an expression relating to the hydraulic head for the shallow drains on the (x,y) coordinate system. Now since the deep drain and shallow drains are on the same coordinate system then potentials can be added to obtain an expression for the hydraulic head of the multi-level drainage system given by:

$$\phi_{MLS} = q_{DD}W_{DD} + q_{SD1}W_{SD1} + q_{SD2}W_{SD2} + \_\_\_\_\_ + q_{SDm}W_{SDm} + C_{DD} + C_{SD}$$

Equation 6-14

Applying Boundary Conditions

In order to determine q_{DD}, q_{SD1}, q_{SD2}, _ _ _ _ _, q_{SDm} and the constants $C_{DD} + C_{SD}$. Applying boundary condition I shown in Figure 6-1, $\phi_{MLS} = d + t$ for x = x, y = d, then:

$$d + t = q_{DD}W_{DD} + q_{SD1}W_{SD1} + q_{SD2}W_{SD2} + \_\_\_\_\_ + q_{SDm}W_{SDm} + C_{DD} + C_{SD}$$

Equation 6-15

when x = x and y = d then the summation terms W_{DD}, W_{SD1}, W_{SD2}, _ _ _ _, $W_{SDm} = 0$ (Kirkham, van der Ploeg & Horton 1997) and the constants C_{DD} and C_{SD} are given by:

$$C_{DD} + C_{SD} = d + t$$

Equation 6-16

Then applying boundary condition II of Figure 6-1, $\phi_{MLS} = r$ for x = 0 and y = r:

$$r = q_{DD}W_{DD} + q_{SD1}W_{SD1} + q_{SD2}W_{SD2} + \_\_\_\_\_ + q_{SDm}W_{SDm} + d + t$$

Equation 6-17

and boundary condition III of Figure 6-1, $\phi_{MLS} = d - \delta + \rho$, for x = na/(m+1) for n = 1 to m, $y = d - \delta + \rho$:

$$d - \delta + \rho = q_{DD}W_{DD} + q_{SD1}W_{SD1} + q_{SD2}W_{SD2} + \_\ \_\ \_ + q_{SDm}W_{SDm} + d + t$$

Equation 6-18

Substitution of x for n=1 to m into Equation 6-18 produces m equations and with Equation 6-17, m + 1 equations with m + 1 unknowns (q terms) which can be solved simultaneously.

Therefore, the general hydraulic head equation for a multi-level subsurface drainage system is given by:

$$f_{MLS}(x,y) = q_{DD}\sum_{n=-\infty}^{\infty}(-1)^n \ln \frac{\cosh\frac{2p\,(y-2-nh)}{a} - \cos\frac{2px}{a}}{\cosh\frac{2p\,(y-2d-2nh)}{a} - \cos\frac{2px}{a}}$$

$$+ q_{SD1}\sum_{n=-\infty}^{\infty}(-1)^n \ln \frac{\cosh\frac{2p\,(y-d+d-2nh)}{a} - \cos\frac{2p\left(\frac{x-a}{m+1}\right)}{a}}{\cosh\frac{2p\,(y-d-d-2nh)}{a} - \cos\frac{2p\left(\frac{x-a}{m+1}\right)}{a}}$$

$$+ q_{SD2}\sum_{n=-\infty}^{\infty}(-1)^n \ln \frac{\cosh\frac{2p\,(y-d+d-2nh)}{a} - \cos\frac{2p\left(\frac{x-2a}{m+1}\right)}{a}}{\cosh\frac{2p\,(y-d-d-2nh)}{a} - \cos\frac{2p\left(\frac{x-2a}{m+1}\right)}{a}}$$

$$+ \mathrm{K\ K} + q_{SDm}\sum_{n=-\infty}^{\infty}(-1)^n \ln \frac{\cosh\frac{2p\,(y-d+d-2nh)}{a} - \cos\frac{2p\left(\frac{x-am}{m+1}\right)}{a}}{\cosh\frac{2p\,(y-d-d-2nh)}{a} - \cos\frac{2p\left(\frac{x-am}{m+1}\right)}{a}} + d + t$$

Equation 6-19

Drain Flows

Drain flow from the multi-level drainage system is given by:

$$Q_{MLS} = Q_{DD} + Q_{SD1} + Q_{SD2} + \_\ \_\ \_\ \_ + Q_{SDm}$$

Equation 6-20

Now the following expression for drain flow from each drain is given by:

$$Q_{DD} = 4\pi k q_{DD}$$

Equation 6-21

$$Q_{SD1} = 4\pi k q_{SD1}$$

Equation 6-22

$$Q_{SD2} = 4\pi k q_{SD2}$$

Equation 6-23

$$Q_{SDm} = 4\pi k q_{SDm}$$

Equation 6-24

Substitution of Equation 6-21 to Equation 6-24 into Equation 6-20 yields the drain discharge for the multi-level drainage system:

$$Q_{MLS} = 4\pi k(Q_{DD} + Q_{SD1} + Q_{SD2} + \_\ \_\ \_\ \_\ \_ + Q_{SDm})$$

Equation 6-25

Stream Function

The stream function for the deep drains is given by Kirkham (1949) as below:

$$y_{DD} = 2kq_{DD}Z_{DD}$$

Equation 6-26

$$Z_{DD} = \sum_{n=-\infty}^{\infty}(-1)^n\left\{\tan^{-1}\left[\tanh\frac{p(y-2nh)}{a}\cot\frac{px}{a}\right]-\tan^{-1}\left[\tanh\frac{p(y-2d-2nh)}{a}\cot\frac{px}{a}\right]\right\}$$

Equation 6-27

Now applying this to the shallow drains the stream function is given by:

$$y_{SD} = 2kq_{SD}Z_{SD}$$

Equation 6-28

Where Z_{SD} is given by:

$$Z_{SD} = \sum_{n=-\infty}^{\infty}(-1)^n\left\{\tan^{-1}\left[\tanh\frac{p(y-d+d-2nh)}{a}\cot\frac{px}{a}\right]-\tan^{-1}\left[\tanh\frac{p(y-d-d-2nh)}{a}\cot\frac{px}{a}\right]\right\}$$

Equation 6-29

Which again is a general expression for each shallow drain in the system, hence potentials of the shallow drains are added to gain:

$$\psi_{SDTotal} = 2k(q_{SD1}Z_{SD1} + q_{SD2}Z_{SD2} + \_\ \_\ \_\ \_ + q_{SDm}Z_{SDm})$$

Equation 6-30

The stream function for the multi-level drainage system (ψ_{MLS}) is then given by the addition of the shallow and deep tube stream functions:

$$\psi_{MLS} = 2k(q_{DD}Z_{DD} + q_{SD1}Z_{SD1} + q_{SD2}Z_{SD2} + \_\ \_\ \_\ \_ + q_{SDm}Z_{SDm})$$

Equation 6-31

which, when expanded yields the general expression for the stream function of the multi-level drainage system:

$$y_{MLS}(x,y) = 2kq_{DD}\sum_{n=-\infty}^{\infty}(-1)^n\left\{\tan^{-1}\left[\tanh\frac{p(y-2nh)}{a}\cot\frac{px}{a}\right]-\tan^{-1}\left[\tanh\frac{p(y-2d-2nh)}{a}\cot\frac{px}{a}\right]\right\}$$

$$+2kq_{SD1}\sum_{n=-\infty}^{\infty}(-1)^n\left\{\tan^{-1}\left[\tanh\frac{p(y-d+d-2nh)}{a}\cot\frac{p\left(\frac{x-a}{m+1}\right)}{a}\right]-\tan^{-1}\left[\tanh\frac{p(y-d-d-2nh)}{a}\cot\frac{p\left(\frac{x-a}{m+1}\right)}{a}\right]\right\}$$

$$+2kq_{SD2}\sum_{n=-\infty}^{\infty}(-1)^n\left\{\tan^{-1}\left[\tanh\frac{p(y-d+d-2nh)}{a}\cot\frac{p\left(\frac{x-2a}{m+1}\right)}{a}\right]-\tan^{-1}\left[\tanh\frac{p(y-d-d-2nh)}{a}\cot\frac{p\left(\frac{x-2a}{m+1}\right)}{a}\right]\right\}$$

$$+\mathrm{K}+2kq_{SDm}\sum_{n=-\infty}^{\infty}(-1)^n\left\{\tan^{-1}\left[\tanh\frac{p(y-d+d-2nh)}{a}\cot\frac{p\left(\frac{x-ma}{m+1}\right)}{a}\right]-\tan^{-1}\left[\tanh\frac{p(y-d-d-2nh)}{a}\cot\frac{p\left(\frac{x-ma}{m+1}\right)}{a}\right]\right\}$$

Equation 6-32

6.2.2 Comparisons of Drainage Configurations

In order to compare different drainage configurations, the newly developed analytical solutions, were programmed into Mathematica (Wolfram, 1991), which allowed easy visualization of the equipotential and streamlines of different drainage configurations. A copy of the Mathematica Notebook is included in the appendix. Equipotential and streamline contour plots for a typical subsurface drainage layout are shown in Figure 6-2 and Figure 6-3 respectively. Figure 6-4 and Figure 6-5 show the Equipotential and Streamline contour plots for a multi-level drainage configuration with the addition of four shallow drains between the two deeper drains.

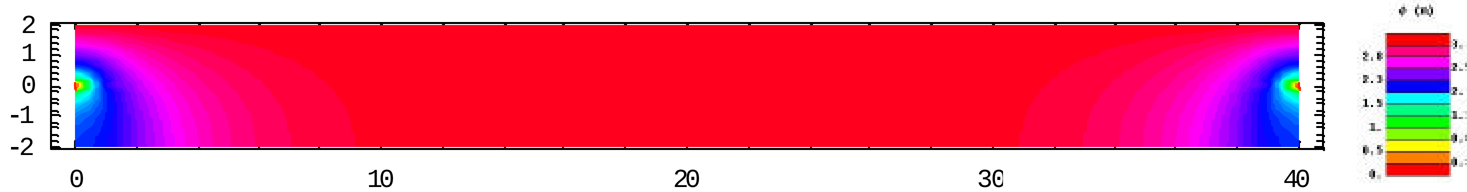


Figure 6-2. Equipotential lines for single level drainage system, with r = 0.1, d=2, h=4, t=0, k=1, a=40

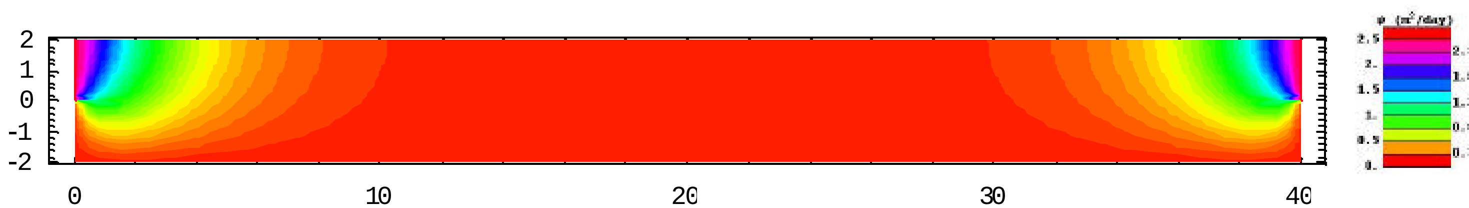


Figure 6-3. Streamlines for single level drainage system, with r = 0.1, d=2, h=4, t=0, k=1, a=40

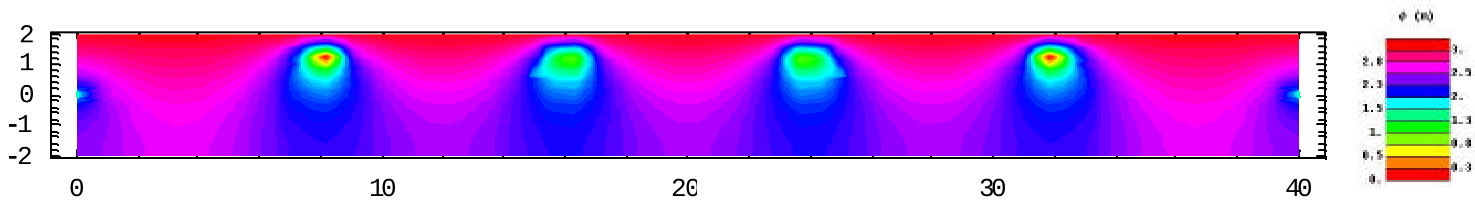


Figure 6-4. Equipotential lines for multi-level drainage system, with r = 0.1, d=2, h=4, t=0, k=1, a=40, m=4, d =0.75,r =0.065

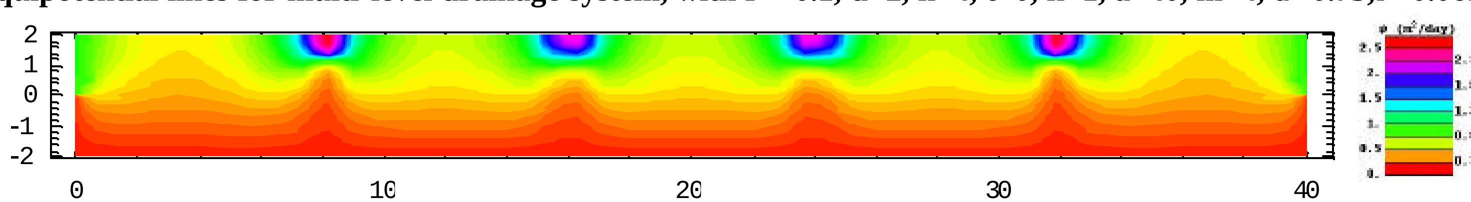


Figure 6-5. Streamlines for multi-level drainage system, with r = 0.1, d=2, h=4, t=0, k=1, a=40, m=4, d=0.75,r =0.065

It can be seen that the multi-level drainage configuration results in markedly different flow characteristics than the single level drainage configuration. The streamline contour plots for the single level and multi-level drainage configurations show the water paths and hence solutes (such as salt) will follow. It can be seen in Figure 6-3 to Figure 6-5 that with the multi-level drainage configuration deep flow paths to the deep drains are reduced and also there is a more even distribution of streamlines throughout the drainage cross section, hence time for leaching of the rootzone at greater distances away from the deep drains are much greater in the single level drainage configuration than the multi-level drainage configuration.

In considering the impacts associated with the disposal of saline drainage water then one of the major objectives of a drainage system should be to minimize the saline drainage effluent from the system. In most semi-arid irrigation areas it has been shown that in general soil salinity generally increases with depth, hence minimization of the depth of water flow paths to the drains often leads to a reduction in the drainage water salinity. Considering the flow paths shown in Figure 6-5 for the multi-level drainage configuration then the water salinity from the system could be hypothesized to be of a reduced salinity compared to a single level system. The flow paths of the multi-level drainage configuration are more evenly distributed over the drainage cross-section and are also considerably shorter than that of the single level system indicating that the removal of salts from within the plant rootzone will occur at a much greater rate than that of the single level drainage system particularly when comparing areas away from the deeper drains in the treatments.

In order to establish if deep drains in the multi-level system could be spaced wider apart an analysis of flows from the single level and multi-level systems was undertaken. A typical configuration with the following parameters $r=0.1$, $d=2.0$, $t=0$, $h=4$, $\rho=0.065$, $k=1$, $\delta=0.75$ was used to investigate the contribution of flow orginating from the shallow drainage system for a single level system (SL), a bi-level system (BLS), a multi-level system with 4 shallow drains (MLS 4), a multi-level system with 8 shallow drains (MLS 8) and a multi-level system with 16 shallow drains (MLS 16). Table 6-1 shows the drainage discharge from the shallow and deep drains and also the percentage of total flow which occurs through the shallow drainage system.

Table 6-1 Drain discharge (m^3/m/d) as a function of deep drain spacing for different drainage configurations

		Deep Drain Spacing							
		10	**20**	**40**	**60**	**80**	**100**	**150**	**200**
SL	Shallow	-	-	-	-	-	-	-	-
	Deep	3.01	3.07	3.07	3.07	3.07	3.07	3.07	3.07
	% of total flow in shallow drains	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
BLS	Shallow	1.17	1.35	1.38	1.38	1.38	1.38	1.38	1.38
	Deep	2.94	3.06	3.07	3.07	3.07	3.07	3.07	3.07
	% of total flow in shallow drains	**28.4**	**30.6**	**31.0**	**31.0**	**31.0**	**31.0**	**31.0**	**31.0**
MLS (4)	Shallow	3.72	4.92	5.41	5.49	5.51	5.51	5.52	5.52
	Deep	2.68	2.94	3.04	3.06	3.07	3.07	3.07	3.07
	% of total flow in shallow drains	**58.1**	**62.7**	**64.0**	**64.2**	**64.2**	**64.3**	**64.3**	**64.3**
MLS (8)	Shallow	5.57	8.58	10.32	10.77	10.92	10.99	11.03	11.03
	Deep	2.46	2.75	2.96	3.03	3.05	3.06	3.07	3.07
	% of total flow in shallow drains	**69.4**	**75.8**	**77.7**	**78.1**	**78.2**	**78.2**	**78.2**	**78.2**
MLS (16)	Shallow	6.98	12.88	18.23	20.17	21.02	21.45	21.88	22.01
	Deep	2.28	2.50	2.77	2.90	2.97	3.01	3.05	3.06
	% of total flow in shallow drains	**75.4**	**83.8**	**86.8**	**87.4**	**87.6**	**87.7**	**87.8**	**87.8**

In order to compare the systems the ratio given by discharge to deep drain spacing is developed:

System Discharge (Q) in m^3/m/d : Deep Drain Spacing (a) in m

The above ratio gives a basis for comparison purposes between the different drainage configurations and allows a comparison between the systems to be made as it represents drainage discharge per unit m spacing between drains. For identical discharge: drain spacing ratios the spacing of the deep drains can be compared and an initial basis for the magnitude of increase in deep drain spacings can be identified. Figure 6-6 shows the relationship between the discharge: drain spacing ratio and spacing of the drains

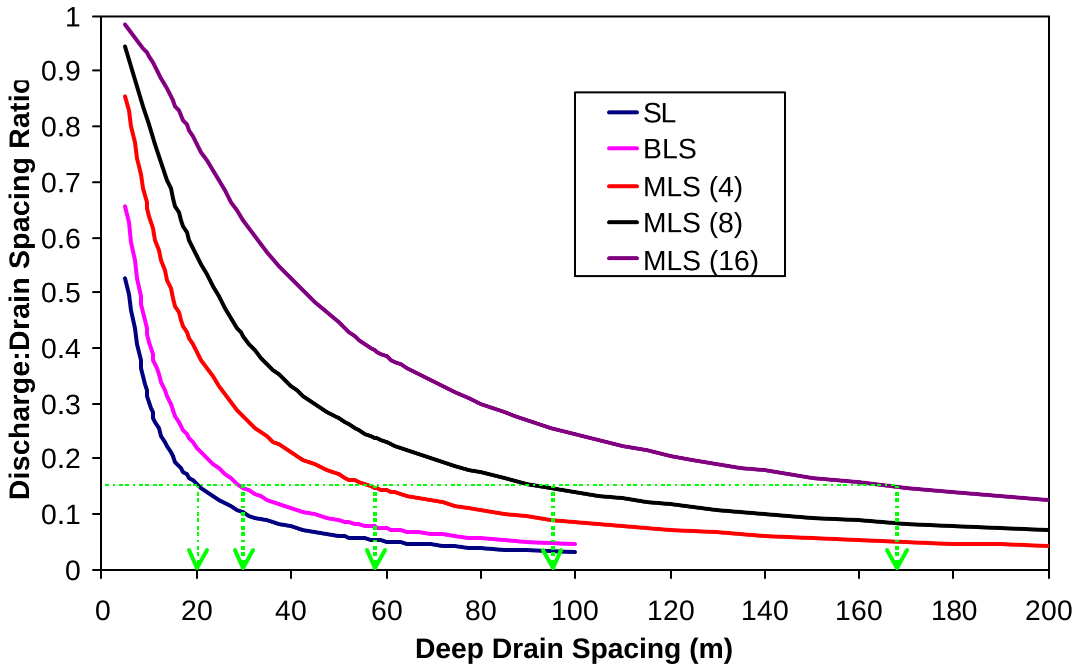


Figure 6-6. Discharge : Drain spacing Ratio as a function of deep drain spacing

Considering a discharge : drain spacing ratio of 0.15 then the associated deep drain spacings are 20m for the single level system, 29m for the bi-level system, 57m for the multi-level system with 4 shallow drains, 95m for the multi-level system with 8 shallow drains and 168m for the multi-level drainage system with 16 shallow drains. Hence, for equal drain discharges, compared to the single level system, the spacing of the deep drains in the multi-level systems can be increased by 45, 185, 375, 740 % for the bi-level, MLS 4 Drain, MLS 8 Drain and MLS 16 Drain configurations over the single-level drainage configuration.

Streamlines for the five drainage configurations are shown in Figure 6-7. Equal drain discharges will occur from each of the five drainage configurations shown in Figure 6-7, hence the total drainage volume from each of the configurations will be the same in ponded conditions for a given area. In considering the streamlines shown in Figure 6-7 the shallower flow paths can be seen with increased shallow drains supporting the assumption that drainage water salinity from the multi-level drainage system will be reduced compared to a traditional single level system. Streamlines are also more evenly distributed in the multi-level drainage configuration than the single-level configuration, hence leaching of salts from the rootzone will be more uniform.

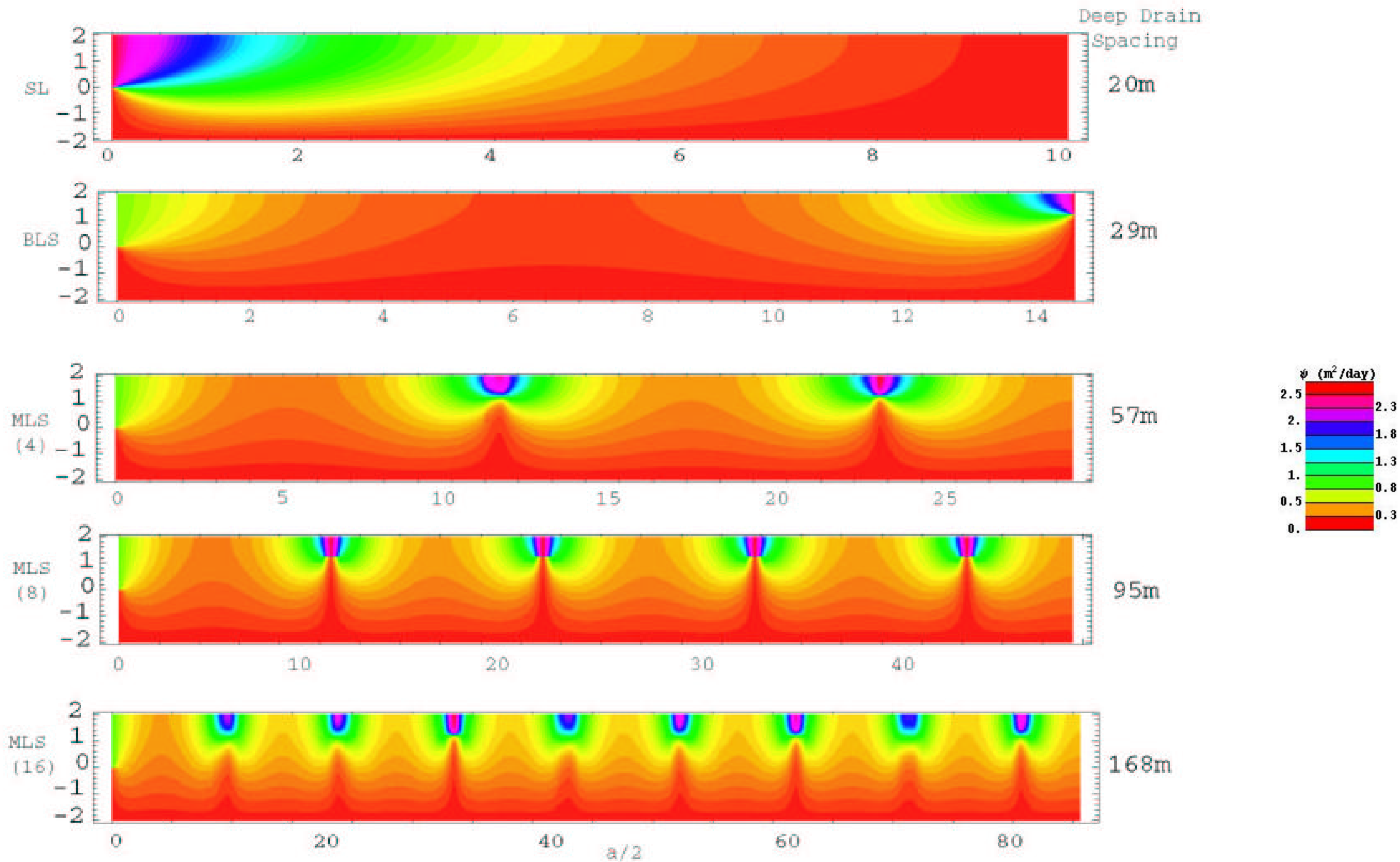


Figure 6-7. Streamlines for the five drainage configurations with equal discharge : drain spacing ratio

6.3 Conclusions

Kirkhams (1949) potential theory was extended to incorporate a multiple series of shallow drains placed between two deeper drains. The theory was then used to compare spacing and drain flow characteristics between a single level drainage system and a multi-level drainage system. The results showed that spacing between deep drains in the multi-level drainage system could be significantly increased in the presence of shallow drains. It was shown that drainage salinity would potentially be reduced in the multi-level drainage system, based on water flow paths, which were reduced in depth and length in the multi-level drainage treatment, particularly in areas distant from the deep drains. Considering these factors then the multi-level drainage system could offer a reduction in salt loads over traditional single level systems and prove to be economically attractive.

Considering a number of assumptions have been made in the analytical solution developed, which may or may not be met in field conditions, then testing of the system in a field situation is needed. While the analytical model above provides extremely useful information on the multi-level drainage system with minimal input data, it also has a number of shortcomings in that only the ponded water condition is considered, drainage behavior is assumed to be ideal and the soil is considered homogenous. In order to investigate the multi-level system then these shortcomings of the analytical model were investigated with field trials of the system, which are presented in the following chapters.

7 Results and Discussion

7.1 MLD Experimental Site

The **MLD** experimental site consisted of two drainage treatments. These being the **M**ulti-**L**evel subsurface drainage treatment, referred to as the **ML** treatment and a **S**ingle **L**evel subsurface drainage treatment, referred to as the **SL** treatment, Figure 4-8 and Figure 4-9 respectively.

7.1.1 Water Application

Over the two-year period in which the field experiment was undertaken a total of 16 irrigation events were monitored and one significant rainfall event. Four irrigations occurred late in the 2000/2001 irrigation season when no crop was present and 12 irrigations during the 2001/2002 irrigation season, during which young *Vitis vinifera* (Semillon Cultivar on own rootstocks) were planted. Irrigation application dates and volumes applied to the two treatments are shown in Table 7-1.

Table 7-1. Irrigation application dates and volumes applied to each treatment during the experimental period

			Applied Water (mm)	
Irrigation Season	**Irrigation Event**	**Date**	**ML**	**SL**
2000/2001	1st Irrigation	3/02/2001	76	74
2000/2001	2nd Irrigation	24/02/2001	34	66
2000/2001	3rd Irrigation	10/03/2001	21	29
2000/2001	4th Irrigation	31/03/2001	26	20
2001/2002	1st Irrigation	8/10/2001	35	33
2001/2002	2nd Irrigation	3/11/2001	35	39
2001/2002	3rd Irrigation	17/11/2001	69	60
2001/2002	4th Irrigation	1/12/2001	64	68
2001/2002	5th Irrigation	15/12/2001	63	66
2001/2002	6th Irrigation	29/12/2001	35	40
2001/2002	7th Irrigation	12/01/2002	41	44
2001/2002	8th Irrigation	25/01/2002	44	50
2001/2002	Rain	4/02/2002	62	62
2001/2002	9th Irrigation	23/02/2002	25	20
2001/2002	10th Irrigation	9/03/2002	29	28
2001/2002	11th Irrigation	23/03/2002	20	21
2001/2002	12th Irrigation	13/04/2002	13	12

Irrigation applications aimed to apply the same volume to each treatment. However due to problems in the 2000/2001 irrigation season with water supply to the treatments there was a large difference in water applied to the ML and SL treatments during the second irrigation. Apart from this irrigation event all water applied to the treatments was within 10mm for each of the irrigation events, and in the majority of events the difference was less. Depths of water application shown in Table 7-1 were calculated using inflow and outflow measuring flumes in each treatment as described in Chapter 5.

Figure 7-1 shows a typical irrigation event and the distribution of water in relation to the vines and inter-row spacing between furrows. Using this irrigation technique water was not directly ponded over either the shallow or deep drains, however during rainfall events water infiltrated over the whole surface area.

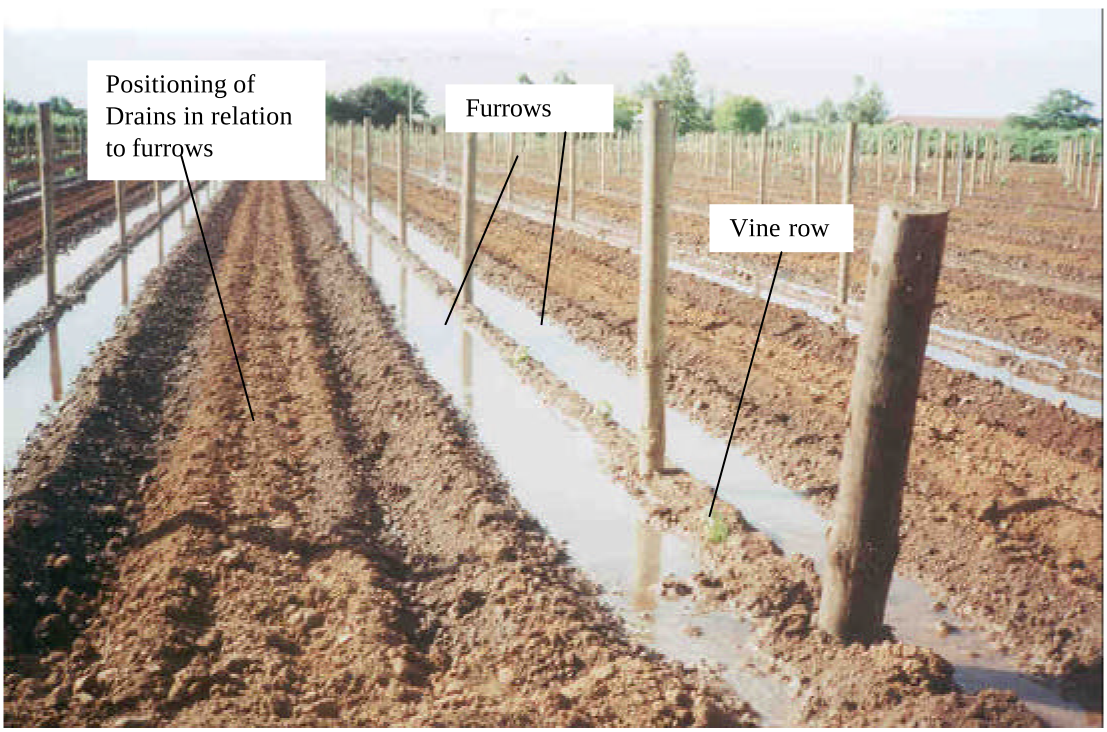


Figure 7-1. Typical irrigation application showing furrow irrigation system used at the trial site

The variation in water applied to the treatments throughout the experiment was due to two factors. Firstly, the initial conditions of the furrows in relation to surface roughness after reworking and reforming, which tended to slow water advance down the furrows increasing opportunity time and hence infiltrated volumes of water. Irrigations applied after reworking of the furrows were generally higher due to the slower advance times and associated increased opportunity times. The second factor was the timing of the irrigation event in relation to the duration of the irrigation season. As the irrigation season progressed, particularly later into the autumn periods the interval between irrigations was increased and the amounts of water applied decreased. This was due to the farm manager's assessment that the vines needed less water. The last irrigation of the 2000/2001 irrigation season was significantly smaller as only one side of the vine was watered (every alternate furrow). This irrigation event produced no subsurface drainage.

7.1.2 Drainage Flows and Salinity

During the 2000/2001 irrigation season drain flows and electrical conductivities from both treatments were measured manually. Unfortunately, ultra sonic flow meters, which were installed in the monitoring sumps, failed to produce quality flow data and hence were discarded. Only manual measurements were therefore available for the 2000/2001 irrigation season. During the 2001/2002 irrigation season more detailed flow and salinity data was collected. Automated procedures for both drain flows using tipping buckets and electrical conductivities using conductivity loggers allowed more rigorous investigations to be made.

7.1.2.1 SL treatment

Drain flow and EC of the drainage water for the SL treatment over the experimental is shown in Figure 7-2.

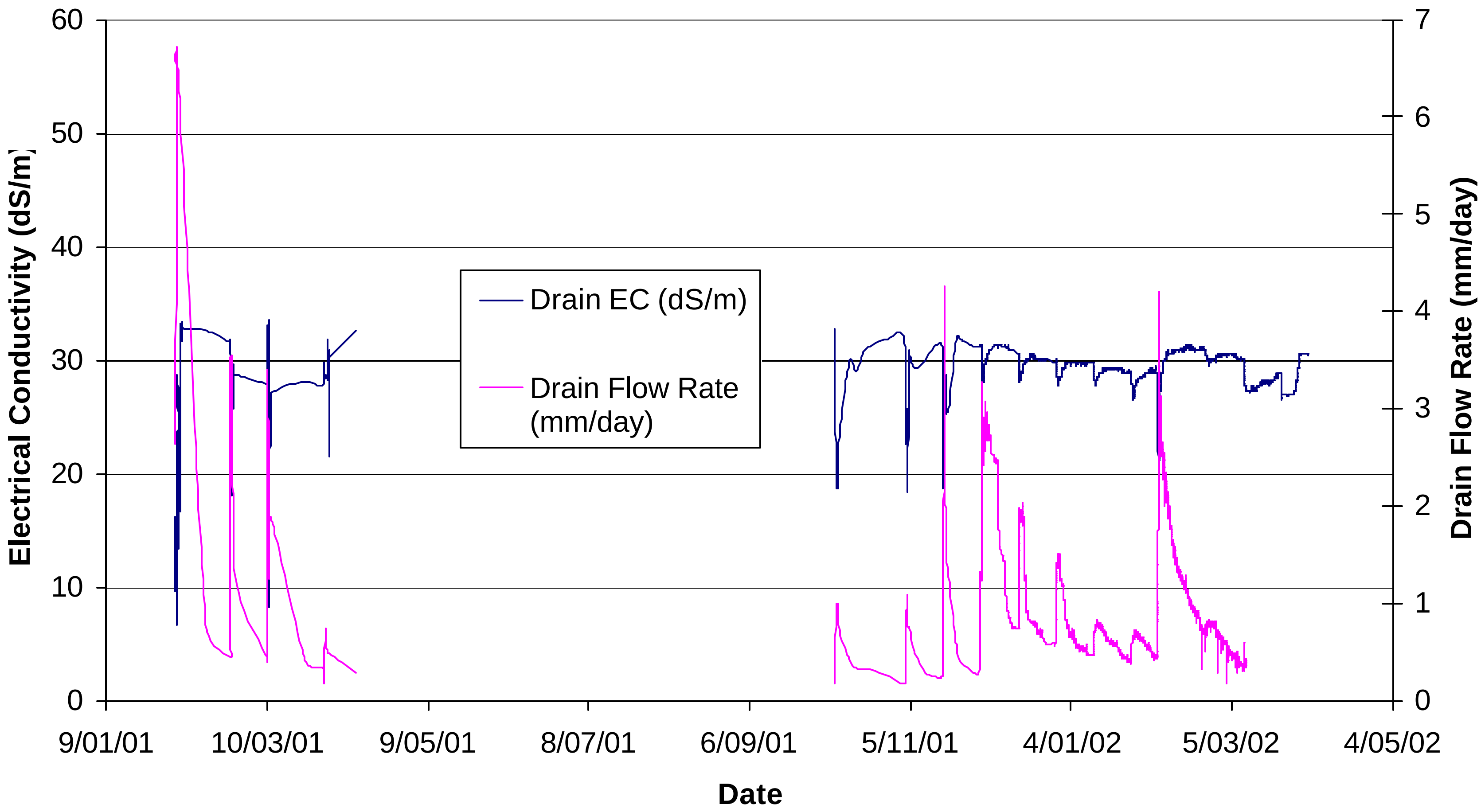


Figure 7-2. Drain flows and drain electrical conductivity of the SL treatment over the experimental period

From Figure 7-2 it can be seen that during the experimental period drain flows only occurred during the irrigation periods of the 2000/2001 and 2001/2002 irrigation seasons. During the winter period there was no drainage from the SL treatment. It can be seen that drain flows responded rapidly to irrigation events before declining steadily back to a baseline drainage rate of between 0.25 and 0.5 mm/day before the next irrigation event. The maximum drainage rate for the SL treatment was approximately 6.5 mm/day during the first irrigation event of the 2000/2001 irrigation season, which corresponds to the maximum intensity irrigation event that was monitored (Table 7-1).

An inverse relationship was seen between the drain flow patterns and the drain salinity (EC), especially at the start of drainage after irrigation. During irrigation events EC declined rapidly by 5-15 dS/m before steadily increasing back to a baseline of approximately 30 dS/m. During the 2000/2001 irrigation season this baseline was less clearly, however this was most likely a result of minimal data being collected due to instrumentation failure and inadequate sampling at low drainage flows to satisfactorily characterize the baseline. Declines in drain EC during the 2000/2001 irrigation season after irrigation events was generally of a larger magnitude than the 2001/2002 irrigation season. This was due to the differences in construction of the irrigation furrows. During the 2000/2001 irrigation season furrows were constructed without the presence of the vine rows and it was difficult for the farm manager to develop straight furrows parallel to the drainage lines. Therefore, during the 2000/2001 irrigation season furrows were situated much closer to the drain line than during the 2001/2002 irrigation season. This would allow a much greater degree of preferential flow to the drainage line to occur and hence see a greater reduction in drain water EC during irrigation events due to increased preferential flow to the drainage line. During the 2000/2001 irrigation season it could also be expected that the back fill material in the drainline trench would be more permeable as the drains were only recently installed. This would also assist increased preferential flow to the drain line and explain the larger reductions in drain water electrical conductivity measured during the 2000/2001 irrigation season.

7.1.2.2 ML Treatment

Figure 7-3 presents the drain flow and drain water salinity (EC) for the ML treatment. The drain flows and salinity have been further divided in Figure 7-3 into drain flow and (EC) from the shallow drains and the deep drain within the ML treatment.

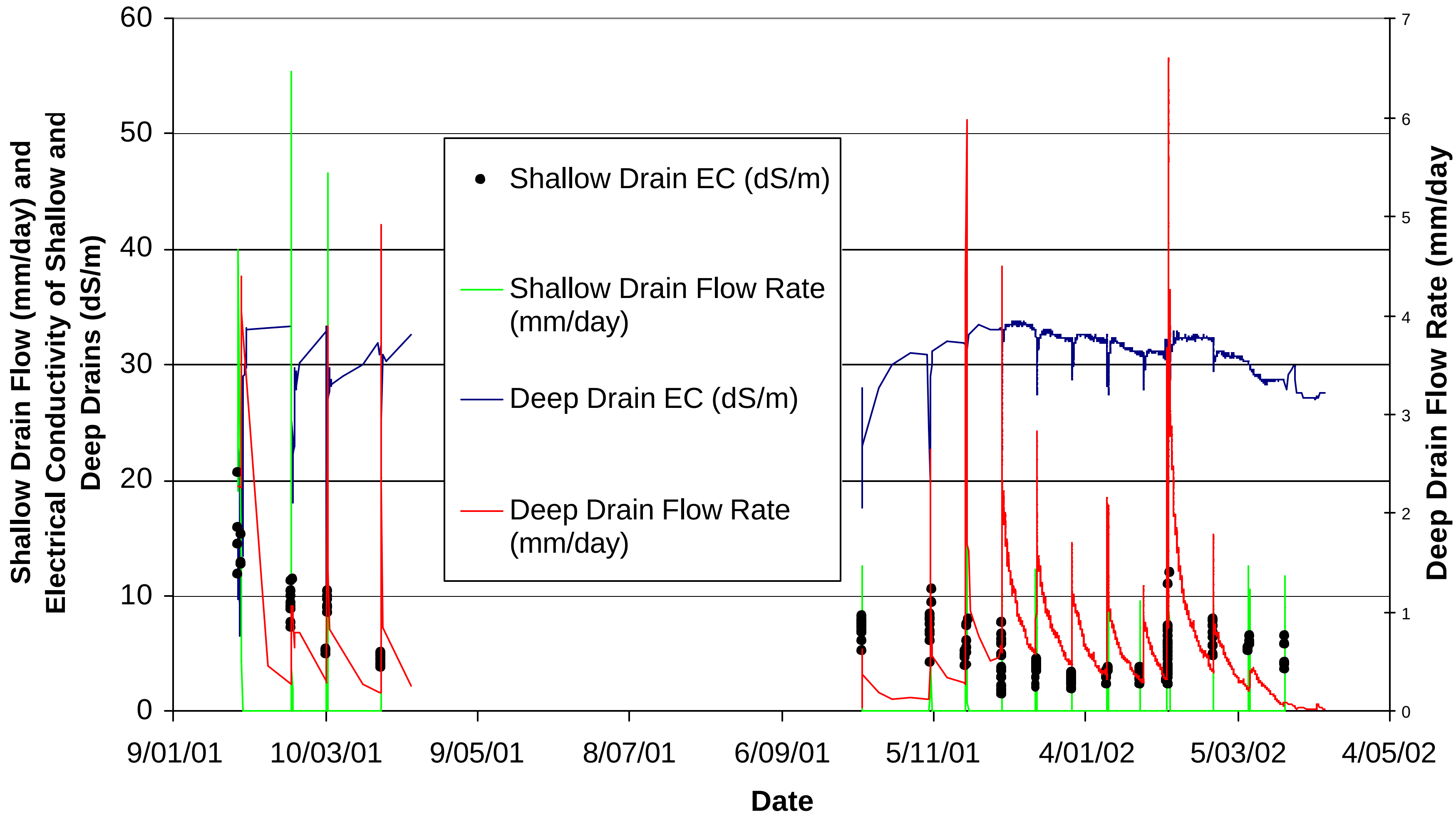


Figure 7-3. Drain flows and drain electrical conductivity for the shallow and deep drains in the ML treatment

It can be clearly seen that there were significant differences between the drain flow characteristics of the shallow drains and deep drain within the ML treatment, both in the drain flow and also the EC of the drainage water.

Shallow Drains

Drainage flow from the shallow drains in the ML treatment were characterised by high intensity short duration discharge events. It can be seen from Figure 7-3 that drainage rates from the shallow drains ranged from 0 –55 mm/day and peak intensities were considerably higher than that measured from the deep drain. Flow durations of the shallow drains were significantly shorter than the deep drains and only occurred immediately after irrigation or rainfall events.

EC of the shallow drains was significantly less than the deep drains in the ML treatment. Shallow drain EC was well under 10 dS/m for the majority of the experimental period apart from the first irrigation compared to the deep drains, which were in most cases above 30 dS/m, highlighting significant differences between the drain flow EC of the shallow drains and deep drain in the ML treatment. Drain salinity of the shallow drains also appeared to show a slight trend of decreasing EC as the irrigation season progressed. The gradual decrease in EC is most likely attributed to leaching of the water in flow paths to the shallow drains with each irrigation event, (with lower EC being recorded with each subsequent irrigation). This was particularly true in the 2000/2001 irrigation season. During the 2001/2002 irrigation season drain salinity of the shallow drains appeared to fall and then stabilise around 4 dS/m until the rainfall event, which caused EC to rise again slightly. This rise in EC after the rainfall event can be attributed to the change in infiltration pattern occurring with the rainfall event, which allows water to infiltrate in inter-row areas and on the outside mounds of furrows where salt typically accumulates during normal furrow irrigation. This then has the effect of redistributing salts through the soil profile. After the rainfall period, which raised drain EC, due to leaching of the areas where salt build-up occurs with normal irrigation patterns, a similar pattern was then observed of decreasing electrical conductivity with each subsequent irrigation event.

Deep Drain

Drain flow and salinity (EC) from the deep drain in the ML treatment is shown in Figure 7-3. It can be seen that the deep drain flow and salinity characteristics were similar to that of the SL treatment. This might be expected as the deep drain in the ML treatment is at the same depth and spacing as the SL treatment. Differences that can be seen however between the two drainage treatments are that the baseline EC of the ML treatment was higher than that of the SL treatment by approximately 3-4 dS/m during the course of the experimental period. This could be due to the more saline conditions found in the ML treatment than the SL treatment. It can also be seen that the deep drains in the ML treatment had significantly higher drainage flow rates immediately after irrigation events when the shallow drains in the ML treatment were flowing.

Comparison of Shallow and Deep Drain Flows

Interactions between the shallow and deep drains in the multi-level drainage system were characterized by markedly different flow and salinity characteristics as outlined previously. There was also an observed interaction between the shallow and deep drains in relation to the flow characteristics of the drains. It can be observed from Figure 7-4 and Figure 7-5 that the shallow drains had a high sharp increase and subsequent decrease in drain flow after recharge events compared with a lower intensity peak in drain flow with the deep drains.

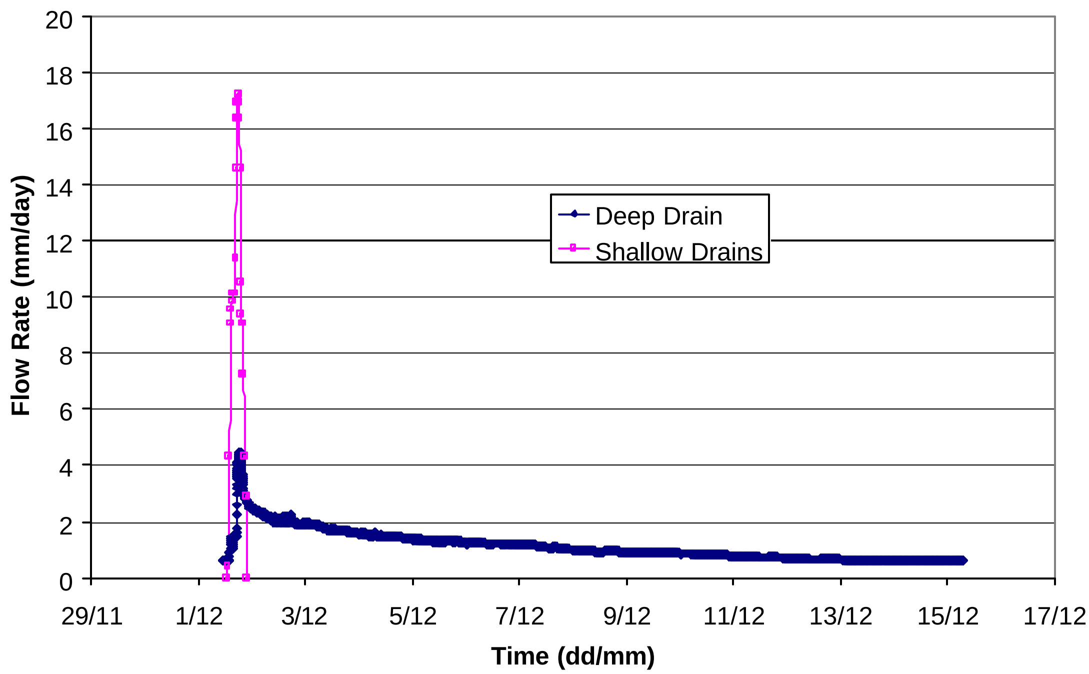


Figure 7-4. Drain flow hydrographs for the shallow and deep drains in the ML treatment following the 4th irrigation of the 2001/2002 irrigation season

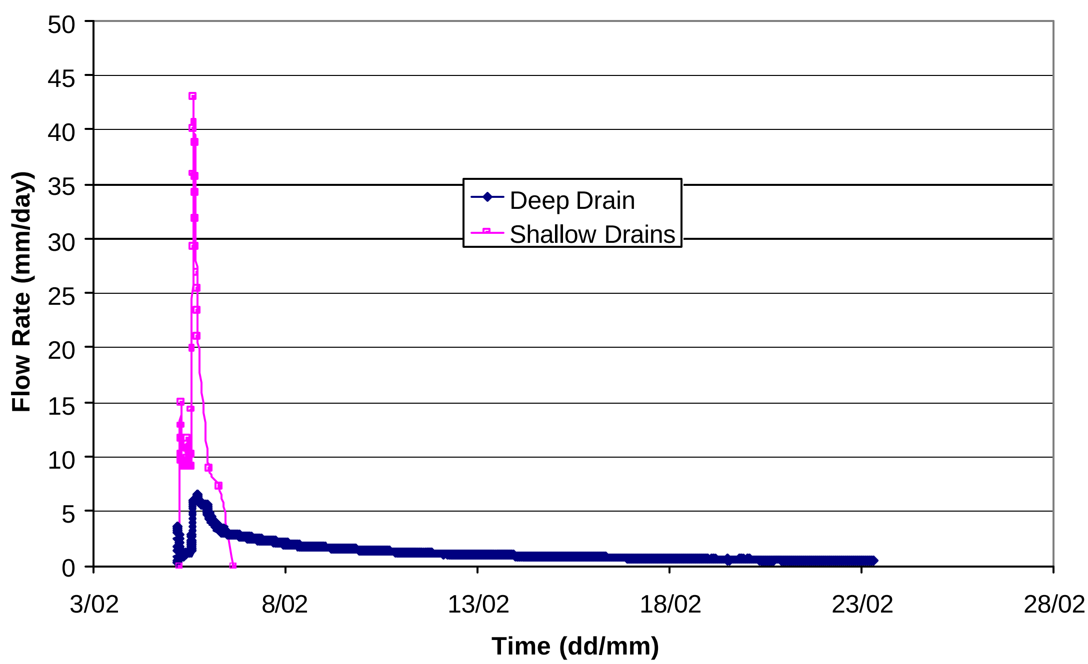


Figure 7-5. Drain flow hydrographs for the shallow and deep drains in the ML treatment following the rainfall event

The shallow drain hydrograph is typical of shallow intensive drainage systems. The drainage flow is from top layers of soil with high porosity that are rapidly drained.

It was difficult to develop conclusions on the interactions between the shallow and deep drains in the multi-level drainage system.

While visual differences between the treatments can be seen clearly in Figure 7-2 and Figure 7-3, in order to provide a more quantitative comparison between the two treatments a water and salt balance was undertaken based on the data presented in Figure 7-2 and Figure 7-3. Water and salt balances for the experimental period are presented in Table 7-2.

Table 7-2. Water and salt balance for the ML and SL treatments over the duration of the experimental period

			2000/2001					2001/2002														Both Seasons
	Event		**1**	**2**	**3**	**4**	**Total**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Rain**	**9**	**10**	**11**	**12**	**Total**	**Total**
ML	**Irrigation (mm)**		77	34	22	26	**159**	36	36	69	65	63	35	42	44	63	25	30	21	13	**541**	**700**
	Drainage (mm)	**Total**	24	10	12	14	**60**	4	12	18	19	14	10	9	6	33	8	4	1	0	**138**	**198**
	Drainage (mm)	**Shallow Drains**	15	5	4	4	**28**	2	6	7	3	2	1	1	1	10	1	1	0	0	**36**	**64**
	Drainage (mm)	**Deep Drain**	9	5	8	10	**32**	2	6	11	16	12	9	8	6	22	7	3	1	0	**102**	**134**
	Leaching Fraction	**Total**	0.31	0.29	0.55	0.54		0.12	0.33	0.26	0.29	0.23	0.29	0.22	0.14	0.52	0.33	0.13	0.05	0.00		
	Leaching Fraction	**Shallow Drains**	0.19	0.15	0.18	0.15		0.05	0.17	0.10	0.04	0.03	0.04	0.03	0.01	0.17	0.06	0.03	0.02	0.00		
	Leaching Fraction	**Deep Drain**	0.12	0.15	0.36	0.38		0.07	0.16	0.15	0.25	0.20	0.25	0.19	0.13	0.36	0.27	0.11	0.02	0.00		
	Salt Applied (kg/ha)		69	30	20	23	**142**	32	32	62	58	56	32	37	40	4	22	27	19	12	**433**	**575**
	Salt Removed (kg/ha)	**Total**	3097	1186	1988	1174	**7445**	551	1319	2309	3452	2593	1882	1601	1145	4901	1381	627	105	0	**21868**	**29313**
	Salt Removed (kg/ha)	**Shallow Drains**	1289	327	245	107	**1968**	78	294	226	78	48	25	27	11	480	58	28	15	0	**1368**	**3336**
	Salt Removed (kg/ha)	**Deep Drain**	1808	859	1743	1067	**5477**	473	1025	2083	3374	2546	1858	1574	1134	4421	1323	599	91	0	**20500**	**25977**
	Average EC (dS/m)	**Shallow Drains**	21	17	11	8		7.2	7.6	5.5	4.6	3.7	2.8	3.3	2.9	4.3	6.4	5.7	4.9			
	Average EC (dS/m)	**Deep Drain**	27.6	28.4	29.7	24.6		29.6	28.5	27.8	32.8	32.3	32.2	31.4	30.8	31.3	30.8	29.0	27.7			
SL	**Irrigation (mm)**		74	66	30	21	**191**	33	40	61	68	67	41	45	51	63	21	28	22	13	**551**	**742**
	Drainage (mm)		14	9	12	3	**38**	8	6	8	19	12	11	9	6	25	8	4	4	0	**120**	**158**
	Leaching Fraction		0.19	0.14	0.40	0.14		0.25	0.15	0.13	0.27	0.17	0.28	0.19	0.12	0.40	0.39	0.14	0.19	0.00	**0.22**	
	Salt Applied (kg/ha)		66	59	27	19	**171**	30	35	55	61	60	36	40	46	4	19	25	19	11	**493**	**612**
	Salt Removed (kg/ha)		2609	1688	2233	634	**7164**	1538	1101	1470	3641	2208	2162	1599	1094	4838	1589	686	615	0	**22541**	**29705**
	Average EC (dS/m)		27.8	28.6	23.4	29.7		28.8	26.7	26.7	29.3	29.5	29.4	29.0	28.5	29.9	30.3	27.3	27.9			

Drainage volumes from the ML and SL drainage treatments are shown in Figure 7-6 for the duration of the monitoring period.

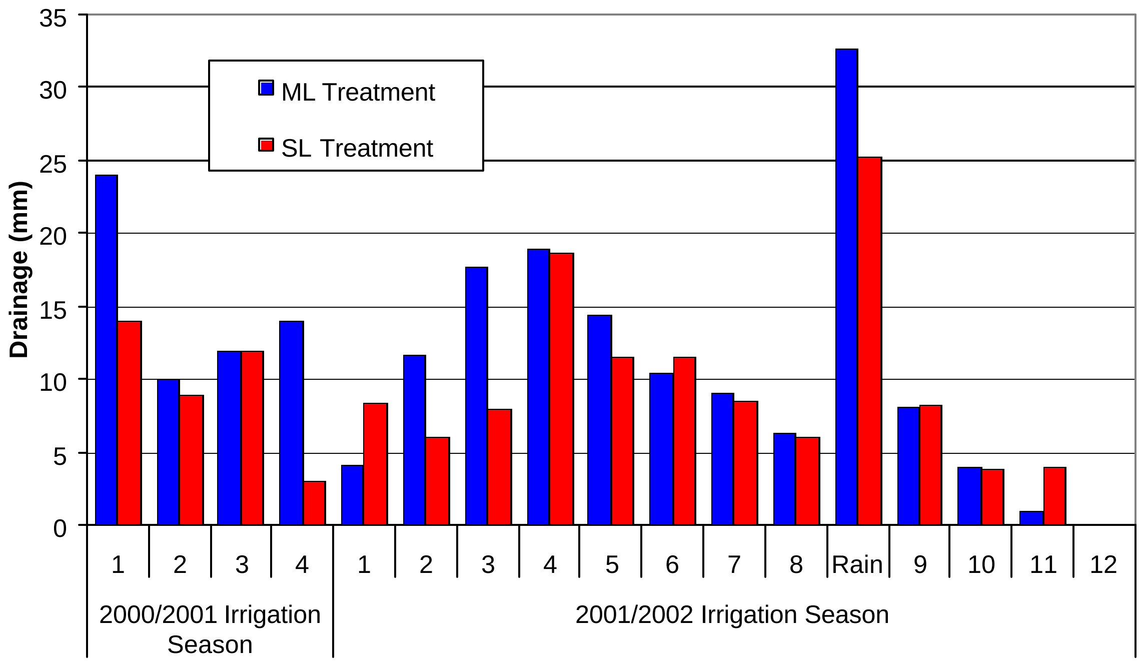


Figure 7-6. Drainage volumes from the ML and SL treatments

Drainage volumes were higher during the 1st and 4th irrigation events of the 2000/2001 irrigation season and the 2nd and 3rd irrigation events and the rainfall event of the 2001/2002 irrigation season in the ML treatment compared to the SL treatment. This increase was largely due to increased discharges in the shallow drains in the ML treatment (Table 7-2). Discharges from the deep drains in the ML treatment were slightly lower compared to the SL treatment during these periods and major differences between drainage volumes in the ML and SL treatments can be attributed to increased flows from the shallow drains in the ML treatment. The increased drainage volumes from the shallow drains during these periods is most likely due to increased preferential flow to the shallow drains and this would most likely be the case during the rainfall event. The increased drainage volumes during the 2nd and 3rd irrigation events in 2001/2002, however, are less clear. Reworking of the furrows was undertaken after the first irrigation event and this may have been the cause for the increased drainage volume from the shallow drains during the two irrigations immediately following. Preferential flow paths to the drains may have slowly become blocked through soil migration with subsequent irrigations, therefore reducing the drainage volumes recorded through the shallow drains. However, subsequent reworking of the furrows before the fourth and ninth irrigation events did not have this effect.

Salt removed from the treatments during each irrigation event is shown in Figure 7-7. It can be seen that there was not a large difference between salt removed in each of the treatments. Larger volumes of salt were removed at the higher drainage events as expected with the rainfall event removing the largest amount of salt through the treatments over the duration of the experimental period.

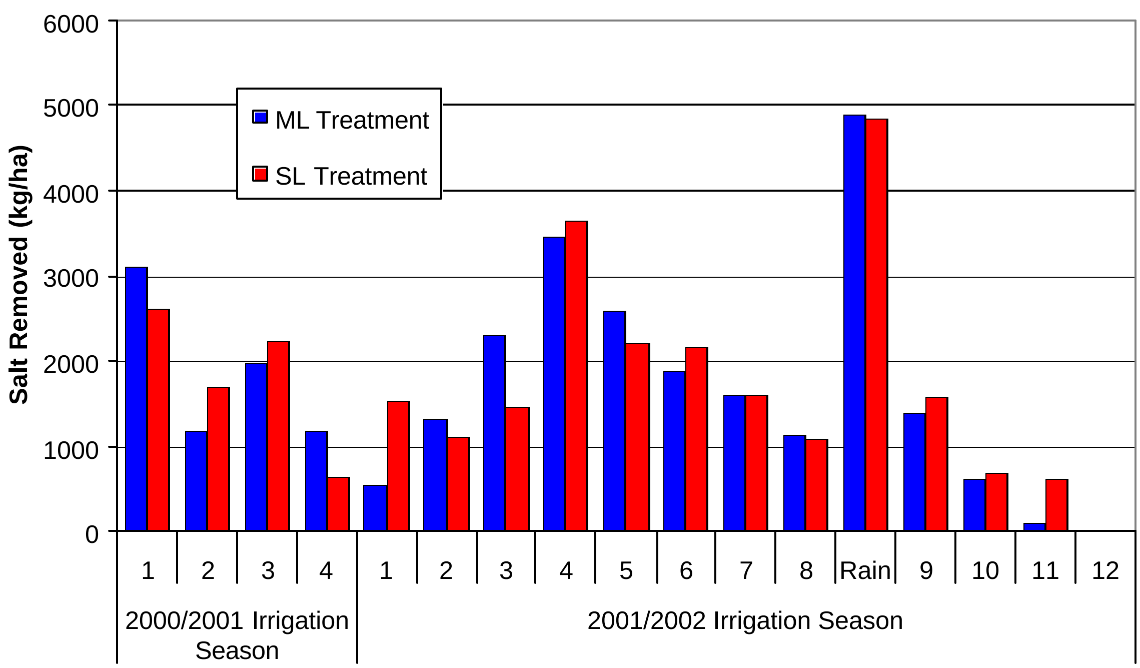


Figure 7-7. Salt removed from the ML and SL treatments

In comparing the total volume of salt removed by each of the treatments it can be seen that the ML treatment removed slightly less salt at 21868 kg/ha compared to 22541 kg/ha for the SL treatment. Total salt applied to the treatments was 432 and 493 kg/ha for the ML and SL treatments respectively. This equates to between 45-50 times more salt being removed through the drainage water than applied through irrigation and rainfall. This ‘extra’ salt above that applied in the irrigation water is from the naturally saline soil and groundwater conditions present. The shallow drains within the ML treatment removed 3.2 times the salt applied through irrigation and drainage water and consequently were much less saline than the deeper drains in the ML and SL treatments. Considering these results it appears that the ML treatment has been effective in reducing drainage water salinity compared to the SL treatment. Salt load per mm of drainage water was 158 kg/ha compared with 188 kg/ha for the SL treatment. Nevertheless, it must be remembered that a greater drainage volume occurred in the ML treatment than the SL treatment. Also affecting this result was the higher soil salinity of the ML treatment over the SL treatment, indeed average electrical conductivities were 2.2 dS/m higher in the ML treatment.

It should also be remembered that the deep drain spacing in the ML treatment was identical to the SL treatment. It was not increased to allow for the presence of the shallow drains as was outlined in Chapter 6. With an increased spacing of the deep drains to account for the increased drainage rate associated with the shallow drains, then the volumes of drainage water from the ML treatment would most likely be reduced and hence salt loading could be further reduced compared to the SL treatment.

7.1.3 Water Table and Waterlogging

7.1.3.1 Soil Moisture Monitoring

Data relating to the soil moisture contents under the drainage treatments are presented below for the 2001/2002 irrigation season. Calibration of the Sentek capacitance probes was difficult due to the sensors being affected by salinity and this has been shown by Mead, Soppe and Ayars (1996). All probes were calibrated with field determined values of volumetric water content and calibration curves developed. However, the continual change in soil electrical conductivity associated with leaching will have an effect on the readings. Therefore absolute values of soil moisture content are difficult to obtain with such sensors particularly in saline environments, and absolute errors of ± 4 m^3/m^3 could be expected with the results presented below. What can be accurately determined with the capacitance probes are relative changes in soil moisture content, which have been used for analysis of the data.

Calibrated volumetric soil water contents collected with Enviroscan soil moisture sensors are shown in Figure 7-8 and Figure 7-9 for the ML treatment representing on the deep drain and ½ deep drain spacing respectively and in Figure 7-10 and Figure 7-11 for the SL treatment representing on drain and ½ drain spacing positions respectively (Figure 4-10).

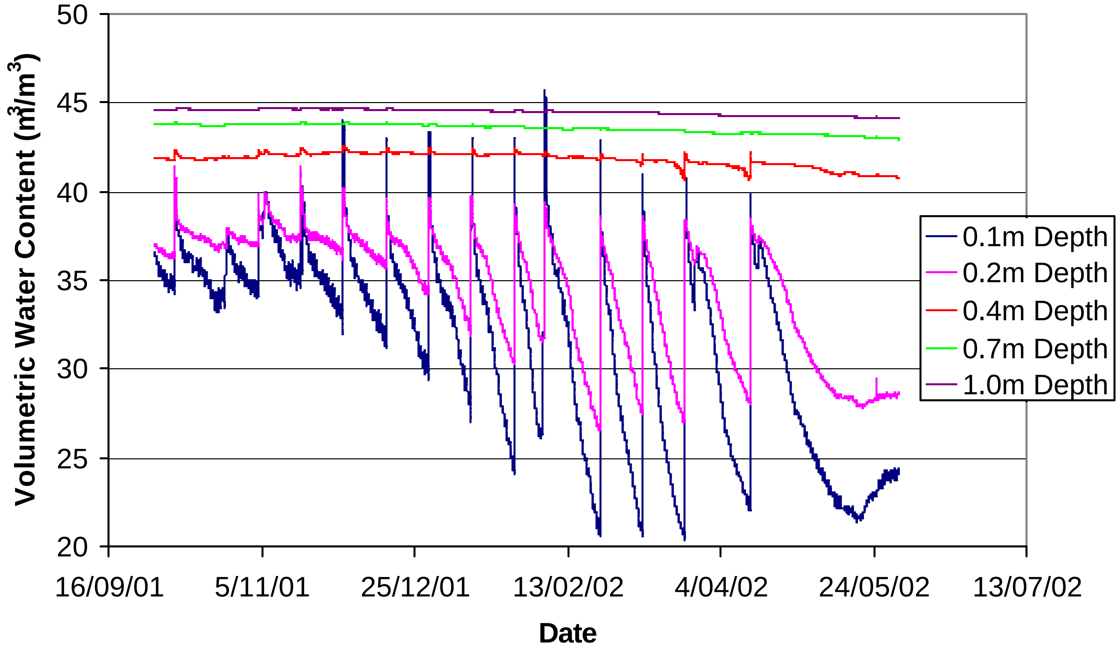


Figure 7-8. Volumetric water content over 2001/2002 irrigation season on the deep drain in the ML treatment (BL1)

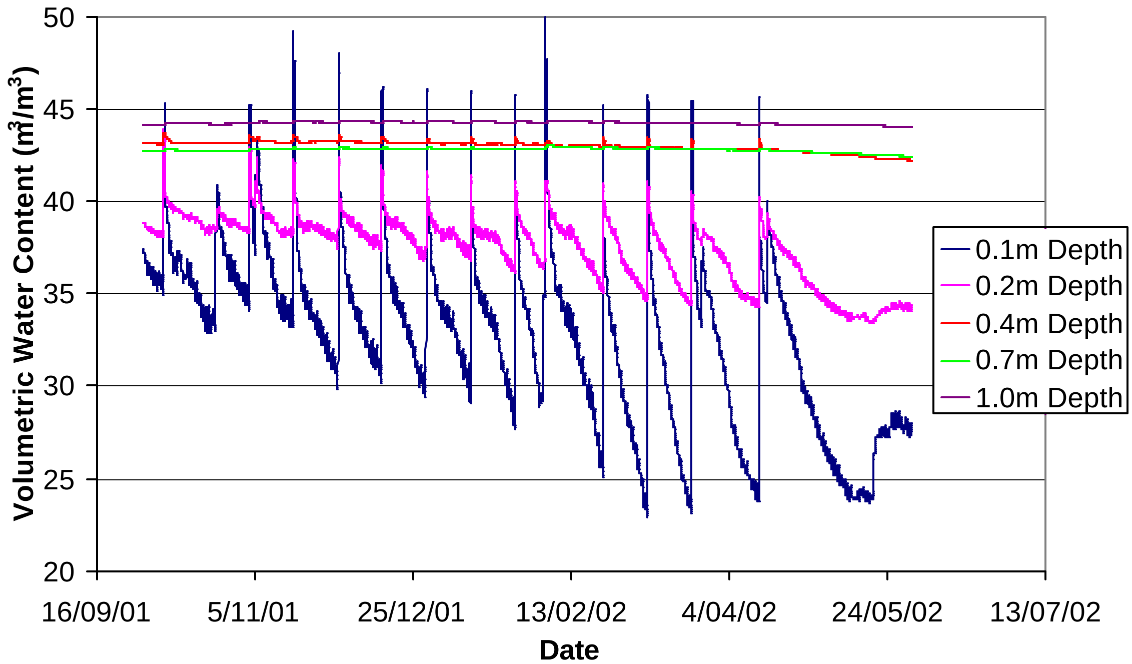


Figure 7-9. Volumetric water content over 2001/2002 irrigation season at ½ deep drain spacing in the ML treatment (BL3)

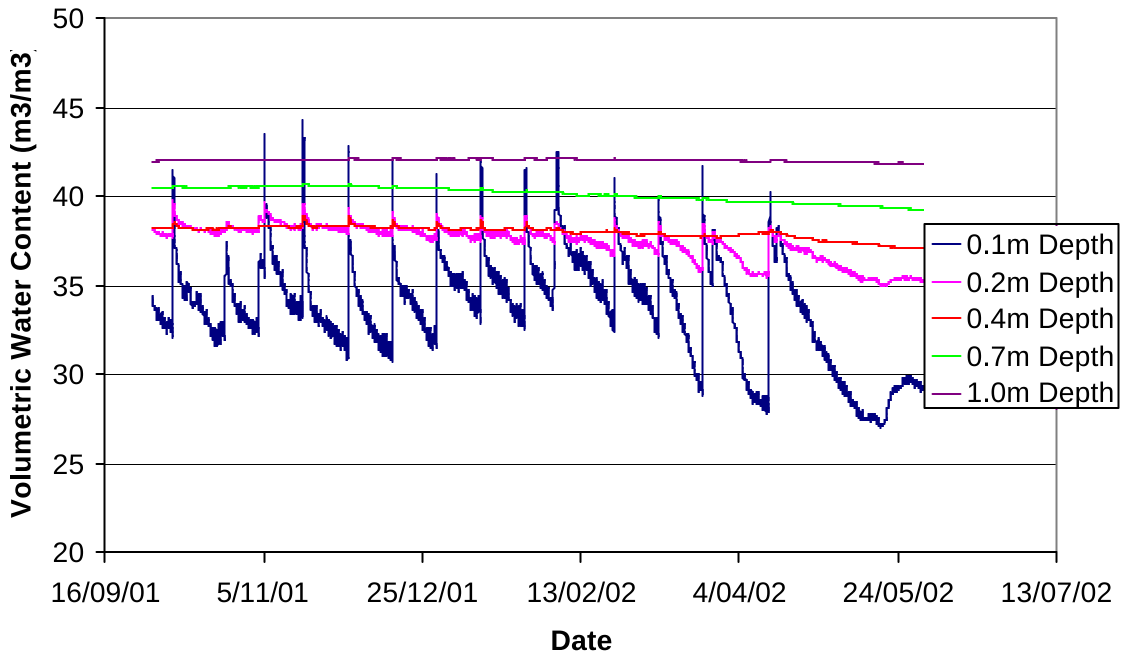


Figure 7-10. Volumetric water content over 2001/2002 irrigation season on drain in SL treatment (C1)

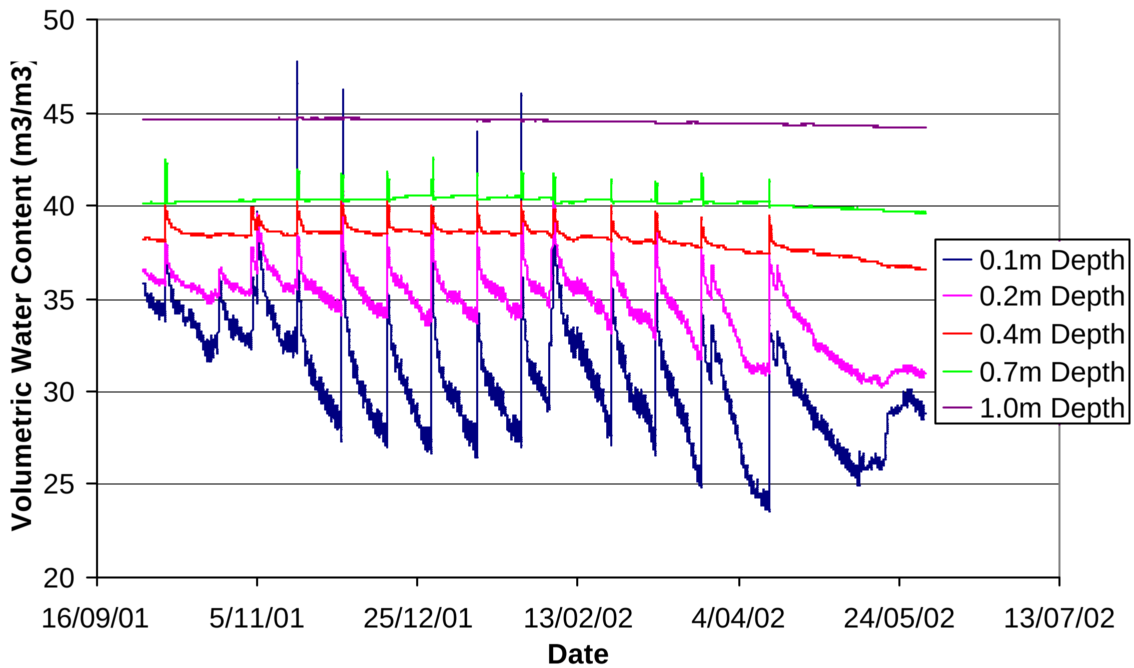


Figure 7-11. Volumetric water content over 2001/2002 irrigation season at ½ drain spacing in SL treatment (C3)

It can be seen that the unsaturated zone characteristics between the two treatments are particularly different in the 0.1 and 0.2m depths in relation to the extraction of water. Water extraction between irrigations was larger in the ML treatment than the SL treatment. This effect was not due strictly to the drainage treatment directly, but rather from the effect of the vines directly adjacent to the probes in the ML treatment surviving and developing throughout the irrigation season, whereas in the SL treatment the vines near the probes did not survive. Figure 7-12 shows the vines near each probe in February of the 2001/2002 irrigation season. This is the cause of the different water extraction patterns between the two treatments, in relation to the different draw down patterns after irrigation events.

Figure 7-12. Vine growth near Enviroscan probes. a. ML treatment on Drain, b. ML treatment mid-drain, c. SL treatment on drain, d. SL treatment mid-drain

It can be seen that with the deeper sensors at 0.7m and 1.0m there is little change throughout the irrigation season. At these depths the sensors are most likely situated in the capillary fringe and hence are close to saturation, hence irrigations do not cause an increase in the volumetric water content, even though drainage water is percolating past these depths.

In assessing the treatments performance in preventing waterlogging then it can be seen that there are two drawdown stages in volumetric water content after irrigation or rainfall events, which are shown in Figure 7-13.

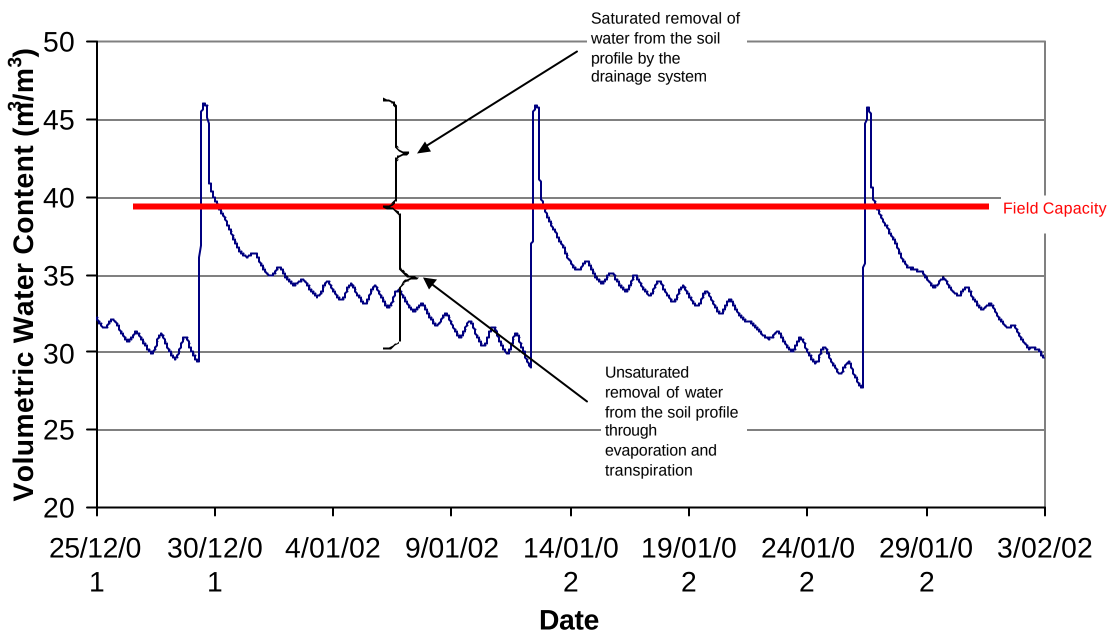


Figure 7-13. Stages of water extraction in relation to removal of water from drainage and evapotranspiration

The first stage is a rapid decline in water content associated with drainage of the water above field capacity (gravity drainage) and the second stage occurs due to slower extraction of water through evaporation and transpiration. The drainage system can only remove water through gravity drainage, hence it is the initial rapid decline that determines the effectiveness in waterlogging control. In order to assess the performance of the drainage treatments in preventing waterlogging then the total time each layer was above field capacity was determined. Total time above field capacity for the 0.1, 0.2 and 0.4m layers for each treatment are shown in Table 7-3.

Table 7-3. Duration of time soil was above field capacity during the 2001/2002 irrigation season

		Days above Field Capacity	
	Depth (m)	On Drain	Mid-Drain
ML	**0.1**	5.9	4.4
	0.2	9.3	4.7
	0.4	0.3	16.9
SL	**0.1**	8.1	15.7
	0.2	9.4	24.0
	0.4	2.1	45.0

It can be seen that both treatments provided similar degrees of waterlogging protection near the deep drain, however at mid-drain spacing of the deep drains the ML treatment provided better waterlogging protection over the SL treatment with a lower time in which the rootzone was saturated.

Depth of vine roots can also be inferred through changes in volumetric water extraction patterns and it can be seen from Figure 7-8 that water extraction occurred just before the last two irrigation events at a 0.4m depth, hence during the experimental period rooting depth of the vine did reach 0.4m in some instances.

7.1.3.2 Water table Regimes

Generally, when investigating waterlogging and the protection provided by subsurface drainage systems, mid-spacing water table height is used as a parameter in most studies. This is the critical point and highest position of the water table, and is generally used for design criteria of a subsurface drainage system. Figure 7-14 shows the water table and piezometry regime of the water table under the ML treatment and SL treatment respectively, at mid-drain spacing of the deep drains for the entire experimental period.

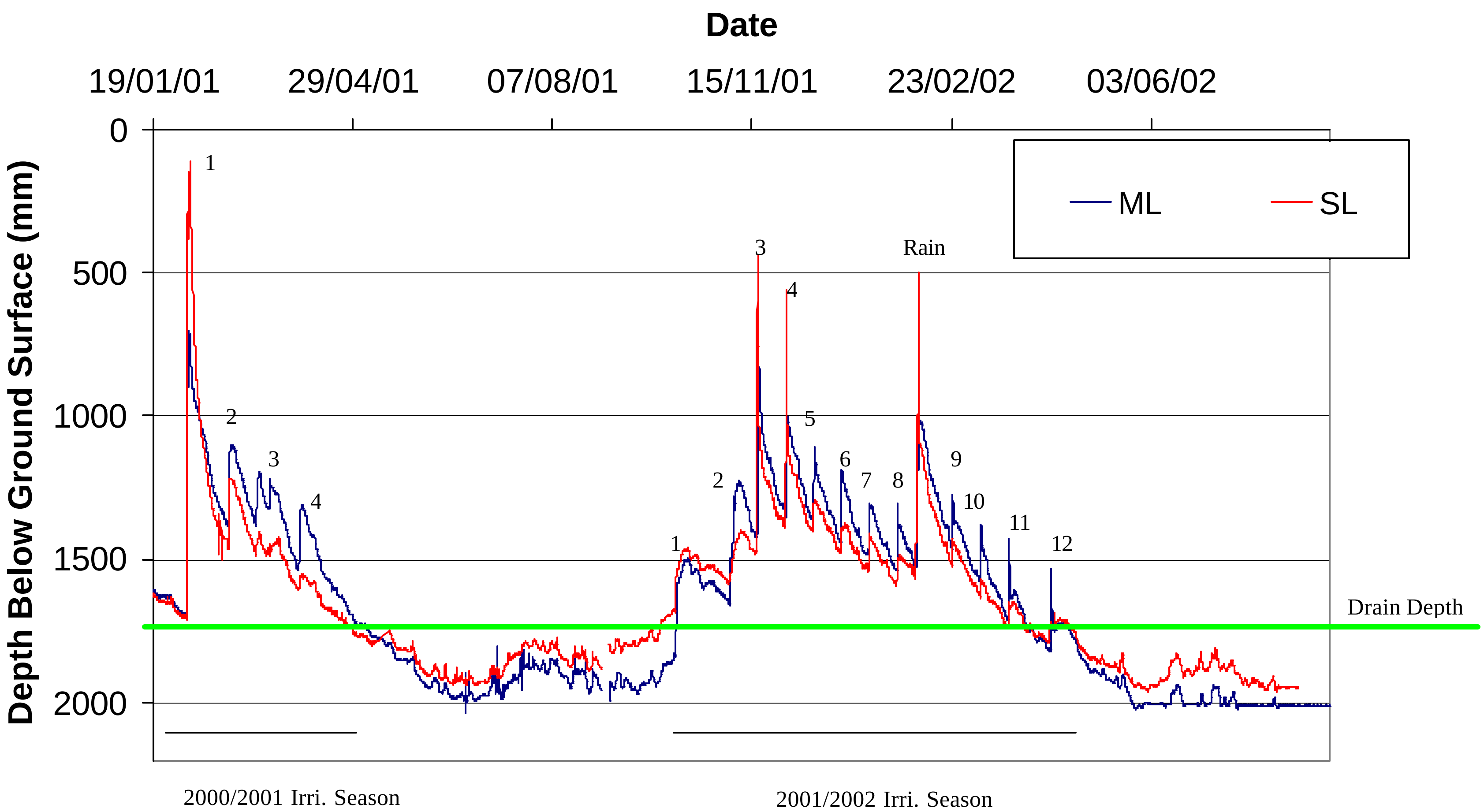


Figure 7-14. 2m testwell data at ½ drain spacing for ML and SL treatments over experimental monitoring period, irrigation events are numbered

It can be seen from Figure 7-14 that the water regimes under the two treatments were different only during high recharge periods, which occurred during the first irrigation of the 2000/2001 irrigation season and after the 3rd and 4th irrigations and rain event, which occurred in the 2001/2002 irrigation season. It is evident that during these high recharge events the ML treatment has been considerably more effective in controlling the water table below rootzone depth. At no time during the monitoring period was the water table within 500mm of the ground surface in the ML treatment. However, during the high recharge periods the water table in the SL treatment reached levels within the rootzone that could be considered detrimental to plant health, on all four occasions when high recharge events occurred.

Table 7-4 presents a comparison between the ML and SL treatments between the number of hours the water table remained above given depths during both irrigation seasons as measured in the seven testwells located in each treatment. It can be clearly seen that the ML treatment is significantly more effective in keeping the water table out of the rootzone.

Table 7-4. Cumulative period of time in which water table levels were recorded above specified depths in the seven testwells located in each treatment

	Cumulative Time Above Depth (hours)	
Water Table Height (mm)	**ML**	**SL**
< 500 mm	84	526
< 750 mm	248	764
< 1000 mm	784	1330
< 1500 mm	17126	14828

At other periods the water table regime in the ML and SL treatments were similar, although water tables depths were slightly higher in the ML treatment than the SL treatment. This may have been due to the slightly lower hydraulic conductivity of the ML treatment compared to the SL treatment. Saturated hydraulic conductivities measured in

Testwells 16 and 33 (Figure 4-10) gave saturated hydraulic conductivities of 0.25 and 0.37 m/day for the ML and SL treatments respectively.

Figure 7-15 and Figure 7-16 show water table heights for hydrographs of the ML and SL treatments respectively for the 2000/2001 irrigation season at positions on the drain, ¼ and ½ deep drain spacing. It can be seen in these figures that a slightly higher water table level occurred in the ML treatment compared to the SL treatment, particularly at ¼ and ½ drain spacing positions, during periods when significant recharge events were not occurring. A similar pattern was observed (Figure 7-14) at the start of irrigation and drainage cycles in 2001/2002. This could be due to soil layers below the shallow drains in the ML treatment having lower hydraulic conductivities than the SL treatment. In general for the entire experimental period (2000/2001 and 2001/2002 irrigation seasons) this difference in water table height between the two treatments was in the order of 5-10cm during the irrigation season, and fell back to similar levels during non-irrigated periods over the winter months (Figure 7-14).

The effectiveness of the ML treatment in controlling water table levels during significant recharge events can be seen clearly in Figure 7-15 and Figure 7-16. Through the entire cross section from the drain to ½ deep drain spacing it can be seen that the ML treatment has prevented waterlogging of the crop with only slight differences in water table levels on the deep drain and at ½ drain spacing. However, in the SL treatment waterlogging control has only been achieved on the drain and not at positions ¼ and ½ drain spacing, during the significant recharge periods.

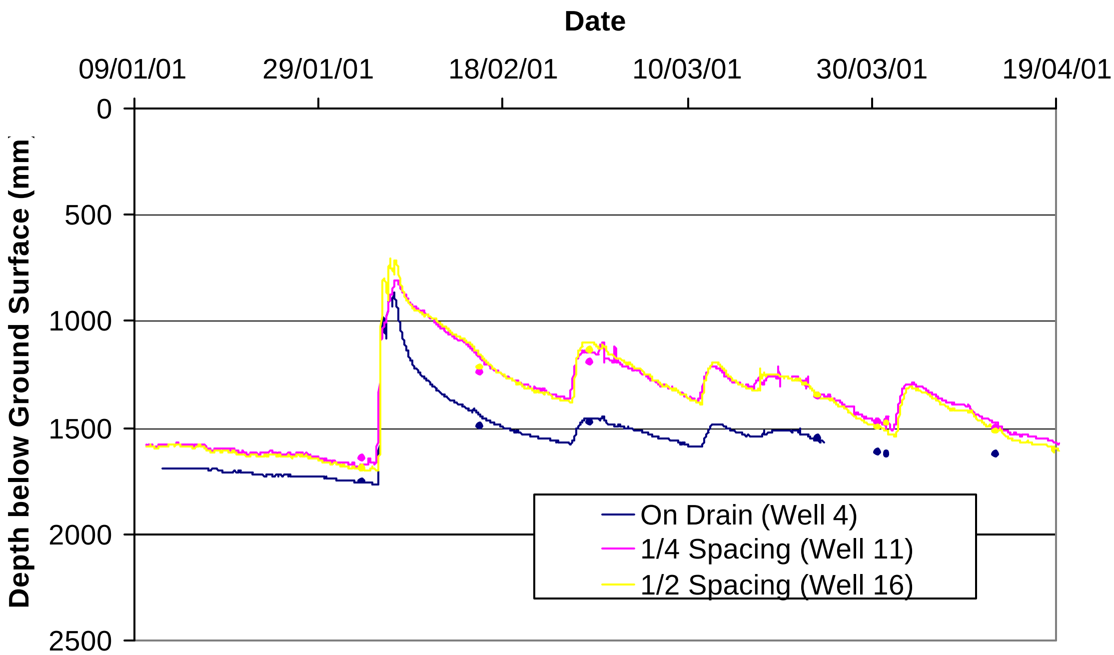


Figure 7-15. Water table depth below ground surface at ½ furrow length for the ML treatment in 2000/2001 irrigation season

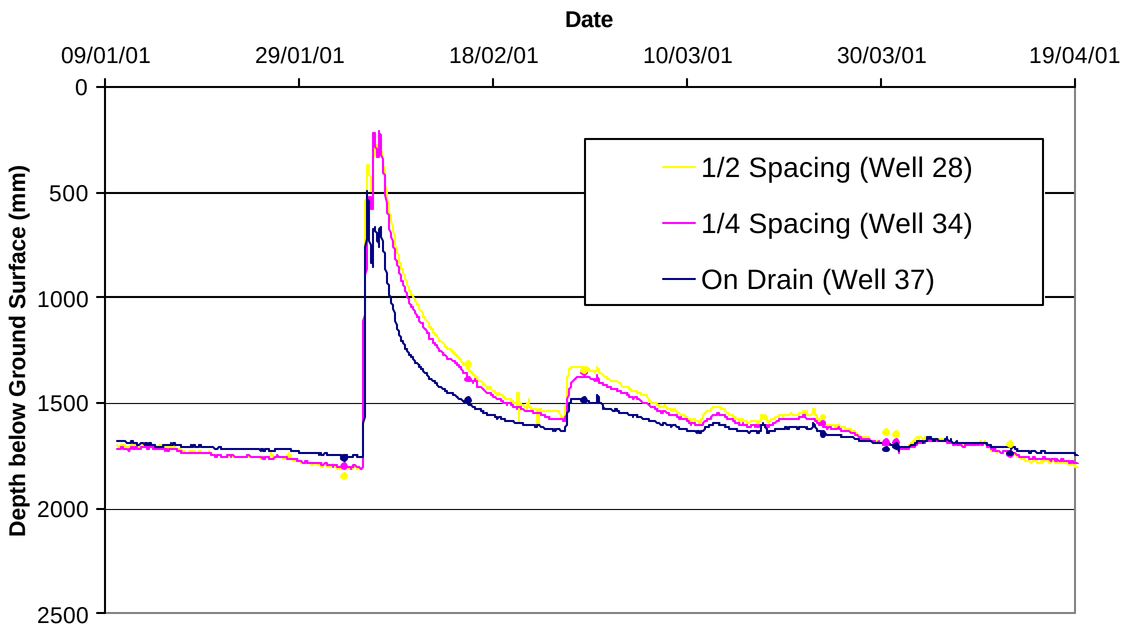


Figure 7-16. Water table depth below ground surface at ½ furrow length for the SL treatment in 2000/2001 irrigation season

Using the water table data from testwells 1,4,8,11,13,16, and 20 in the ML treatment and testwells 25,28,32,34,35,37, and 41 from the SL treatment 3 dimensional plots of water table heights were constructed for the entire length of the field plots and are shown in Figure 7-17 and Figure 7-18. These water table heights were measured during the first irrigation of the 2000/2001 irrigation season, which caused the greatest increase in water table levels throughout the experimental period.

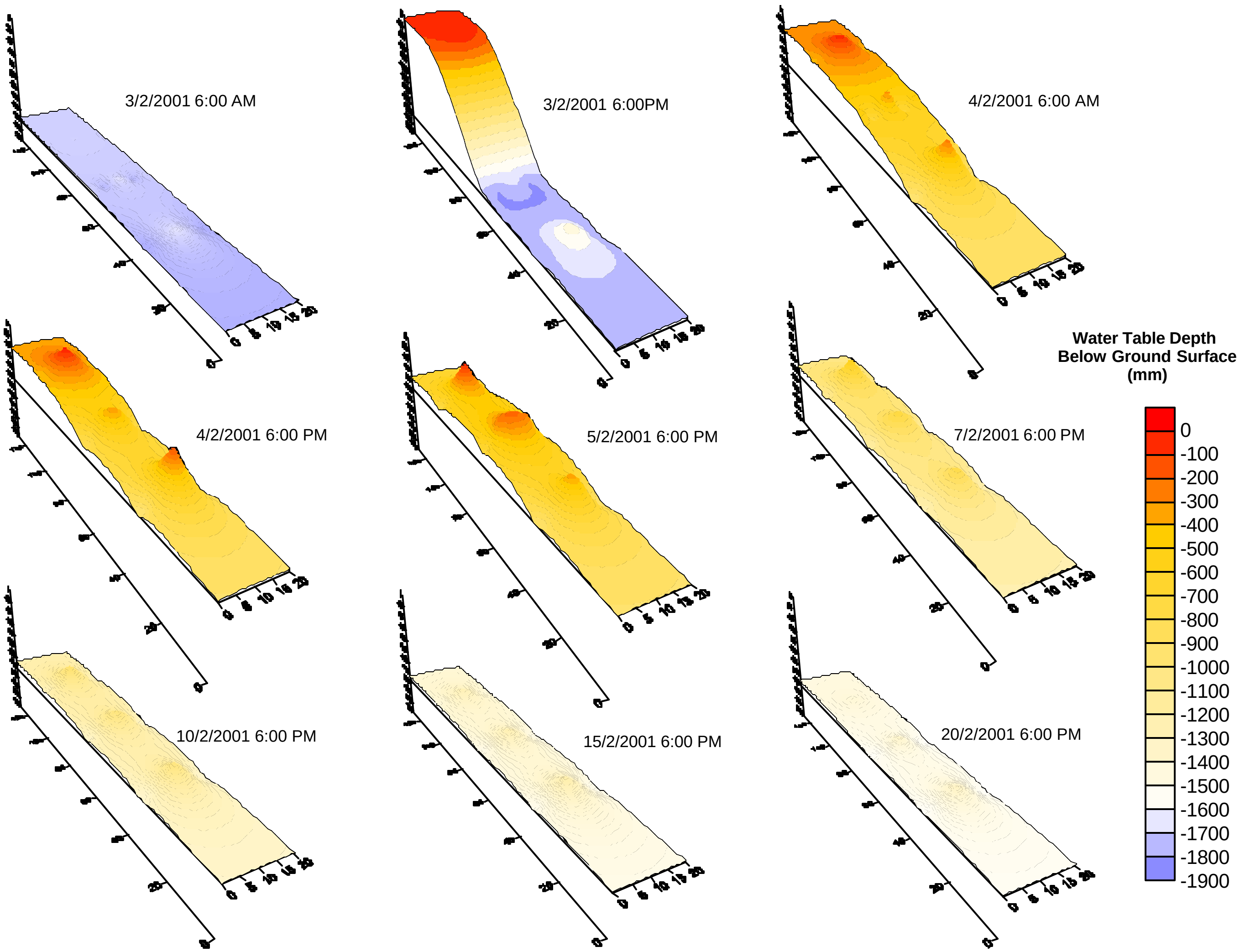


Figure 7-17. Water table depth below ground surface for the SL treatment after 1st irrigation of 2000/2001 irrigation season

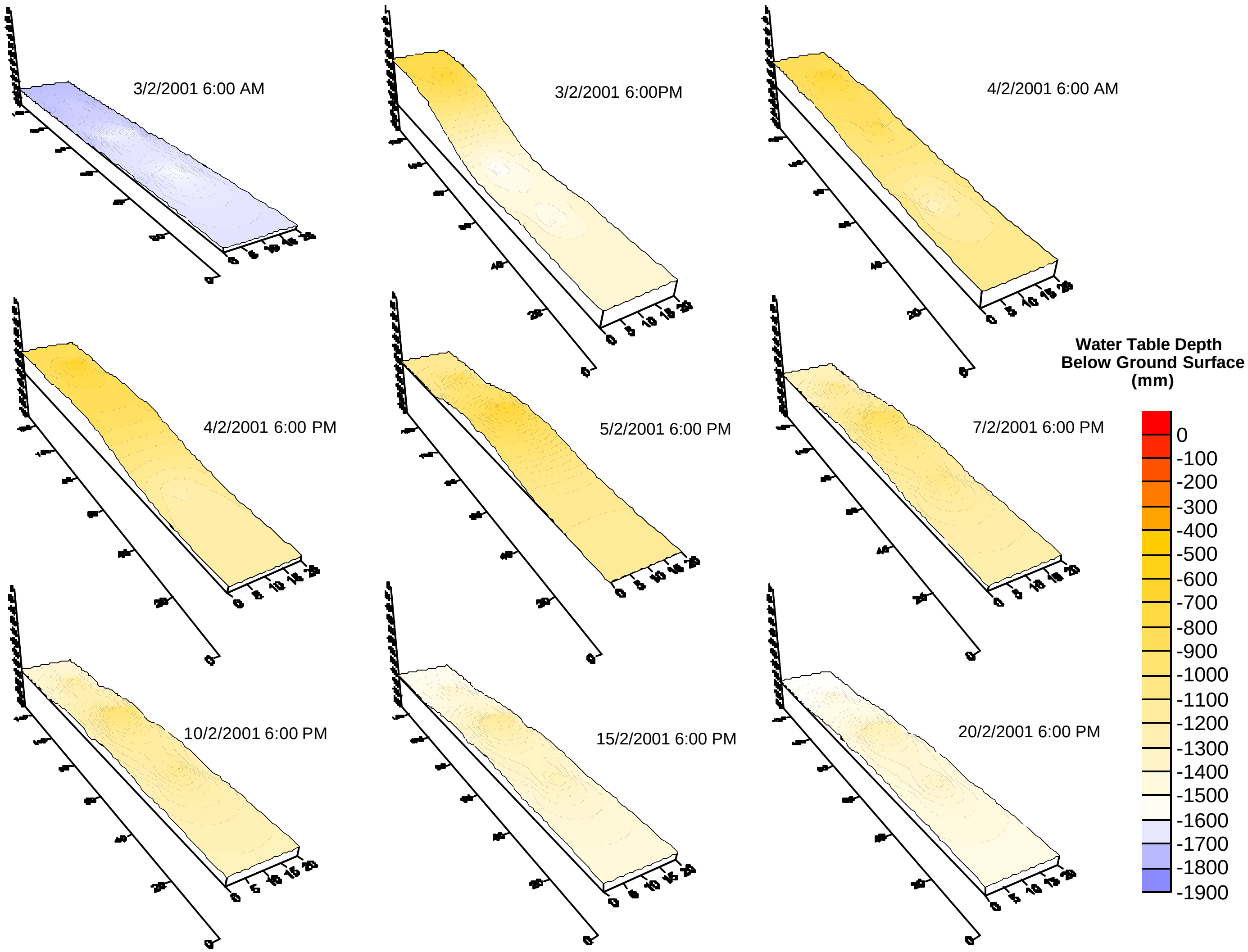


Figure 7-18. Water table depth below ground surface for the ML treatment after 1st irrigation 2000/2001 irrigation season

It can be seen from Figure 7-18 that the ML treatment has been more effective in controlling water table levels than the SL treatment (Figure 7-17). At no time during the irrigation did the water table level increase above 750mm from the soil surface in the ML treatment, whereas in the SL treatment, particularly at the supply end of the field elevated water table levels remained for up to 3 days after the irrigation event.

Based on the water table data the ML treatment can be seen to be clearly more effective in preventing waterlogging than the SL treatment. Water table levels after high recharge events are rapidly reduced due to the presence of the shallow drains, which are extremely effective in preventing waterlogging of the rootzone.

Deep Piezometers

The deep piezometers showed differences in the piezometric heads between the 4m and 7m depths. Figure 7-19 shows the hydraulic gradient between the 4m and 7m piezometers located at ½ drain spacing in the two treatments. Negative hydraulic heads indicate a downward hydraulic gradient and positive hydraulic heads an upward gradient.

It can be seen from Figure 7-19 that generally during the irrigation seasons when irrigations were occurring there was a negative hydraulic gradient indicating a downward movement of water. During the non-irrigated periods however, a positive gradient was found in the treatments indicating a net upward movement of water. There also appeared to be a noticeable difference in hydraulic head between the two drainage treatments in the 2000/2001 irrigation season.

It is also interesting to note that initial hydraulic gradients for both treatments before the start of irrigation in the 2000/2001 irrigation season were positive indicating net upward movement of water. This may explain the extremely high salinity levels found at the experimental site due to the area acting as sink and discharge point in the region over a number of years when the area was not drained.

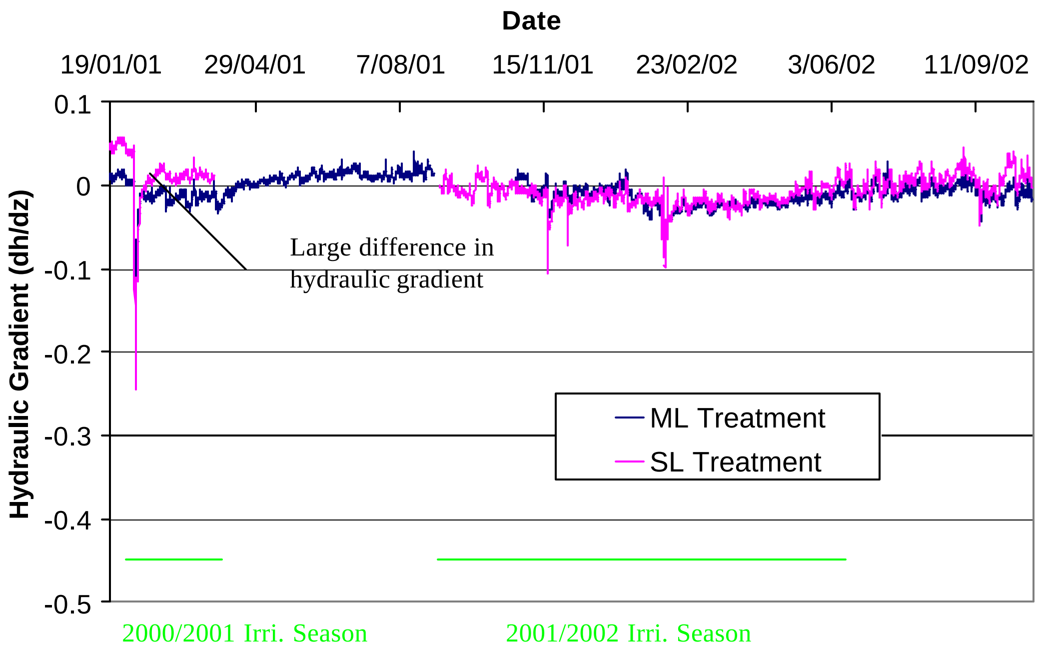


Figure 7-19. Hydraulic head gradient from 4m to 7m depth below each drainage treatment during the experimental monitoring period

7.1.4 Leaching Patterns

7.1.4.1 Soil Salinity

Soil salinity was monitored in each of the treatments over the experimental period with EM38 surveys and soil coring as described in Chapter 5. Results from each of the three EM38 surveys are presented in Figure 7-20, Figure 7-21 and Figure 7-22. These figures show calibrated predictions from EM38 readings and soil coring for each treatment. The ESAP software package (Lesch, Rhoades and Corwin, 2000) was used to develop these depth related soil ECe values for each treatment based on horizontal and vertical EM 38 readings and 12 soil cores taken during the EM38 survey. The Spatial Regression Modelling (Stochastic Calibration) module was used in ESAP to predict values of saturated paste extract electrical conductivities at nine depth increments corresponding to soil coring intervals for both the ML and SL treatments over the course of the experiment. The first EM38 survey was conducted before the installation of the subsurface drainage system and a subsequent survey was carried out after the first irrigation season. A final EM38 survey was conducted at the end of experimental period, being the end of the 2001/2002 irrigation season.

For all EM38 surveys the following model developed through statistical analysis with the ESAP software was used to relate saturated paste electrical conductivity (ECe) to the EM 38 conductivity readings:

$$\ln(ECe) = b_0 + b_1(EMv) + b_2(EMh) + b_3(y)$$

where:

ECe = estimated saturated paste electrical conductivity (dS/m)
b_0, b_1, b_2, b_3 = regression parameters calculated by ESAP
EMv = EM38 vertical reading
EMh = EM38 horizontal reading
y = spatial coordinate in y direction

Table 7-5 shows R-squared values and the estimated coefficient of variation values for each depth increment for the three EM38 surveys undertaken. It can be seen that there was generally a good regression found between the measured values and those predicted by the EM38 meter, particularly in the shallower soil layers above a 0.5m depth. Over the duration of the experiment it appeared that the relationship between EM38 readings and soil salinity became less correlated. This is due to other soil properties such as bulk density, soil temperature and soil moisture having a greater effect on the ground electrical conductivity readings when soil salinity is lower.

Table 7-5. R-squared values and estimated coefficient of variation values between measured soil ECe and predicted values with ESAP for each EM38 survey

	13/06/2000		16/05/2001		9/05/2002	
Depth (m)	**R^2**	**CV%**	**R^2**	**CV%**	**R^2**	**CV%**
0.075	0.92	21.7	0.85	35.7	0.83	55.5
0.225	0.93	25.1	0.99	9.1	0.89	28.0
0.375	0.90	16.2	0.91	34.8	0.98	14.7
0.525	0.81	16.4	0.97	14.5	0.84	42.5
0.675	0.53	22.8	0.92	16.5	0.77	53.2
0.825	0.39	25.6	0.94	13.7	0.88	33.7
1.05	0.78	16.9	0.90	12.0	0.59	45.2
1.35	0.79	18.6	0.91	11.3	0.71	55.0
1.65	0.69	19.9	0.95	9.2	0.63	52.4
Bulk Average 0.075-0.825	0.86	15.8	0.99	7.5	0.91	25.3
Bulk Average 1.05-1.65	0.78	17.5	0.94	9.2	0.71	42.2

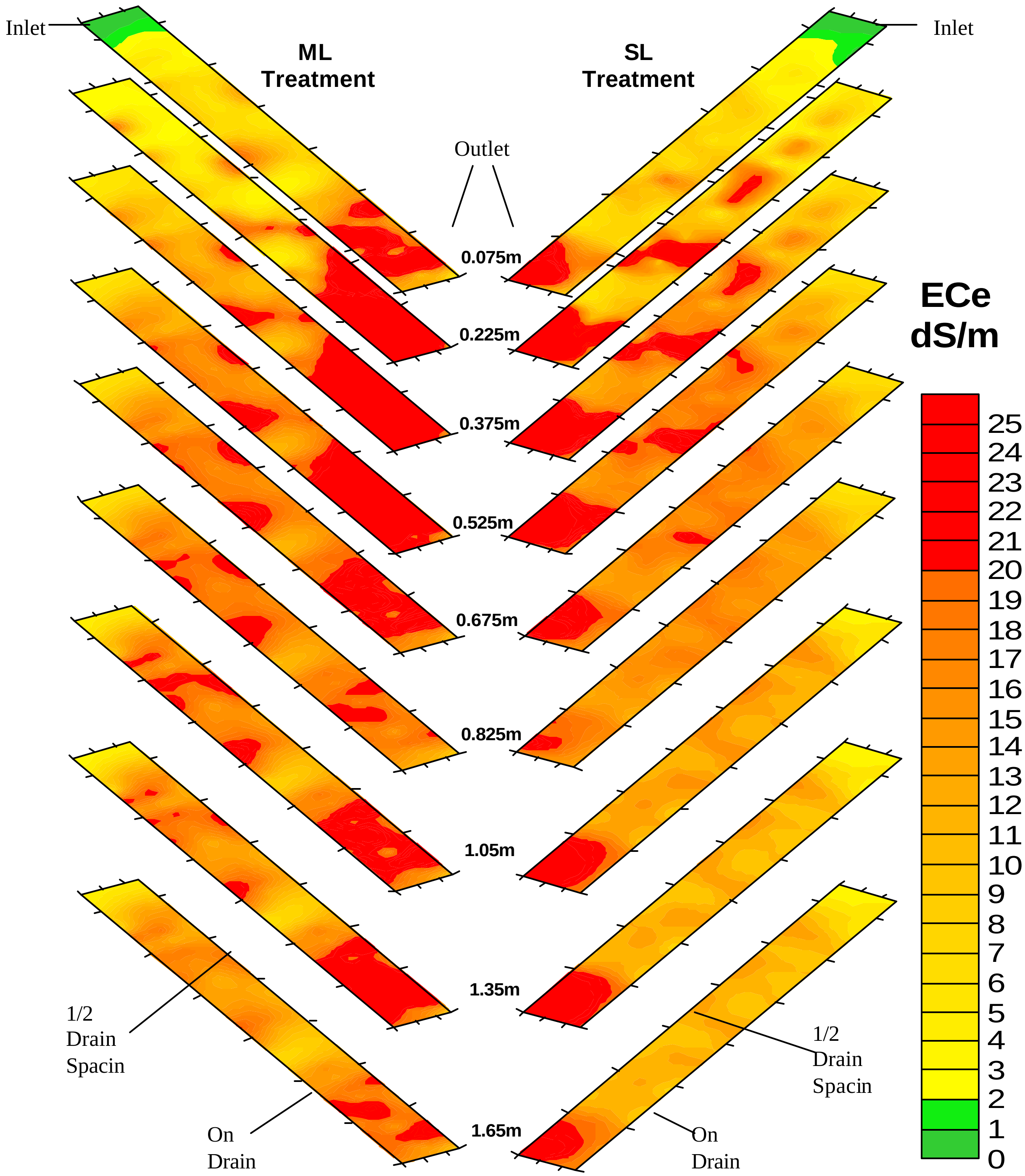


Figure 7-20. Soil ECe (dS/m) with depth for the ML and SL treatments before drainage installation, 13/06/2000

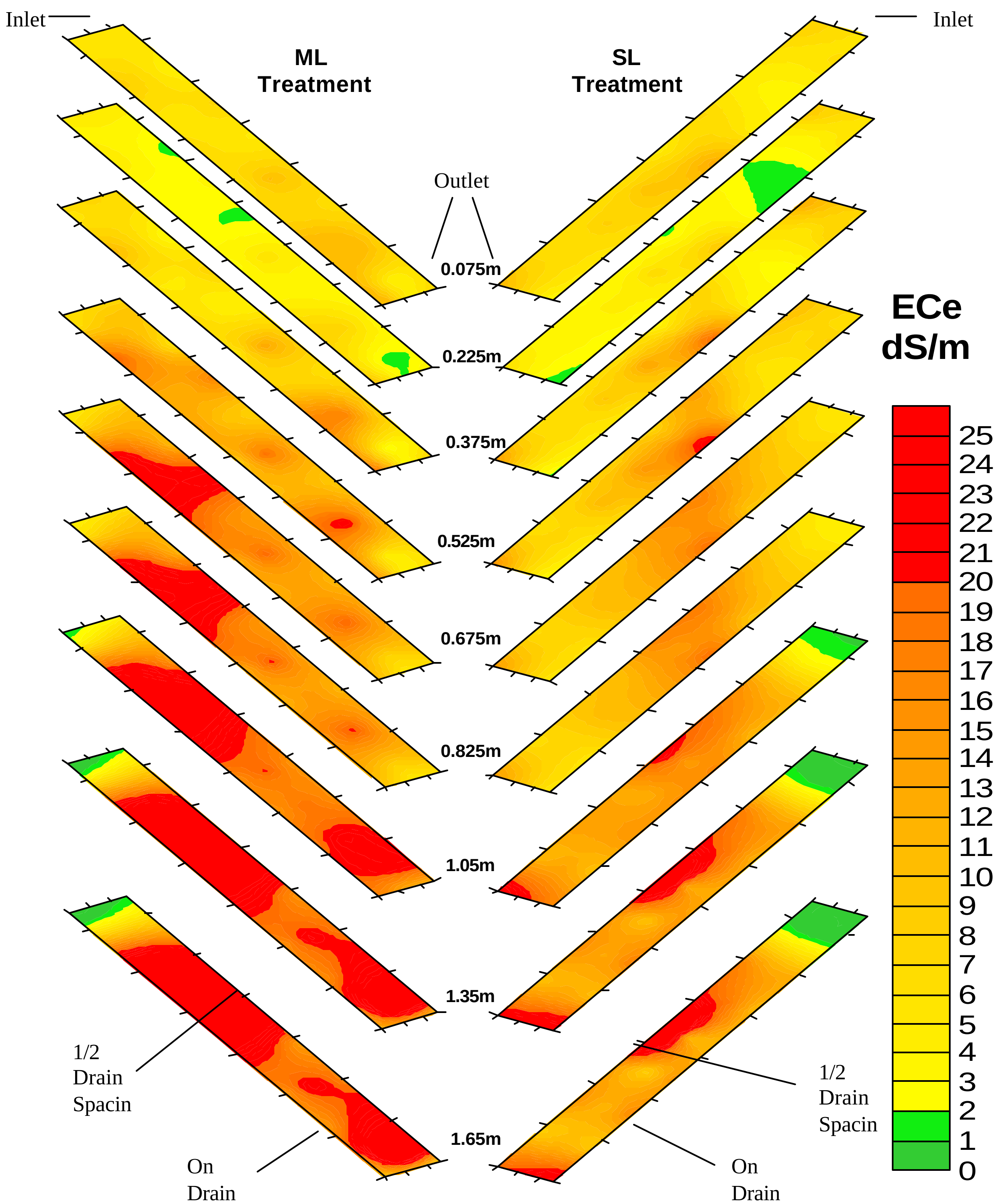


Figure 7-21. Soil ECe (dS/m) with depth for the ML and SL treatments after 2000/2001 irrigation season, 16/05/2001

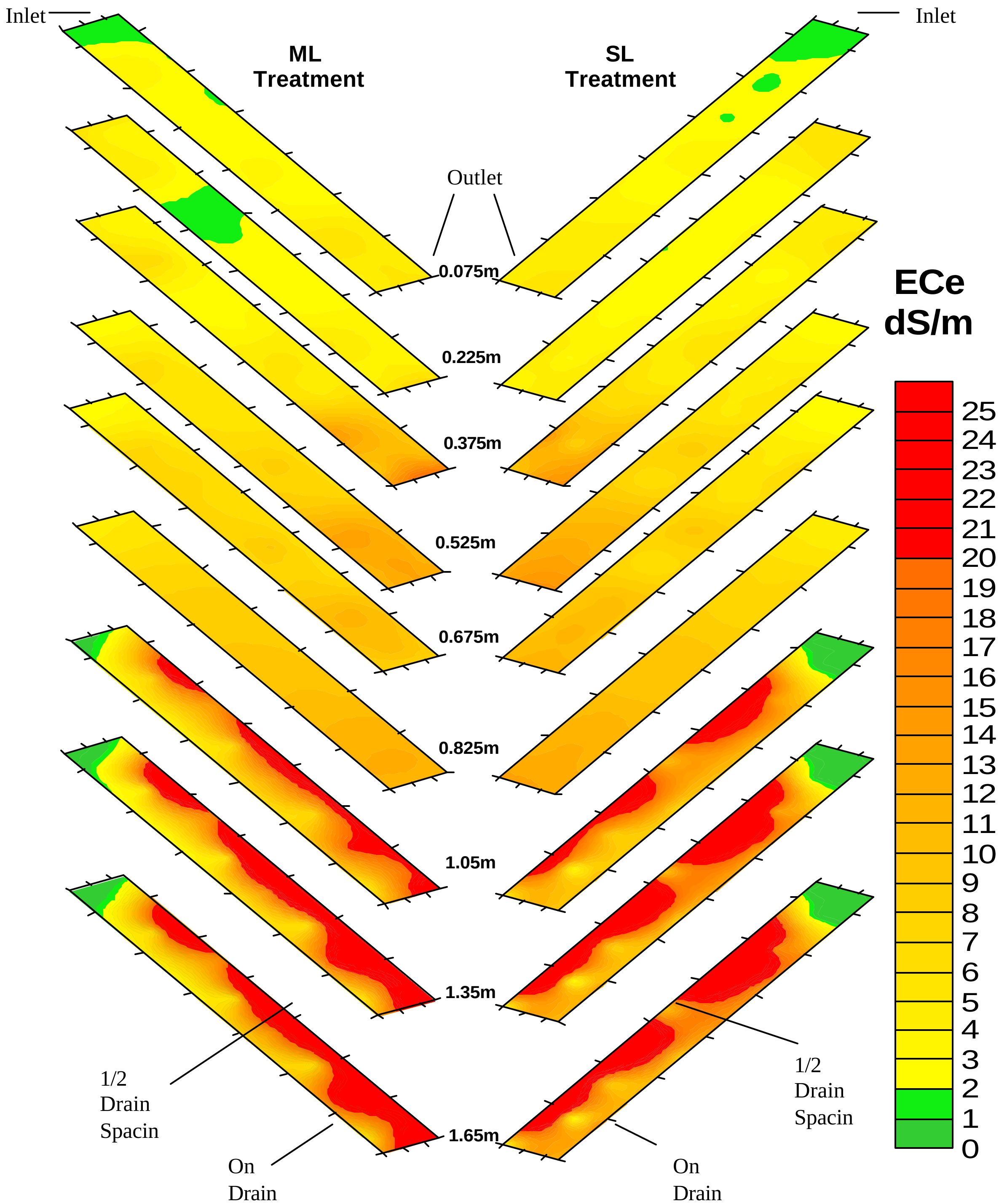


Figure 7-22. Soil ECe (dS/m) with depth for the ML and SL treatments after 2001/2002 irrigation season, 9/05/2002

Figure 7-20 shows that initially the ML treatment was more saline than the SL treatment, particularly at the outlet end of the treatment. Soil salinity also varied widely throughout both treatments with a general increase from the supply to the outlet end of the treatments. Soil salinity generally increased with depth particularly in the ML treatment. The SL treatment had lower salinity levels particularly at depths greater than 1.0m compared to the ML treatment. Salinity profiles in the SL treatment trended to increase to a depth of 0.8-1.0m and then decreased below these depths.

Figure 7-21 shows soil salinity after the first irrigation season. It can be seen that there has been a general downward displacement of salt in both treatments, but this is particularly evident in the ML treatment. The upper soil layers in both treatments were significantly leached of salts and the movement of these salts appears to have occurred to the deeper soil layers in both treatments. The EM survey taken after the 2001/2002 irrigation season is shown in Figure 7-22. It can be seen that there has been a further significant reduction in salt in both treatments and the initially elevated salinity levels in the ML treatment have been reduced to levels similar to the SL treatment. The effect of the deep drain in the ML treatment and SL treatment can also be clearly seen in the 1.05, 1.35 and 1.95m depths. Leaching close to the drain has been much greater than away from the drain in both treatments. There is a slight trend toward resalinisation at depth in the SL treatment.

Based on the EM surveys presented the change in ECe of the treatments for both the 2000/2001 and 2001/2002 irrigation seasons are shown in Figure 7-23 and Figure 7-24 respectively. The depths 0.075-0.825m and 1.05-1.65m are shown and essentially represent the rootzone of the plant and depth below the rootzone.

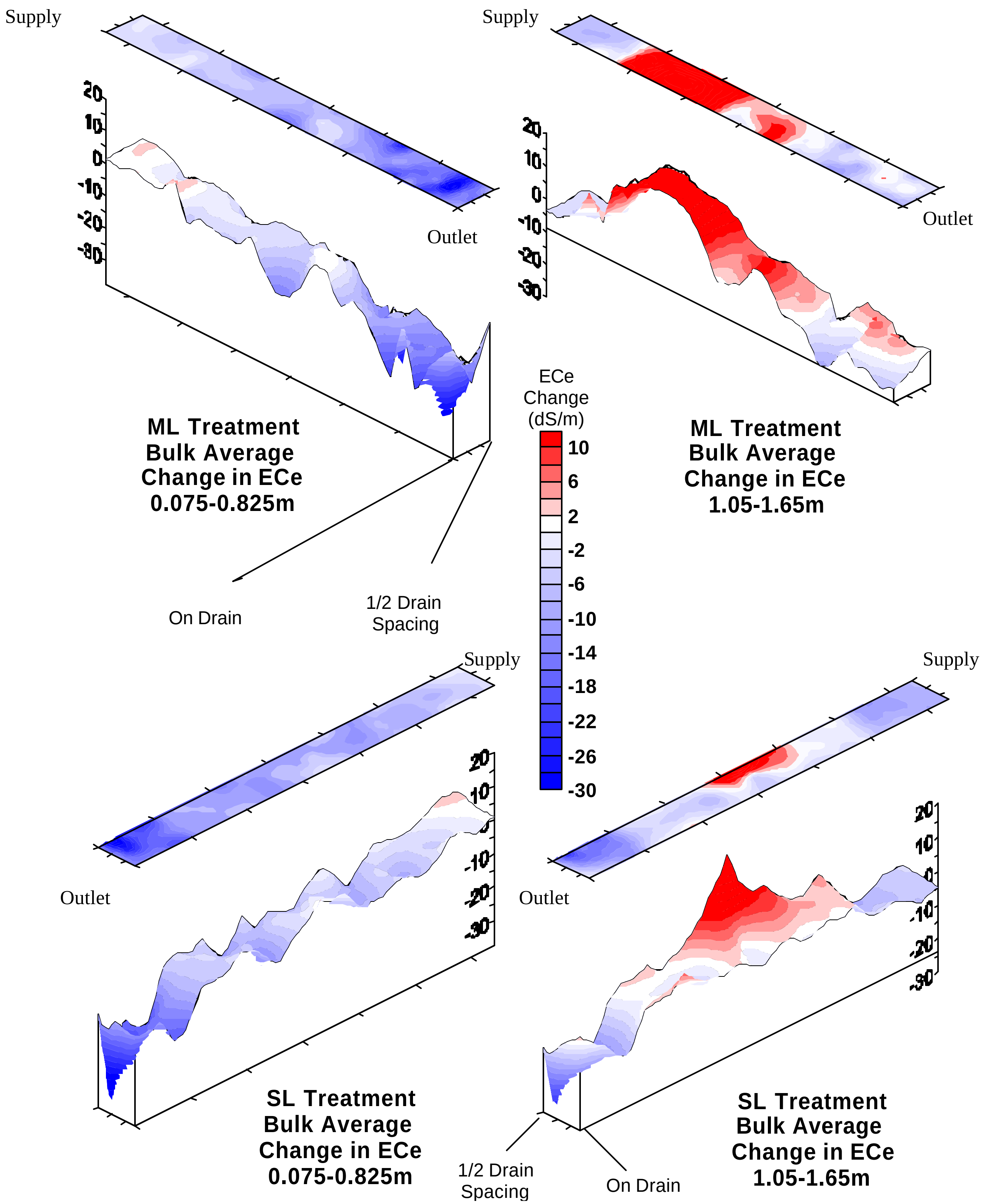


Figure 7-23. Bulk average ECe change for 0.075-0.825 and 1.05-1.65m depths for the ML and SL treatments for the 2000/2001 irrigation season

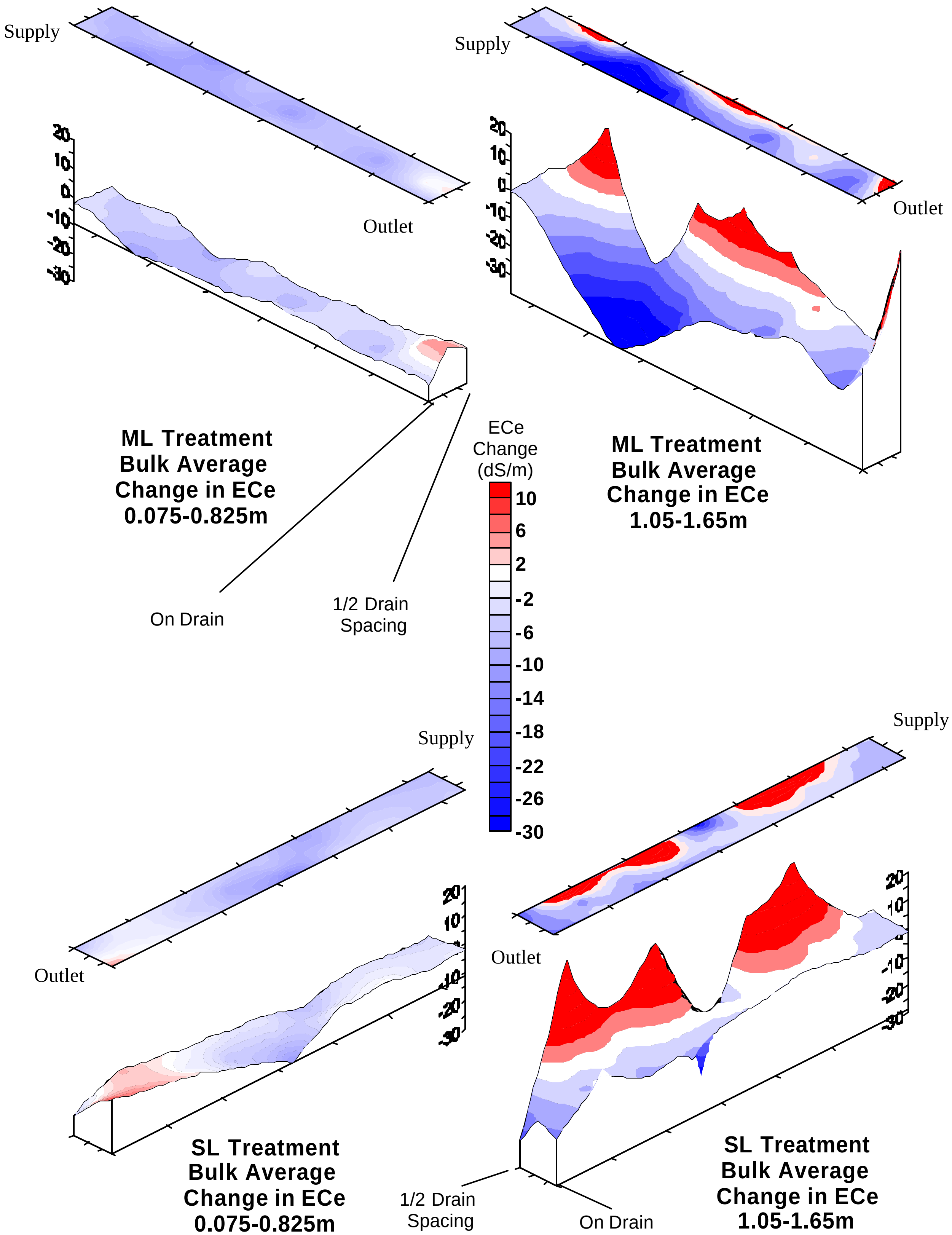


Figure 7-24. Bulk average ECe change for 0.075-0.825 and 1.05-1.65m depths for the ML and SL treatments for the 2001/2002 irrigation season

It can be seen that during the first irrigation season (Figure 7-23) the ML treatment has decreased the ECe in the rootzone, particularly at the outlet end of the treatment where ECe levels were initially high. There has also been a significant increase in ECe below the rootzone. The SL treatment showed a similar trend, however the increase in ECe below the rootzone was not as large and also only occurred at mid-drain spacing.

The change in ECe during the 2001/2002 irrigation season again followed a similar pattern, however the reduction in ECe particularly in the rootzone was lower than the previous irrigation season even though the volume of water applied to the treatments was larger. Increases in both treatments of soil ECe only occurred below the rootzone at mid-drain spacing in the treatments.

Table 7-6 shows mean soil $EC_{1:5}$ values determined on 6 cores taken in each of the treatments along with standard deviations, cores were taken at positions next to wells 2,5,8,14,17 and 20 in the ML treatment and 26,28,31,36,38 and 41 in the SL treatment. It can be seen that there is a large variation within each of the treatments as has been previously seen with the EM38 results. Also shown are the % change in $EC_{1:5}$ for each of the irrigation seasons and over the entire experimental period along with the salt removed from each soil layer based on the soil cores. Salt removed from each of the soil layers was calculated based on the relationship 1 dS/m = 640 mg/L (Tanji 1991) and soil bulk densities shown in Figure 4-2. Use of the soil cores were chosen rather than the EM for these calculations as the regressions with the EM surveys were not always high and coefficients of variation were high particularly in the latter surveys (Table 7-5). The amount of salt removed from each of the soil layers is significantly larger than that drained from both treatments. This can be attributed to two main factors. Firstly, the large field variation present in the treatments and secondly soil cores were taken on the vine rows where irrigation furrows were situated. Therefore, movement of salt into the inter-row areas would not be accounted for with the soil cores and salt leaching horizontally from the vine row area where the furrows are situated to the inter-row area would not be represented.

Table 7-6. Average Soil $EC_{1:5}$, percentage change in soil $EC_{1:5}$ and change in salt storage for the ML and SL treatments

		Before Drainage Soil EC		End 2000/2001 Season Soil EC		End 2001/2002 Season Soil EC		% Change in EC			Change in Salt Storage (kg/ha)*		
	Depth (m)	Mean	SD	Mean	SD	Mean	SD	2000/2001	2001/2002	Total	2000/2001	2001/2002	Total
ML	**0.05**	1.55	0.64	1.34	0.53	0.74	0.55	-13.2	-45.1	-52.3	-980	-2903	-3883
	0.2	1.64	1.19	0.77	0.42	0.46	0.26	-53.0	-39.6	-71.6	-8312	-2922	-11234
	0.45	2.42	1.06	1.82	1.18	1.27	0.99	-24.6	-30.2	-47.4	-8580	-7937	-16517
	0.75	2.97	0.46	2.58	0.73	1.79	0.83	-13.3	-30.5	-39.8	-5712	-11330	-17042
	1.05	3.02	0.57	2.77	0.57	1.95	0.75	-8.3	-29.7	-35.5	-3600	-11875	-15475
	1.35	2.92	0.59	2.85	0.50	2.32	0.62	-2.3	-18.7	-20.6	-960	-7692	-8652
	1.65	2.52	0.59	2.74	0.53	2.51	0.35	8.7	-8.3	-0.3	3168	-3264	-96
Total											**-24976**	**-47923**	**-72899**
SL	**0.05**	0.82	0.38	1.08	0.73	0.59	0.39	32.2	-45.5	-28.0	1264	-2363	-1099
	0.2	1.00	0.64	0.56	0.33	0.52	0.35	-43.7	-6.7	-47.5	-4184	-362	-4546
	0.45	1.70	0.33	1.31	0.54	0.98	0.16	-22.7	-25.4	-42.3	-5537	-4788	-10325
	0.75	1.95	0.39	1.72	0.42	1.22	0.38	-11.7	-29.4	-37.7	-3288	-7286	-10574
	1.05	1.98	0.21	1.83	0.29	1.10	0.44	-7.3	-40.2	-44.6	-2076	-10608	-12684
	1.35	1.78	0.19	1.78	0.15	1.11	0.60	0.5	-37.7	-37.4	120	-9670	-9550
	1.65	1.68	0.17	1.68	0.29	1.36	0.64	-0.1	-18.8	-18.9	-24	-4543	-4567
Total											**-13724.8**	**-39620**	**-53345**

*Negative values indicate salt removal, positive values indicate salt addition

However, the removal of salt from the individual layers does provide a means of assessing the effect of the two drainage treatments. It can be seen that the ML treatment has been more effective in removing salts from within the upper soil layers compared to the SL treatment and also that the removal of salt in the deeper soil profile is larger in the SL treatment than in the ML treatment. Figure 7-25 shows the percentage change in soil $EC_{1:5}$ over the duration of the experimental period. Essentially the salt profile changes in the ML treatment would represent an ideal situation, with the salt being removed from within the rootzone of the plants, without the removal of excess salts stored below the rootzone depth. Typically, with existing subsurface drainage systems salt leaching occurs to a significant depth often well below the plant rootzone. For the Semillon vines grown during the experiment it appeared that the root depth during the duration of the experiment was no deeper than 0.4m, based on the Enviroscan readings shown in Figure 7-8, whereas for mature vines the rooting depth would be greater. Cox (1995) in studying root distributions in well water furrow irrigated vineyards with mature vines in the region found maximum rooting depths of 0.6-0.8m. Therefore, leaching of salts essentially only needs to be done within the plant rootzone of 0.8m depth and any leaching occurring below such depths is essentially non-beneficial to the plant. Considering this criteria, then it can be seen that the ML treatment has been significantly more effective in achieving this aim.

The significant decrease in percent change in $EC_{1:5}$ shown in Figure 7-25, particularly in the upper soil layers may be related largely to the flow characteristics occurring with the shallow drains, with the topsoil layers becoming saturated and horizontal flow occurring to the shallow drains, which is discussed later.

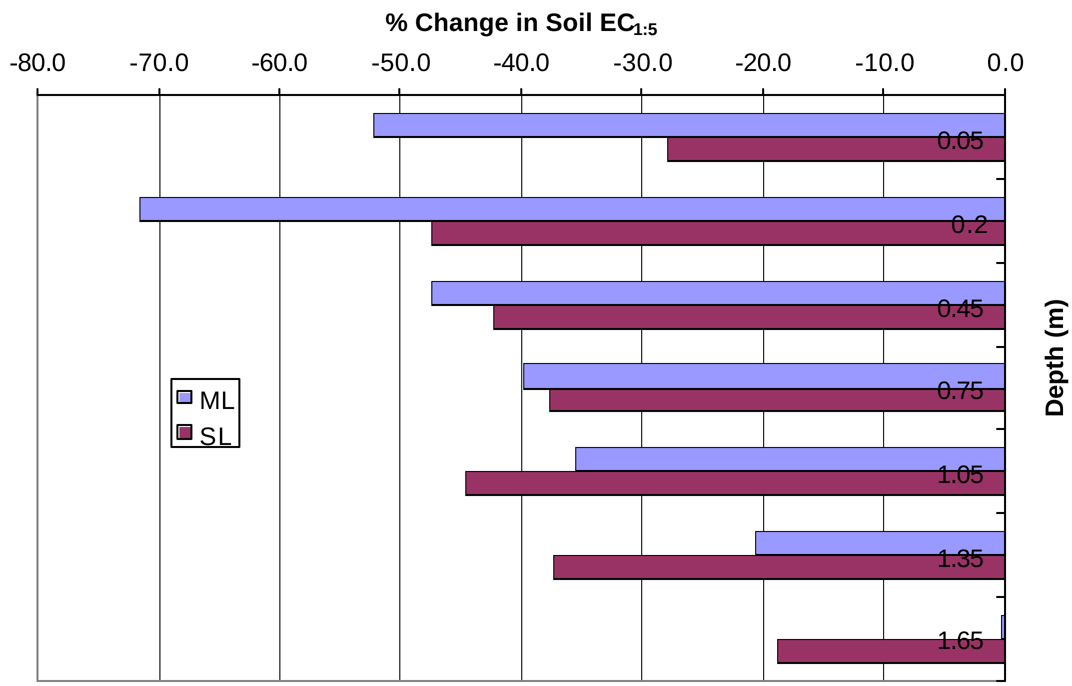


Figure 7-25. Percentage change in soil $EC_{1:5}$ over the duration of the experiment for the ML and SL treatments, average of 6 cores

<u>SAR</u>

Sodium absorption ratio of soil water extracts calculated with ICP analysis was undertaken at positions on the deep drain and at ½ deep drain spacing in each of the treatments, adjacent to wells 4, 16, 28 and 38, at the start and end of the experimental period. Figure 7-26 shows change in SAR with soil depth for both the SL and ML treatments. It can be seen in Figure 7-26 that SAR reduction was similar in each treatment. Considering these cores are both taken next to a deep drain then it could be expected that the difference between the two treatments would be small. Figure 7-27 shows SAR with depth at ½ deep drain spacing. This shows that the ML treatment has been more successful in reducing SAR than the SL treatment as a greater difference between the treatments would be expected at ½ drain spacing than on the deep drains. This is due to the greater effect of the shallow drain at ½ drain spacing.

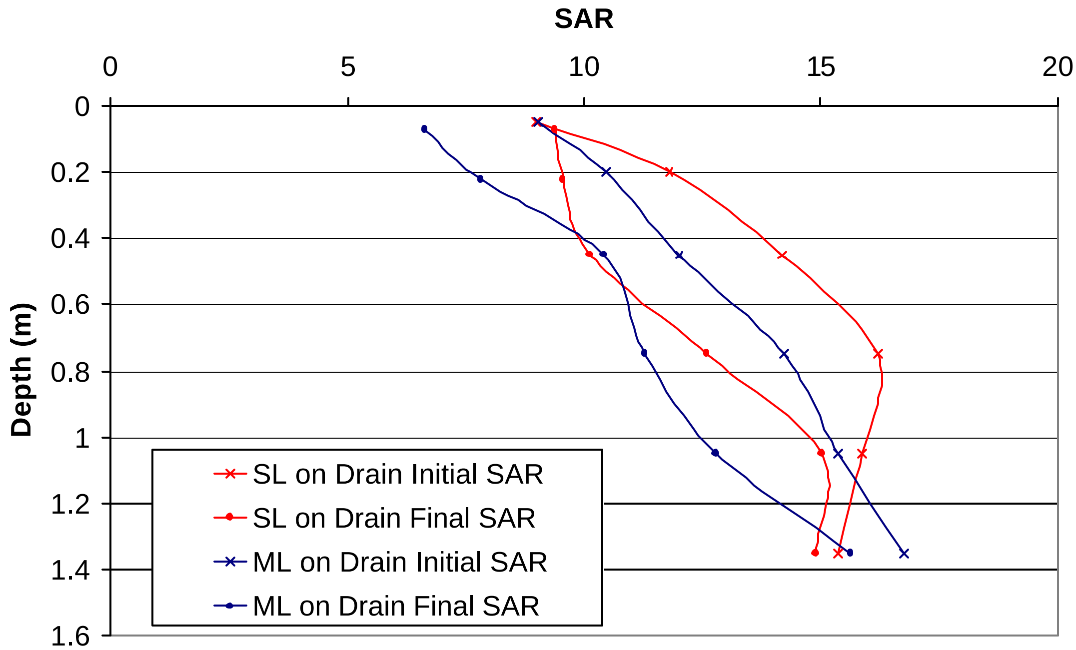


Figure 7-26. Change in SAR profiles in SL and ML treatments over the experimental monitoring period on the drain

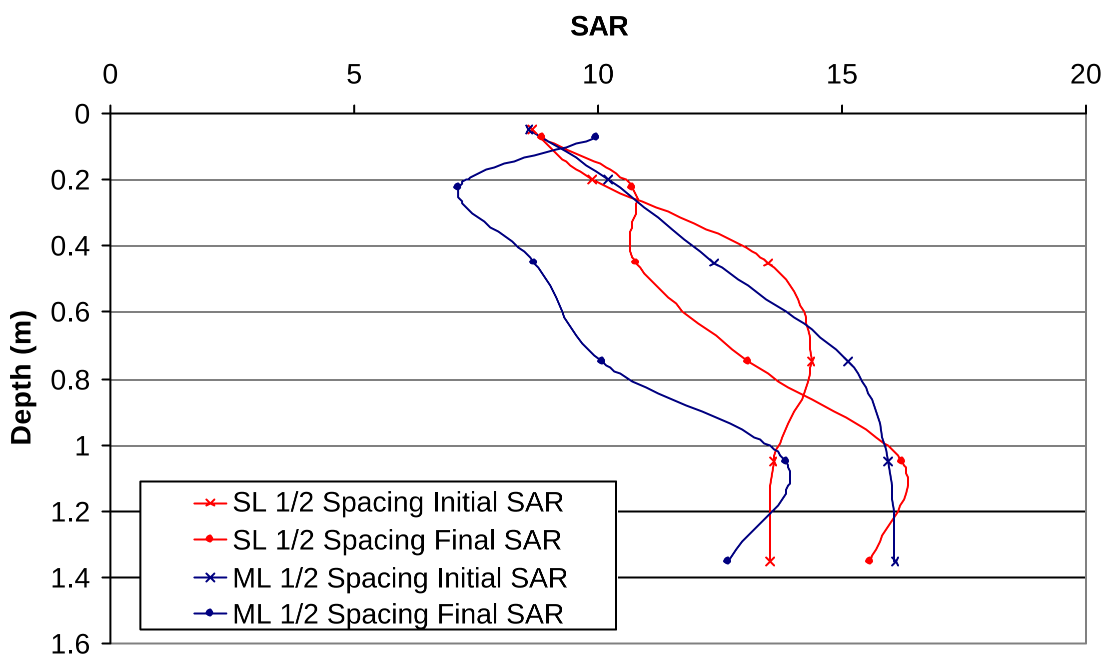


Figure 7-27. Change in SAR profiles in SL and ML treatments over experimental monitoring period at ½ deep drain spacing

The decrease in SAR in association with decreasing EC during the experiment saw no noticeable loss of permeability in the treatments during the experimental monitoring period as indicated by drainage flow rates. It appears from Figure 7-27 that the SL treatment may be more susceptible to problems associated with high SAR levels than the ML treatment. This is particularly evident at mid-drain spacing. Northcote and Skene (1972) define non-sodic soils with a SAR < 5, hence classification of the soils in both treatments is saline-sodic, however the soils are only weakly sodic. Therefore, with the continued decline in SAR with leaching then the ML treatment particularly may not suffer extensive problems with loss of permeability. Sodicity issues will only become apparent once soil EC levels decline and it is likely that by this time the SAR would have declined below 5 based on the trends shown in Figure 7-26 and Figure 7-27.

7.1.5 Processes Effecting Drainage Salinity

Previous sections have presented the key results of the experiment but have not investigated the detailed interactions involved and the effects that parameters such as drain flow, water table depth and soil salinity have on the salinity characteristics of the drainage effluent. It can be seen based on the results presented previously, that there are major differences between the multi-level and single-level drainage systems in relation to there behaviour regarding drain flows, salt leaching, water table regimes and subsequently drainage salt loads. In order to accesses the flow processes of the multi-level drainage system and the affect these have on the drainage water salinity, the interaction between physical parameters and drain water salinity are described below.

7.1.5.1 Drain Flow

Deep Drains

A direct relationship between drainage water salinity and flow rate was found in the experiment. Higher drainage flows caused a reduction in the salinity of the drainage water (Figure 7-28). During each recharge event there was a hysteresis effect in the observed relation between the drain water salinity and the drainage flow rate.

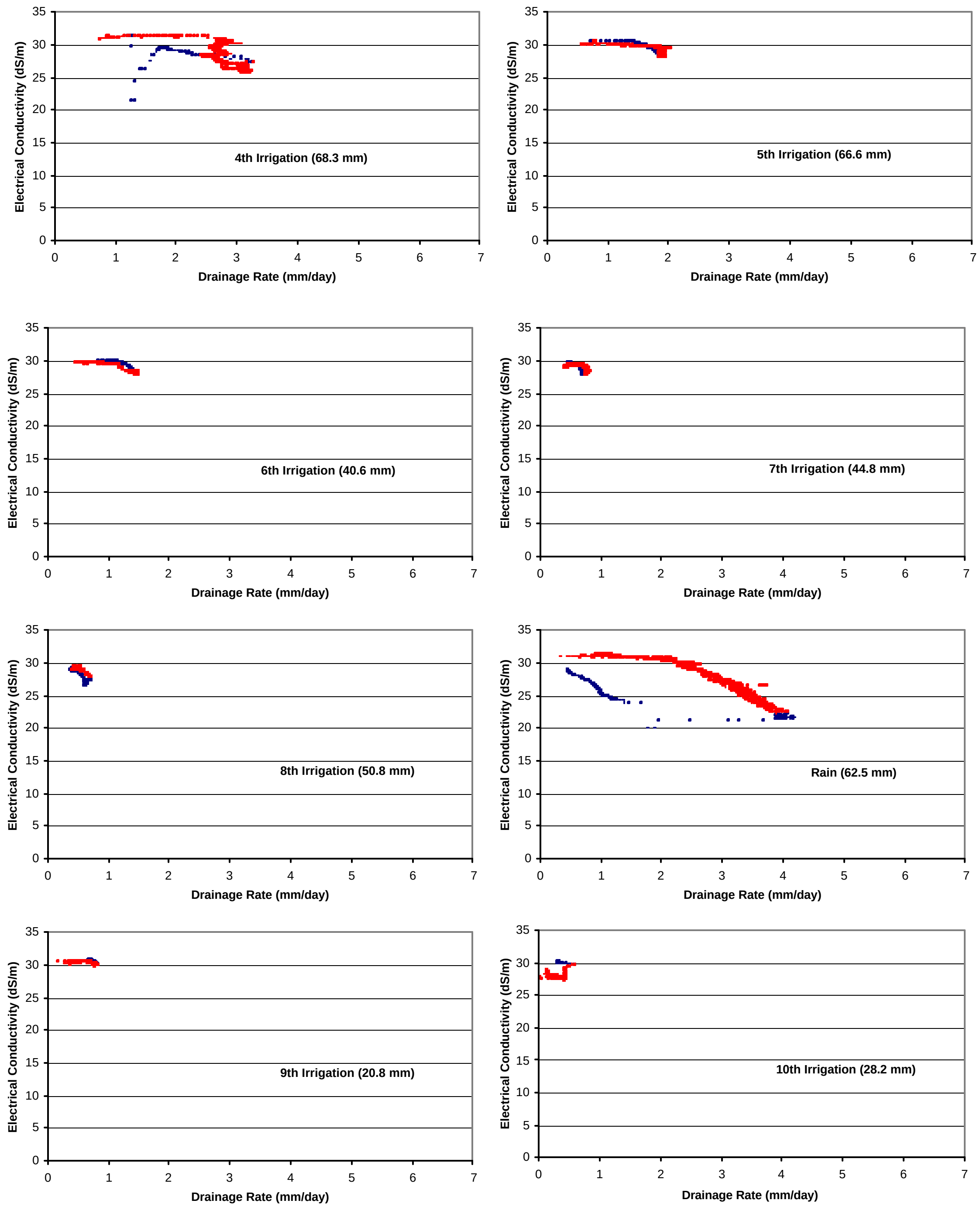


Figure 7-28. Relationship between drainage salinity and drainage discharge rate as observed in the SL treatment, Blue represents rising limb and red falling limb

This relationship occurred during all recharge events in the SL treatment, however the difference between the rising (Blue) and falling limb (Red) was more prominent during the higher recharge events, as shown in Figure 7-28. The hystersis behaviour can be explained by preferential flow reaching the drains during the recharge event, which dilutes the salinity of the drainage water thereby causing lower salinity drain flows than would be expected for a given drainage rate. The falling limb is of a higher drain salinity than the rising limb for a given flow rate due to less preferential flow entering the drain and hence less dilution of the drainage water from non-saline irrigation and rainfall water.

The deep drain on the ML treatment showed a similar pattern during the rainfall event however the hysteresis effect was different during irrigation events (Figure 7-29)

.

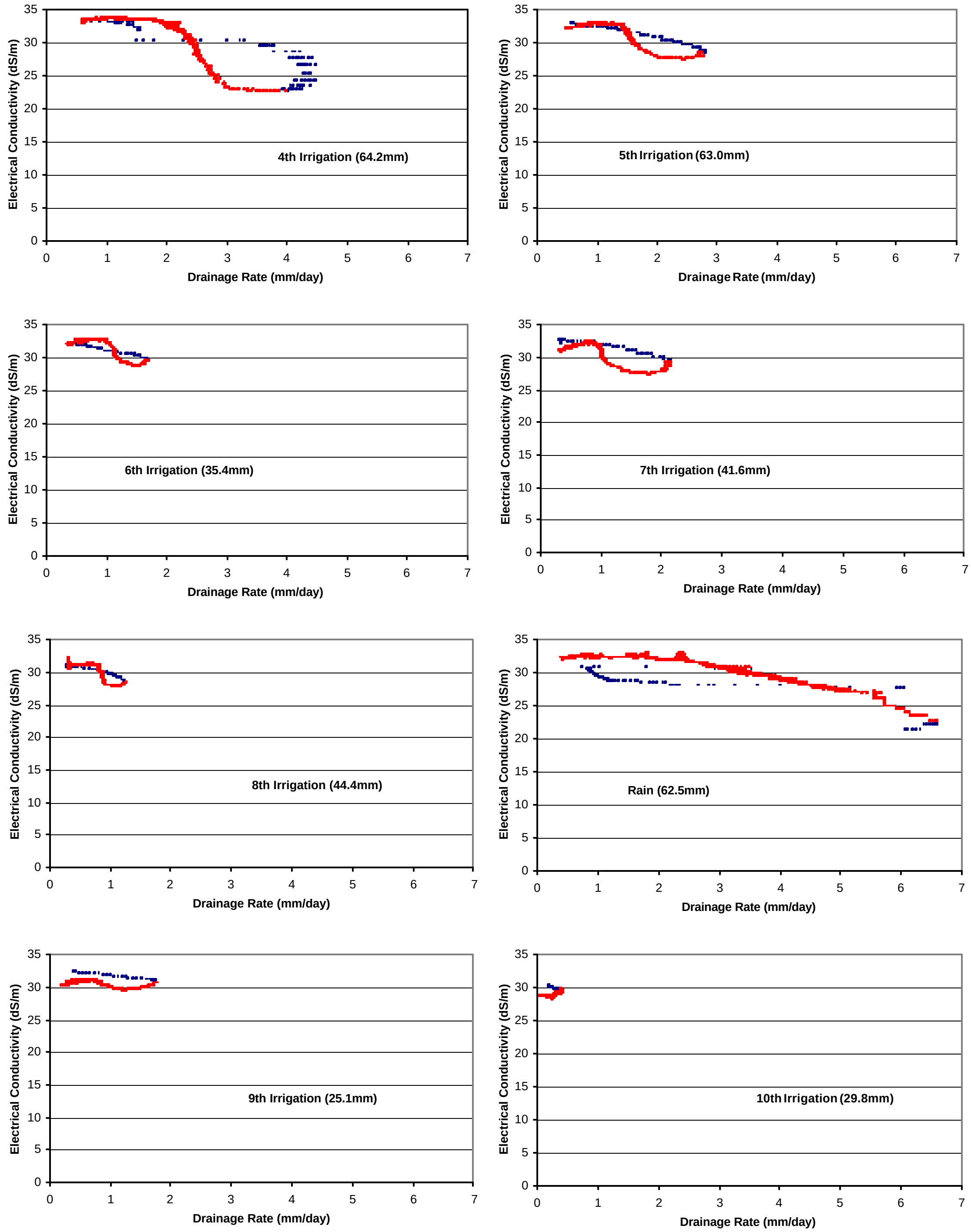


Figure 7-29. Relationship between drainage salinity and drainage discharge rate as observed in the ML treatment, Blue represents rising limb and red falling limb

It can be seen that the relationship between drain water salinity and discharge during the rising and falling limbs were different than for the SL treatment. It can be seen that generally the rising limb electrical conductivities were higher than the falling limb for a given drain discharge during the higher drainage rates on the rising limb. A possible explanation for this behaviour may involve the interaction of the shallow drains in the ML treatment affecting the electrical conductivity of the deep drains causing this abnormality. The shallow drain trench may have the effect of providing a mass preferential flow path through the shallow restrictive layers that allows less saline water to enter the deeper drains once the shallow drains become surcharged. During the initial stages the shallow drains remove efficiently water from the drain trench however at later stages there may be movement of water occurring from the shallow drain trench to the deeper drains once the shallow drains become surcharged, hence causing the drop in deep drain salinity.

It is difficult to explain this behaviour of the interaction between the deep and shallow drains within the MLD system without more extensive experimentation. The use of water path traces that may allow further more detailed explanation of the behaviour of the hystersis pattern measured in the MLD treatment. What can be deduced from the drainage rate electrical conductivity relationship is that there is a general relationship of decreased electrical conductivity with increased drainage rates. This is particularly evident when ignoring the rising limb of the curve and concentrating on the falling limb when preferential flow paths to the drains are not dominating the drain flow process. The falling limb is also of the most importance since its duration is typically much greater than that of the rising limb.

Shallow Drains

Figure 7-30 shows the relationship between shallow drain discharge and drain water salinity in the ML treatment for the falling limb of the drain flow hydrograph. It can be seen from Figure 7-30 that there is a general fall in electrical conductivity with increasing drain discharge. It can also be seen that as the irrigation season progressed the electrical conductivity showed a general decrease for each irrigation event, until the rainfall event, which increased the electrical conductivity of the drain flows.

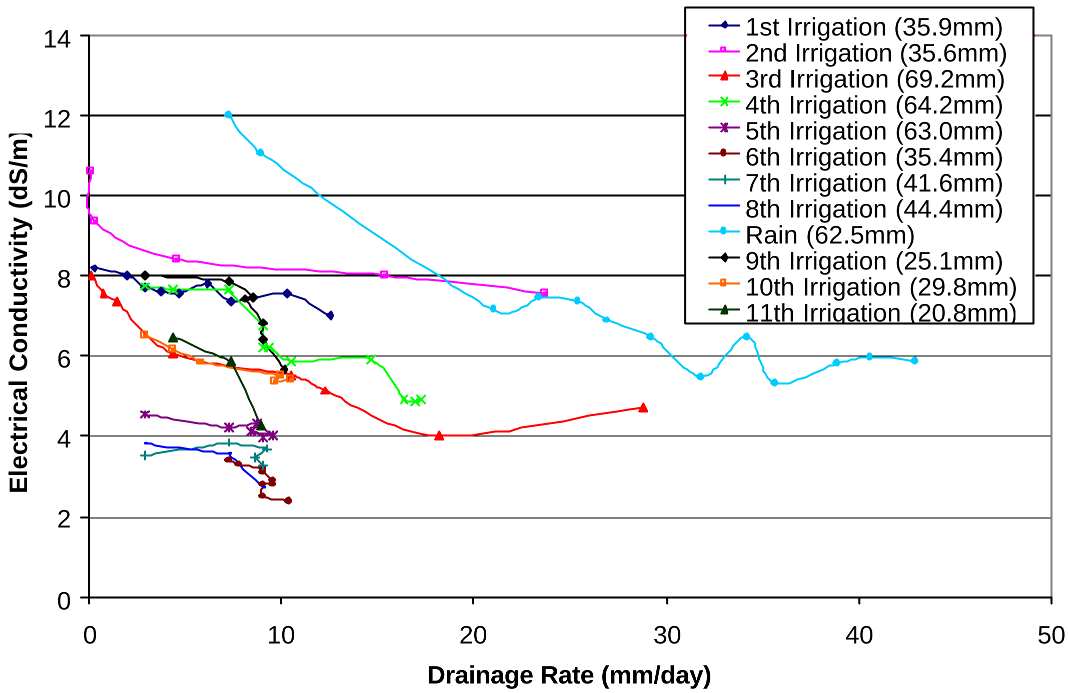


Figure 7-30. Relationship between shallow drain discharge rate and drain water salinity in the ML treatment

Decreases in EC of the drain water with increasing drain flow would be expected. This can be explained by high preferential flow causing the higher drainage rates, which in turn reduce the drain water EC. It can be seen from Figure 7-30 that EC of the drainage water varied considerably over the drainage rate, often with a 50% change in drainage water salinity between the highest and lowest drainage rates measured for each irrigation event.

7.1.5.2 Water Table Depth

Deep Drains

Water table depth had a large effect on the drain water salinity of the deep drains. This can be seen in Figure 7-31 and Figure 7-32, which shows the relationship between water table depth and drain water electrical conductivity for the ML and SL treatments respectively.

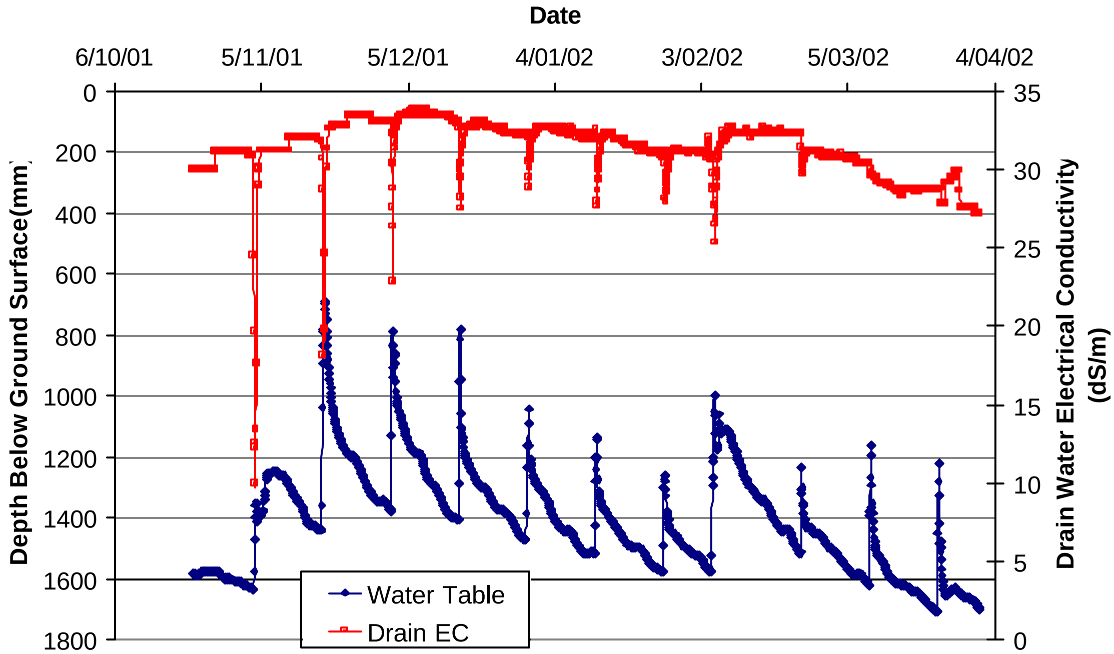


Figure 7-31. Average water table depth and drain water electrical conductivity over the 2001/2002 irrigation season in ML treatment

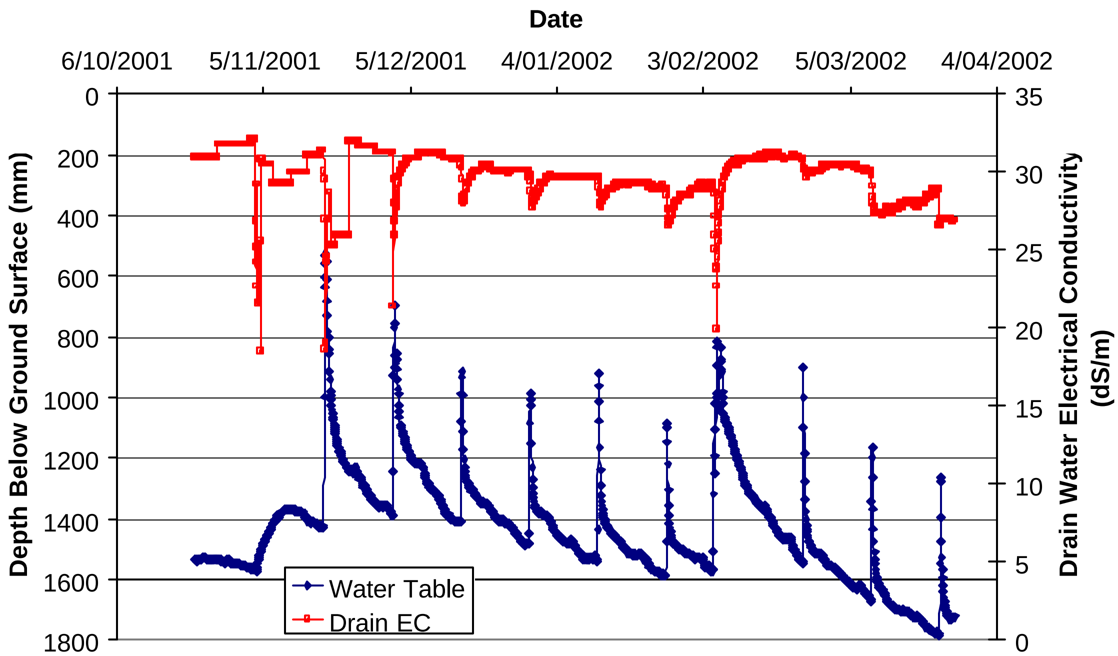


Figure 7-32. Average water table depth and drain water electrical conductivity over the 2001/2002 irrigation season in SL treatment

It can be seen that at higher water table depths the salinity of the drainage water is decreased. This effect has also been observed previously by Christen and Skehan (2000) in similar subsurface drained fields in the Murrumbidgee Irrigation Area. The most likely explanation for such an occurrence is that at high water table levels dilution occurs due to the inflow of deep percolation water through the area above drain depth, thereby reducing deeper groundwater flow to the drain. Flow paths to drains are changed which results in increased flow through the shallower soil layers reaching the drain, which tend to be less saline, and hence causes a reduction in drain water salinity. This is associated with the high water tables being caused by application of low salinity irrigation water.

Figure 7-33 shows drain water salinities for the ML and SL treatments in greater detail for selected irrigation events in the 2001/2002 irrigation season. It can be seen that the return of drain water salinity after recharge periods back to baseline salinity level was faster in the ML treatment than in the SL treatment.

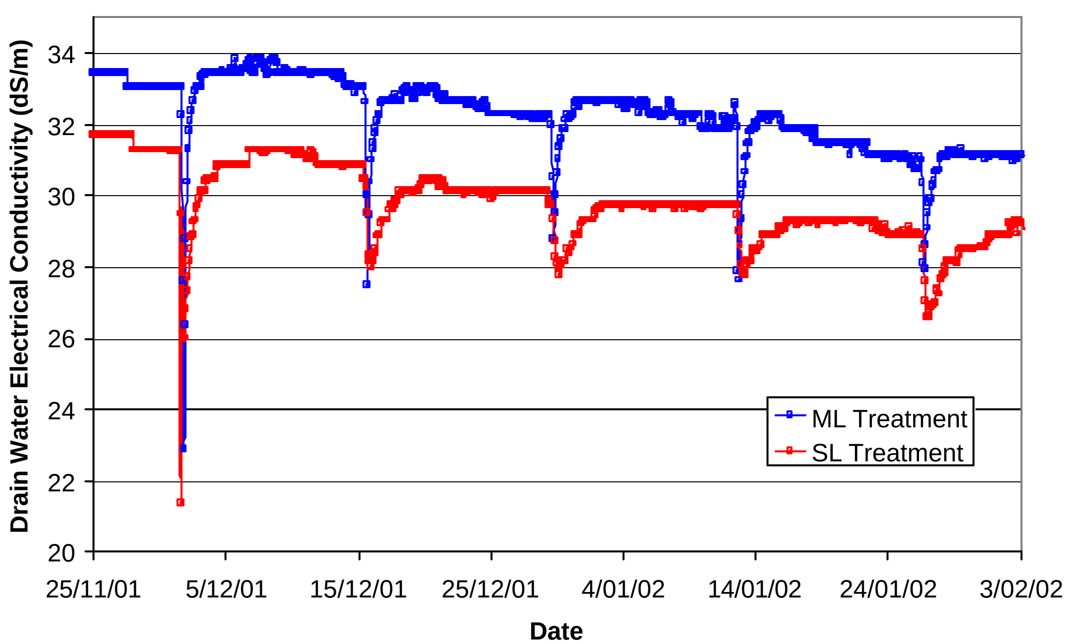


Figure 7-33. Drain water salinity for the ML and SL treatments for the 3rd, 4th, 5th, 6th and 7th irrigation events of the 2001/2002 irrigation season

This may have been due to the effect of the shallow drains in the ML treatment removing a large proportion of the drainage water before it had time to percolate to deeper depths, hence reducing the effect of suppression of the deeper groundwater flow to the drains. In such a small experimental area the effect of regional piezometric levels would be considered significant hence groundwater flow to the deeper drains in the multi-level system would to a degree be controlled by the regional groundwater pressure. If a large majority of the locally percolated water was removed with the shallow drains yet regional influences on the deep drains remained then it could be expected that there would be a more rapid increase in the drain water salinity, then without the presence of the shallow drains. This effect appears to have been present in the experimental study and would have effected the results, acting to increase deep drain flows in the multi-level drainage system to a greater extent than would have occurred if the whole area was also protected with shallow drains. While this may be seen as a shortcoming of the experiment, this situation is most likely to occur in practice under field conditions in typical situations.

Shallow Drains

It is apparent from the water table data that the shallow drains are not behaving as typically expected (ideal drains) with drainage occurring in many situations when the water table level is below the shallow drain depth. This essentially means that a proportion of the shallow drain flow originates from what can be considered preferential flow, or flow from an initially saturated top soil surface layer, which promotes horizontal flow into the drain trench and then into the shallow drain. Considering irrigations did not occur directly over the shallow drain then direct preferential flow is unlikely the cause of the drain flows from the shallow drains. Soil auguring to a 0.4m depth was undertaken during the 9^{th} irrigation event on the bed between two furrows and the holes used to observe for the presence of a perched water table in the upper soil layers. Figure 7-34 taken during the irrigation event clearly shows the presence of a perched water table in the upper soil layer.

Figure 7-34. Presence of shallow perched water table during irrigations

Therefore, in situations of the shallow drains flowing when the water is not applied directly above the drain, the flow mechanism to the drains are essentially that shown in Figure 7-35, with the more permeable topsoil becoming saturated and horizontal flow to the shallow drain trench occurring. This flow mechanism to the shallow drains has been reported by Leeds-Harrison, Spoor and Godwin (1982) who investigated water flow paths to mole drains in well-structured clay soils. The authors found that flow to the mole drains was largely attributed to horizontal movement of water in the saturated topsoil flowing into mole fissures and down the leg slot into the mole drain. Considering this flow mechanism in the shallow drains, then their effectiveness in removing salt would be largely confined to the upper soil layers, if this was the dominant form of water flow to the shallow drains, due to the presence of a restrictive lower hydraulic conductivity layer.

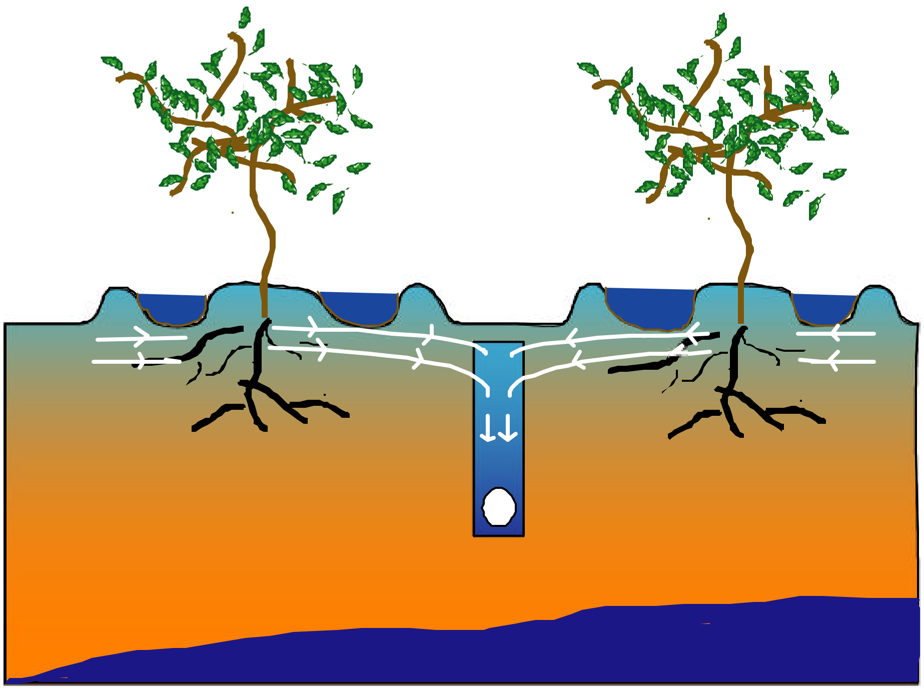


Figure 7-35. Diagrammatic representation of preferential flow paths to the shallow drains due to presence of a perched water table

Figure 7-36 shows the particle size analysis for the ML treatment and it can be seen that there is a large increase in clay content at a depth of 0.4m, which forms a restrictive layer causing the above defined flow mechanism to occur.

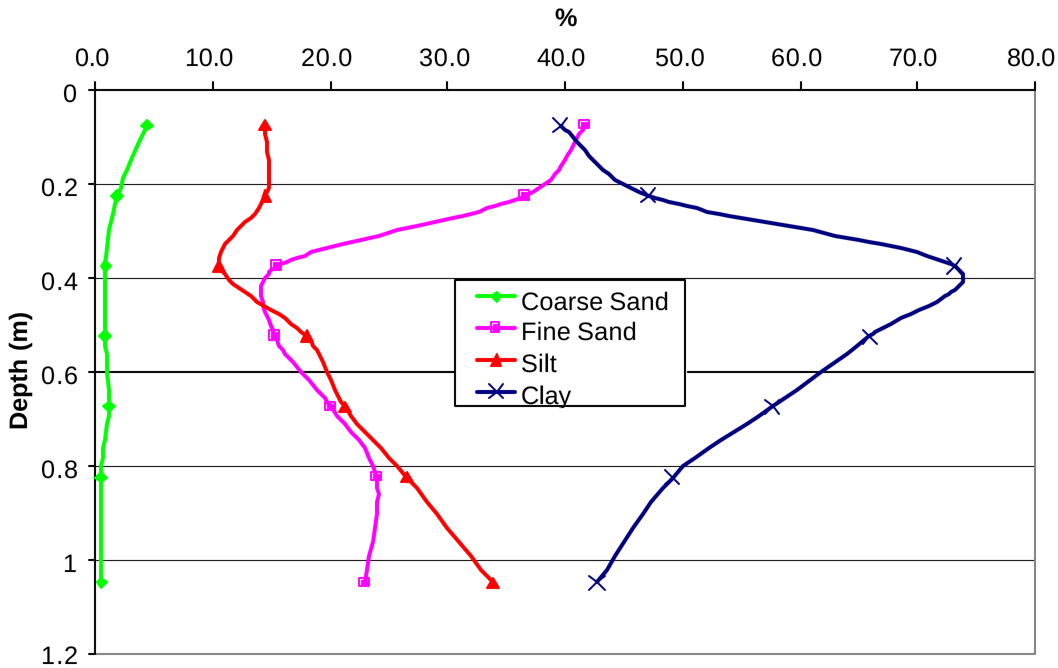


Figure 7-36. Particle size analysis for the ML treatment

7.1.5.3 Soil Salinity Profile

The effect of the soil salinity profile on drain water salinity can be clearly seen by comparing the drain water salinities of the deep and shallow drains in the multi-level drainage system. There was a six-fold reduction in drain water salinity between the deep and shallow drains. This large difference can be attributed partly to the reduced soil salinity levels in the shallow soil layers.

Figure 7-37 shows the average drain water salinities for each of the irrigation events for the shallow and deep drains in the ML treatment along with changes in the average soil salinity levels determined from the EM38 surveying. It can be seen that the shallow drain salinity appears to be closely related to the soil salinity in the shallower surface horizons, which are considerably less than those of the deeper soil layers. This may explain why there is such a large difference in the drain water salinity between the deep and shallow drains in the multi-level drainage system.

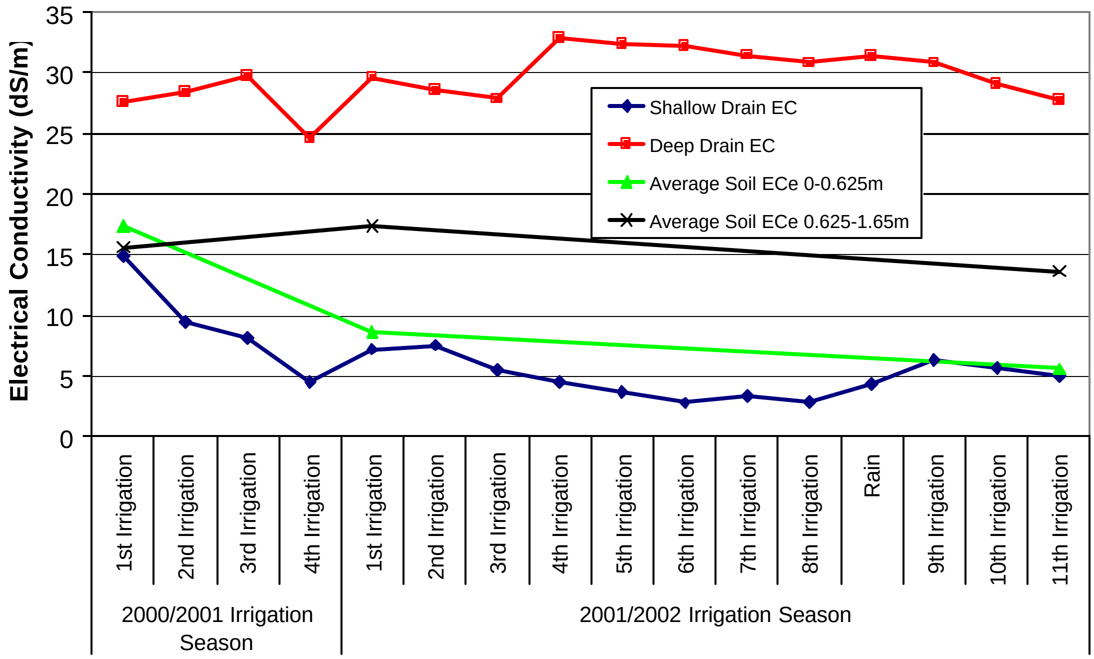


Figure 7-37. Drain water salinities for the deep and shallow drains in the ML treatment and average soil salinity changes in the 0-0.625m and 0.625-1.65m depths

The effect of the soil salinity profile can therefore be seen to have a large influence on the quality of the drainage water from subsurface drainage systems. The shallower drains in the Multi-level drainage system have shallow flow paths, which percolate through shallower soil layers, which are not as saline as the deeper layers. This leds to decreased salinity of the drainage water from the shallower drains compared to those of the deeper drains which have much higher salinities due to the deeper flow paths associated with these drains and the higher soil salinity found in these deeper layers.

7.1.6 Conclusions

Based on the experimental results from the field trial comparing the multi-level and single level drainage treatments the following conclusions can be drawn:

1. Shallow drains were found to have significantly lower drainage salinities than deeper drains. There was a six fold reduction in drain water salinity between the shallow and deep drains in the multi-level system.

2. The combination of deep and shallow drains in a multi-level drainage system provides a reduction in drainage water salinity. Therefore, problems of disposal of saline drainage water are reduced compared to single-level drainage systems.

3. The multi-level drainage system provided greater leaching of the main root zone than the single level system, but without increasing drainage salt loads. This was due to the shallow water flow paths present in the multi-level system.

4. The multi-level drainage system provided a greater degree of waterlogging protection than the single-level system.

It can therefore be seen that in a field situation improvements in minimizing drainage salt loads can be achieved through the use of a multi-level drainage system.

7.2 Controlled Drainage Experiment

Results from the controlled drainage experiment have been divided into three main sections, which are:

1. The effects of controlled drainage on the water table regimes and drain flow characteristics, which essentially investigates the ability of controlled drainage structures to manipulate field water table levels and drain flows compared to uncontrolled drains.

2. The contribution of capillary rise from a saline shallow water table to crop evapotranspiration, which determines the potential benefits associated with controlled drainage.

3. The effects of controlled drainage practices on vine yields and soil salinity, which determines the practical impacts of implementing control drainage strategies.

7.2.1 Effect of Controlled Drainage on Water Tables

Irrigation events that produced higher recharge were used to investigate the differences between controlled and uncontrolled drainage systems. During high recharge events water table differences between the treatments could be clearly seen. Over the course of the experimental monitoring period the first irrigation of the 2000/2001 irrigation season produced the greatest recharge. Irrigation applied to the F, C1 and C2 treatments are shown in Figure 7-38. The water application distribution to the treatments was determined using the SIRMOD (Walker, 1999) surface irrigation simulation model. Details on model inputs are given in Section 7.2.3.2. The difference between the two controlled drainage treatments C1 and C2 was due to differences in irrigation application technique and management. The C2 treatment aimed to apply water more uniformly than the C1 treatment. This was achieved through increasing the inflow rates to the furrows using two siphons and decreasing the time to cut-off, hence decreasing infiltration opportunity time.

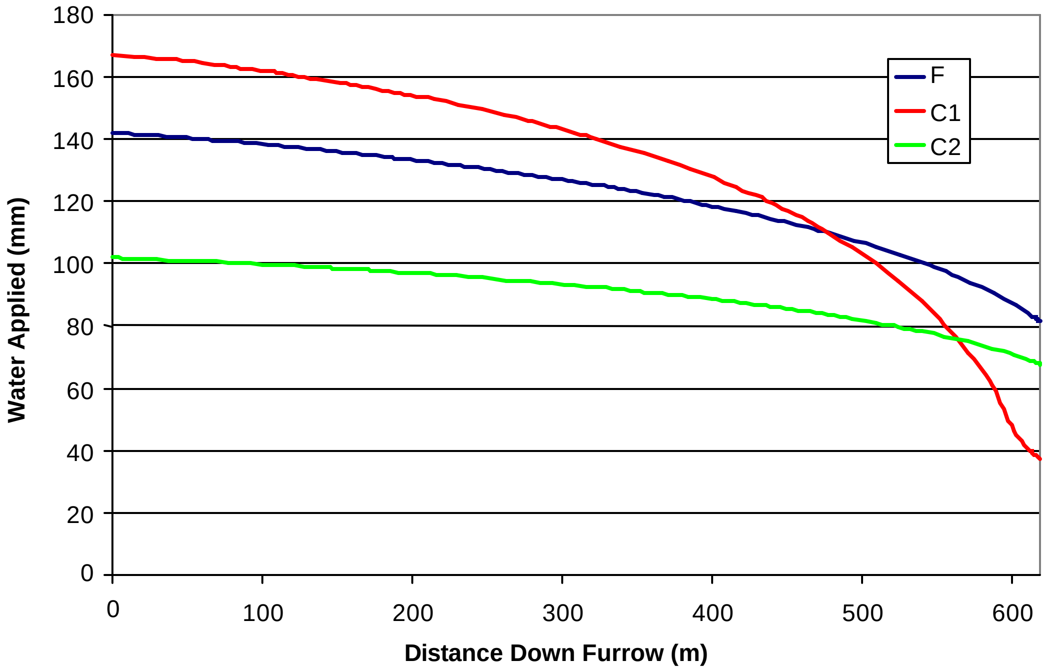


Figure 7-38. Water applied to the control and uncontrolled areas as a function of distance down the furrow for the first irrigation of the 2000/2001 irrigation season

Three dimensional water table heights constructed from the testwell data for this irrigation event for the each of the treatments are given in Figure 7-39, Figure 7-40 and Figure 7-41 for the F, C1 and C2 treatments respectively.

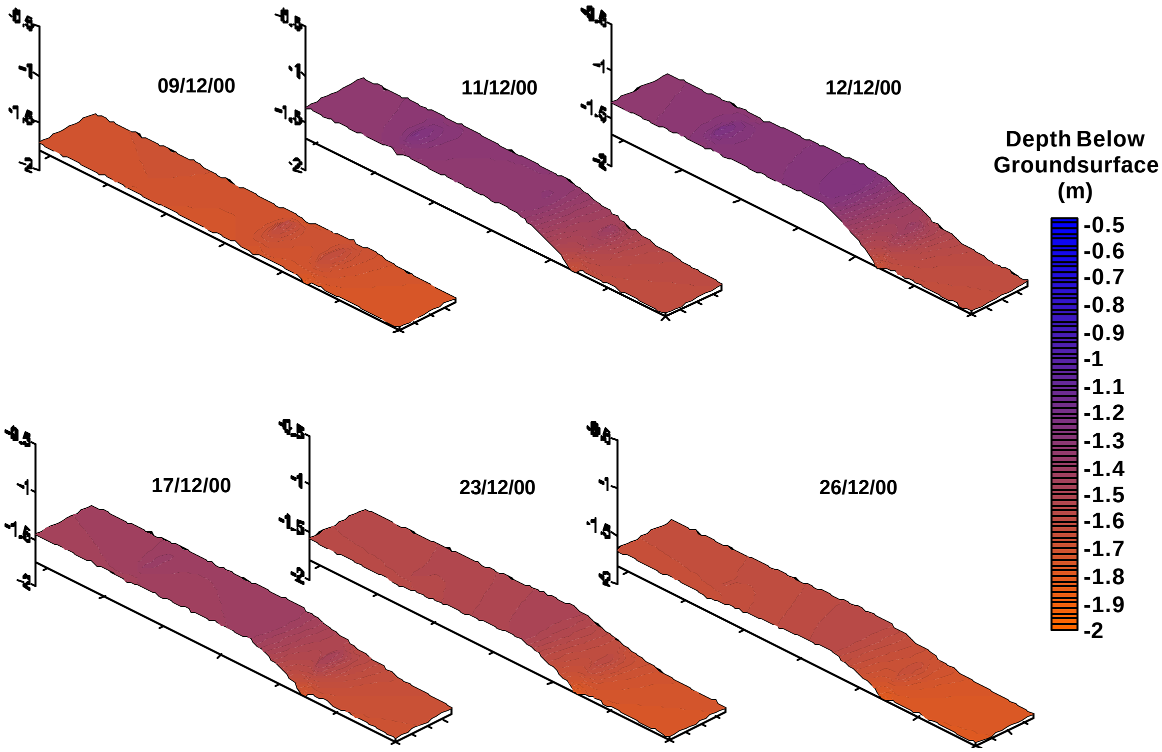


Figure 7-39. Water table contour heights under the free drainage treatment F

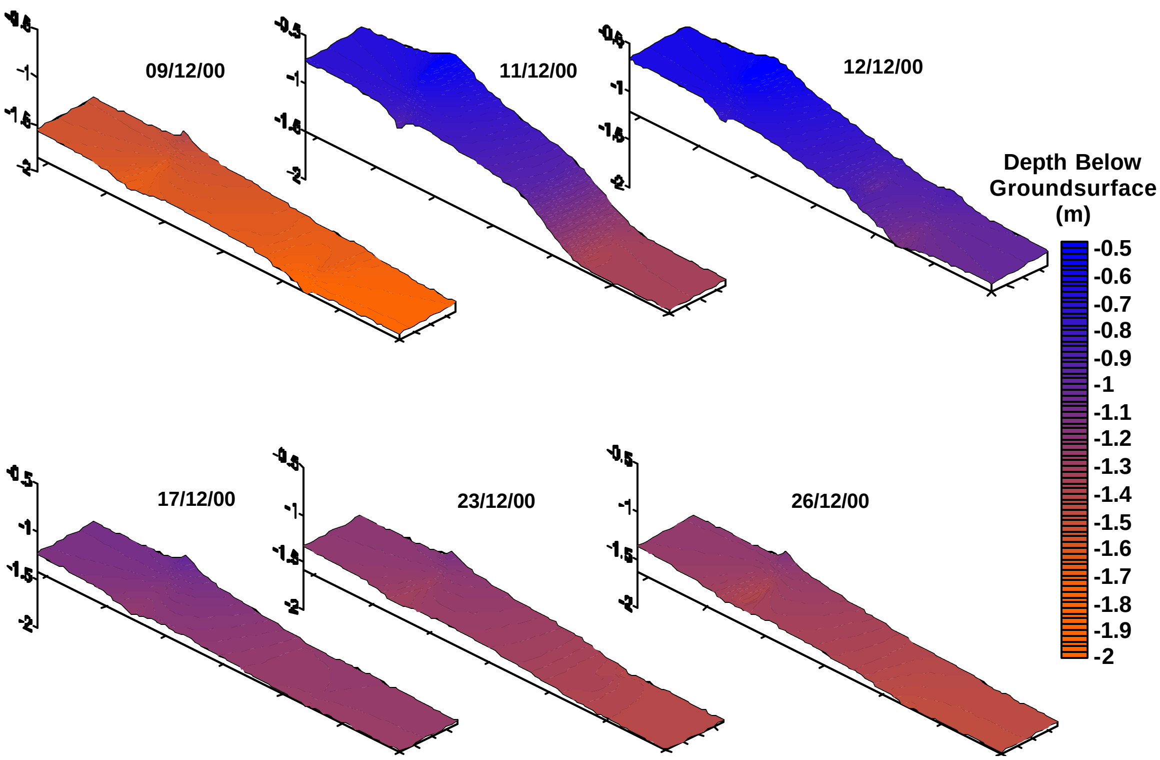


Figure 7-40. Water table contour heights under controlled drainage treatment C1

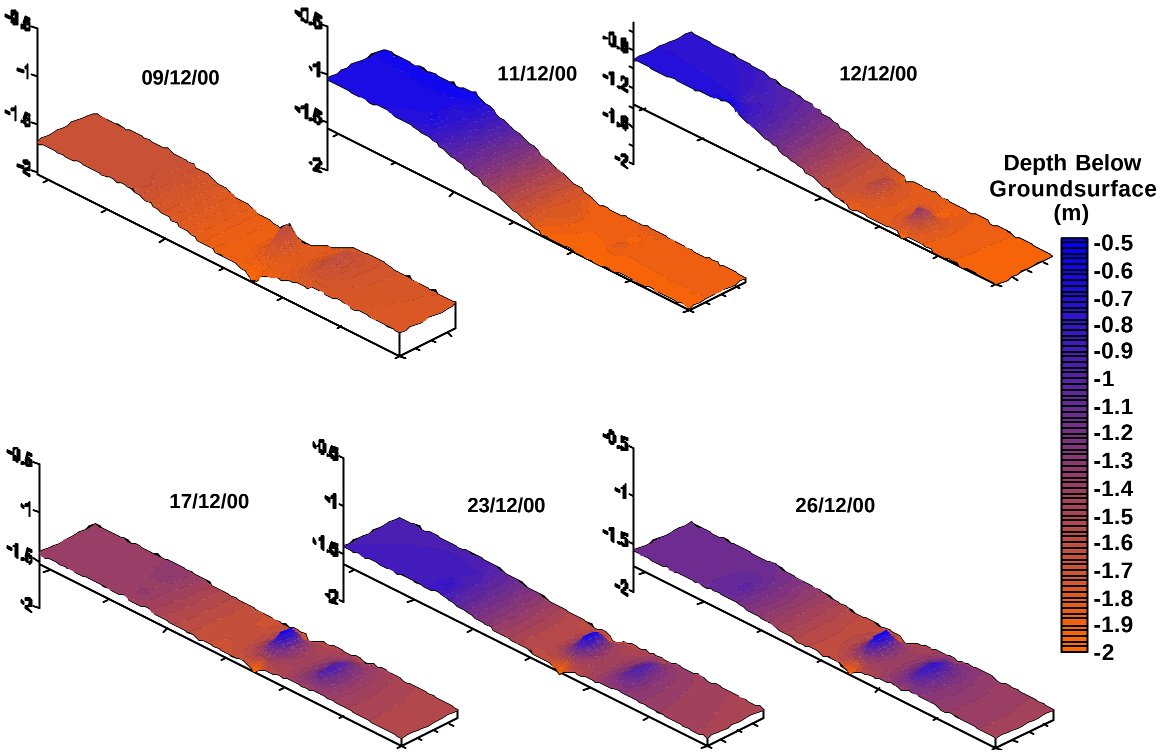


Figure 7-41. Water table contour heights under controlled drainage treatment C2

It can be seen that water table variation within treatments showed a general trend of a higher water table at the supply end of the treatments compared to the outlet end for all treatments. The controlled drainage treatments (Figure 7-40, Figure 7-41) showed a much greater rise in the water table level and elevated water table levels were present for a much longer period of time than in the free drainage treatment (Figure 7-39). The time that the average water table depth was above specified depths for a 17-day period between the start of the 1st irrigation and the commencement of the 2nd irrigation is shown in Table 7-7.

Table 7-7. Water table depths between the first and second irrigation

Watertable depth	Number of Days		
	F	C1	C2
< 1m	0	1	0
1 to 1.5m	5	11	11
> 1.5m	12	5	6

It can be seen that the controlled drainage plots (C1,C2) had a higher proportion of time that the water table depth was above 1.5m allowing potential beneficial use by the crop. The controlled drainage did not significantly increase the time the water table was above 1m, hence waterlogging protection was still provided.

7.2.2 Effect of Controlled Drainage on Drain Flow and Salt load

Due to the controlled drainage practices having a large effect on the water table this also affected the drain flows and hence salt loads. During both irrigation seasons subsurface drainage from all treatments was rather small compared to typical irrigated fields in the area, due to the low volumes of irrigation water applied. The F treatment in which the drains were allowed to discharge freely showed a general trend of decreasing drainage volumes as the irrigation season progressed. Figure 7-42 and Figure 7-43 show the drainage discharge from the free drainage treatment F for the 2000/2001 and 2001/2002 irrigation seasons respectively. Also shown are the respective irrigation and rainfall amounts applied to the field over the period when drainage was occurring. Commencement of drain discharge in the 2000/2001 irrigation season corresponds to the installation of the subsurface drainage system, which occurred from the 5/11/2000 to the 8/11/2000. During the first five irrigations, drain flows steadily decreased with no drainage occurring after the 25/2/2001.

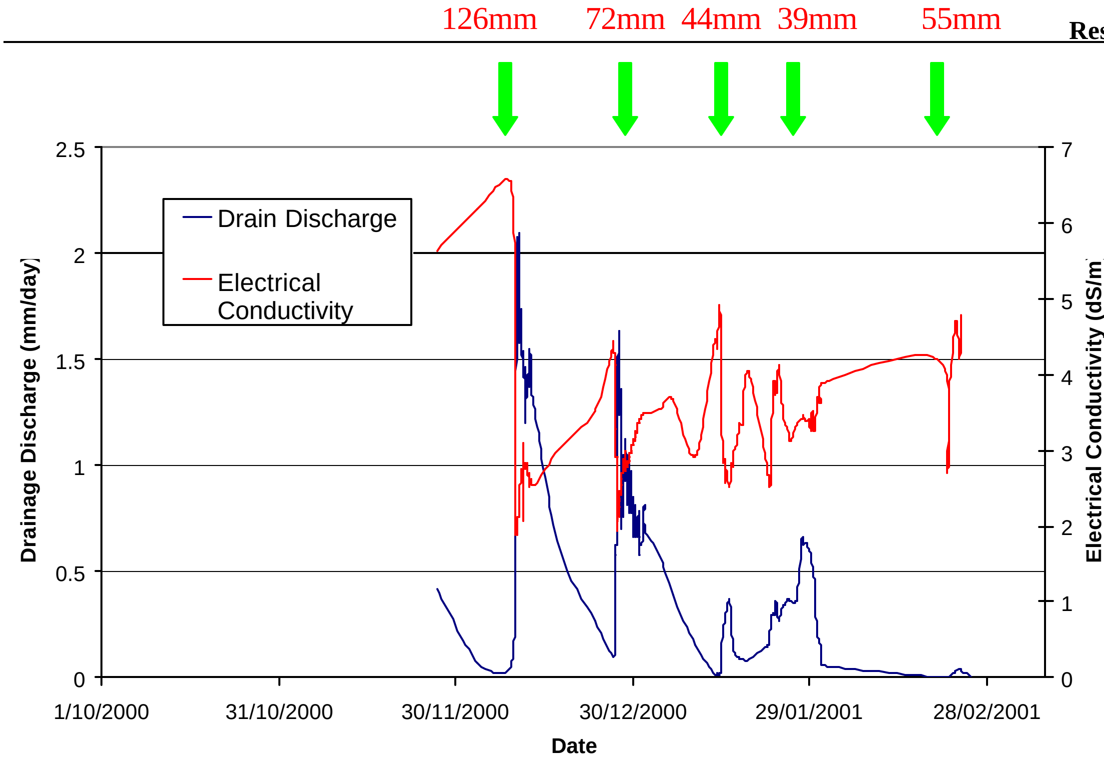


Figure 7-42. Drain discharge and electrical conductivity for the F treatment over the 2000/2001 irrigation season

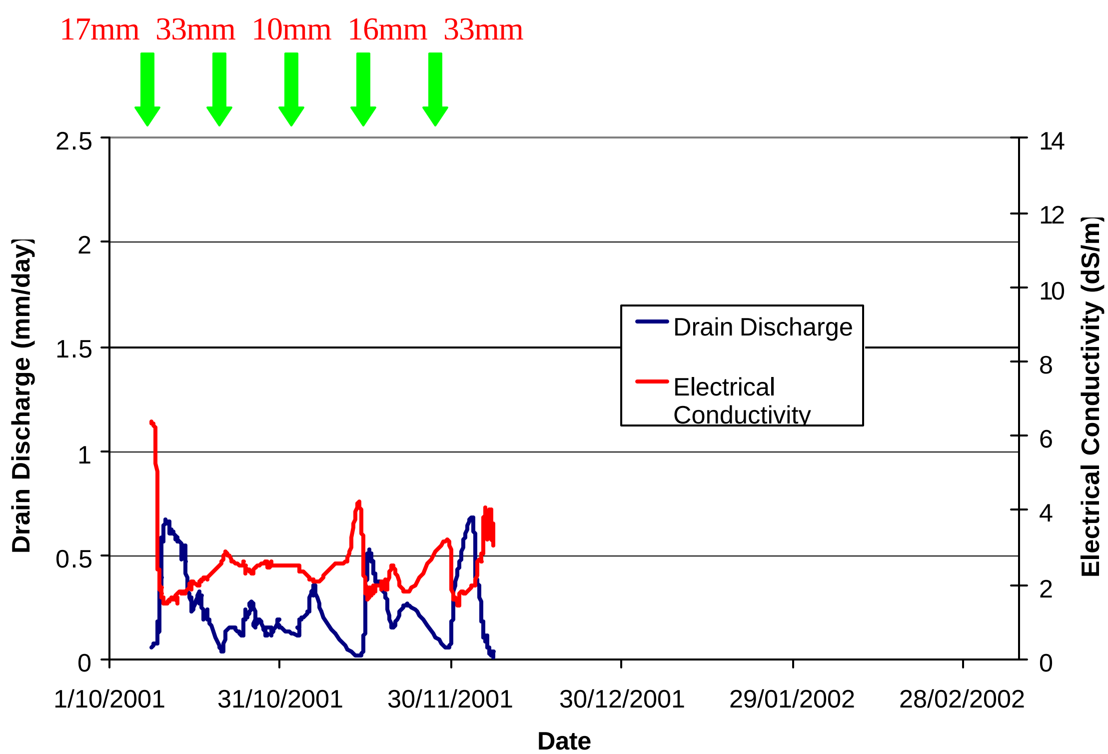


Figure 7-43. Drain Discharge and electrical conductivity for the F treatment over the 2001/2002 irrigation season

It can be seen that irrigation events caused rapid rises in drainage discharge, which caused a subsequent rapid reduction in drain electrical conductivity. Drain flows then receded steadily back to a baseline flow rate which caused a steady increase in drain water salinity. Drainage discharges from the F treatment during the 2001/2002 season were of a much lower magnitude than those of 2000/2001. This was largely due to the smaller volumes of applied water during the 2001/2002 irrigation season. The first two irrigations were only applied to alternate sides of the vines to reduce water application. Also tillage of the treatment was minimized during the 2001/2002 irrigation season when the furrows were first constructed. This allowed a much faster application of water to occur and reduced opportunity time during the initial irrigations thereby reducing the volume of water applied.

During the experimental period the controlled drainage treatments only discharged drainage water on two occasions. The first occasion was during the 1st irrigation event of the 2000/2001 irrigation season. The second occasion was during the 2nd irrigation event of the 2001/2002 irrigation season when the control structures were removed to allow some leaching to occur.

Figure 7-44 presents a comparison of the drain discharges between the treatments during the first irrigation of the 2000/2001 irrigation season. It can be seen that the control drainage treatments produced significantly less drainage than the free drainage treatment and the hydrographs of the treatments were different. The control treatments tended to have drainage durations, which only lasted for between 38-41 hours. Peak discharges also occurred at a later time in the controlled drainage treatment compared to the free drainage treatment. Peak discharges for the controlled treatments varied, however the sharp increasing peak measured on C2 was due to preferential flow to the drain occurring over the trench line. During this event it was observed that surface water entered the tile line for a short period of time during the irrigation event, which produced this elevated increase in peak discharge over the C1 treatment. In contrast the free drainage treatment had higher drainage flows and over a longer duration. Drainage from the free drainage treatment occurred for over 320 hours until the next irrigation event occurred, hence there was continuous drainage from the treatment.

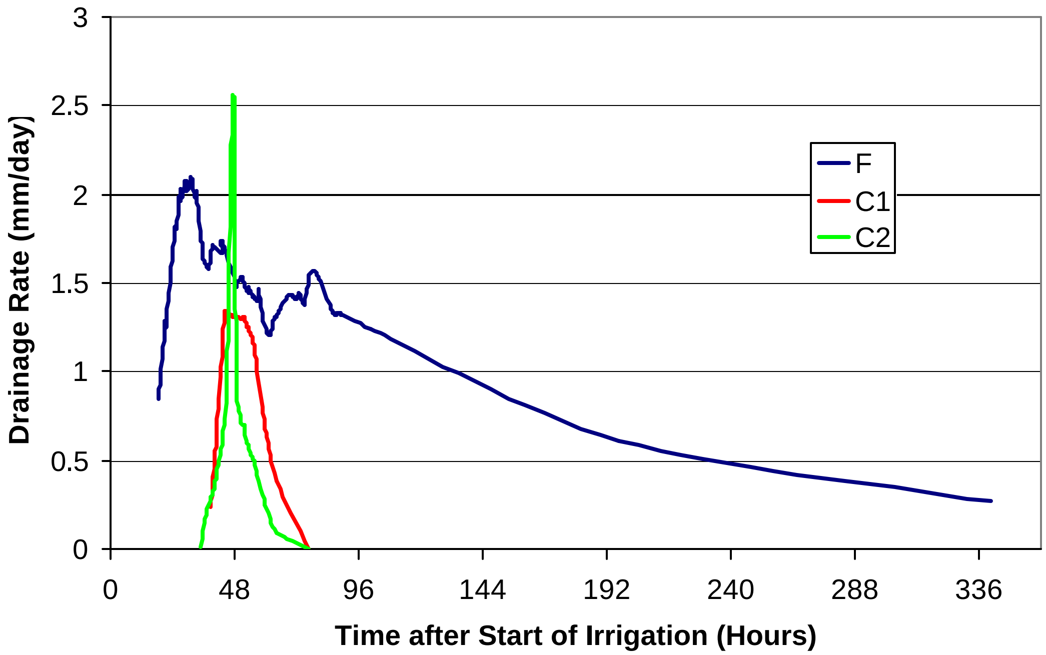


Figure 7-44. Drain flows under free drainage and controlled drainage treatments during the first irrigation of the 2000/2001 irrigation season

This had a large effect on the amount of salt generated from each of the treatments. Table 7-8 shows the total amount of drainage and salt removed from each of the treatments during the first irrigation event of the 2000/2001 irrigation season. It can be seen that the free drainage removed significantly more salt than the controlled drainage treatment and well above that applied through the irrigation water.

Table 7-8. Total Drainage and salt removed for the 1st irrigation of the 2000/2001 irrigation season

Treatment	Drainage (mm)	Average Salinity (dS/m)	Salt Applied (kg/ha)	Salt Removed (kg/ha)
F	9	2.84	80	164
C1	1	1.85	90	12
C2	1	2.03	61	13

The drainage electrical conductivity was found to also vary with drain discharge rates. Figure 1.15 shows the relationship between drain discharge and electrical conductivity for the F treatment for the two irrigation seasons.

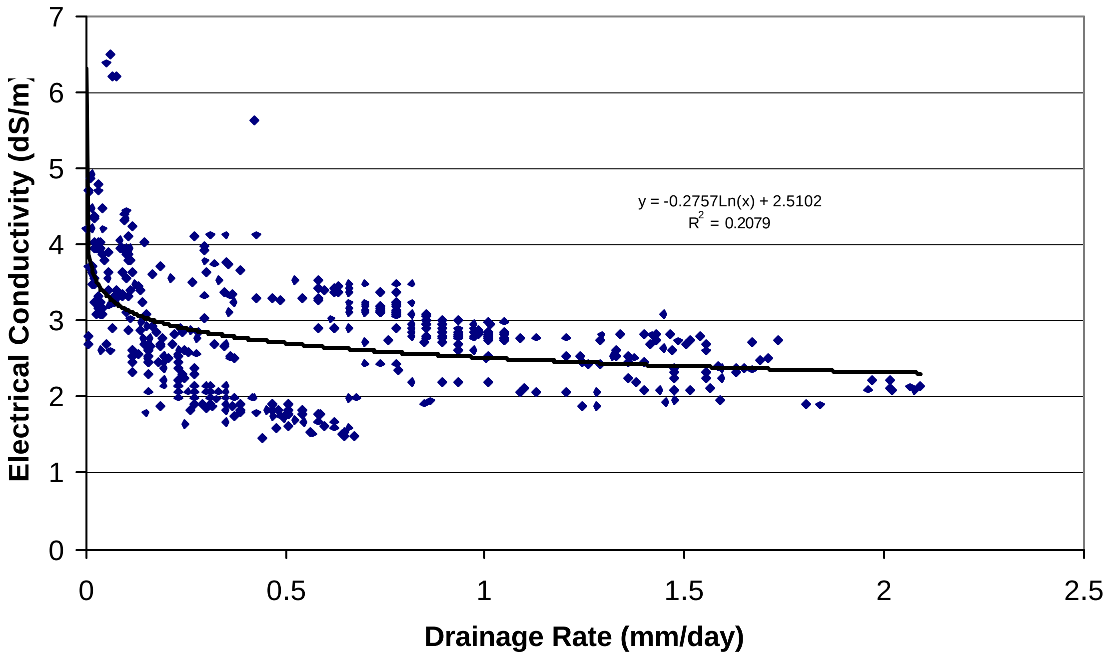


Figure 7-45. Relationship between drain discharge and electrical conductivity for the F treatment

Drainage from the C1 and C2 treatments only occurred during two periods over the monitoring period, hence it was difficult to assess the relationship between drain discharge and electrical conductivity based on the limited data. From the two periods in which drain discharge did occur, the first period mentioned above and the second period during the second irrigation of the 2001/2002 irrigation season provided a further opportunity to compare the effects of drain discharge and electrical conductivity between controlled and uncontrolled periods. During the first irrigation of the 2000/2001 irrigation season, control structures were in place in the C1 and C2 treatments when drain discharge occurred, however during the second irrigation of the 2001/2002 irrigation season the control structures were removed from the treatments and allowed to drain freely, in order to allow a period of salt leaching to occur. Drain discharges and electrical conductivities from these two periods are shown in Figure 7-46 and Figure 7-47 for the C1 and C2 treatments respectively.

It can be seen that the control structures which were in place during the first irrigation of the 2000/2001 irrigation season, that took place on the 11/12/2000, had a significant effect in reducing the drainage discharge volumes compared to the second irrigation event in the 2001/2002 irrigation season when the controls structures were removed from the treatments. A four-fold increase in irrigation application was applied when the control structures were in place on the treatments, yet drain volumes were still significantly reduced compared to the period when control structures were removed. Table 7-9 shows drain flow volumes and salt load for each of the treatments during these periods.

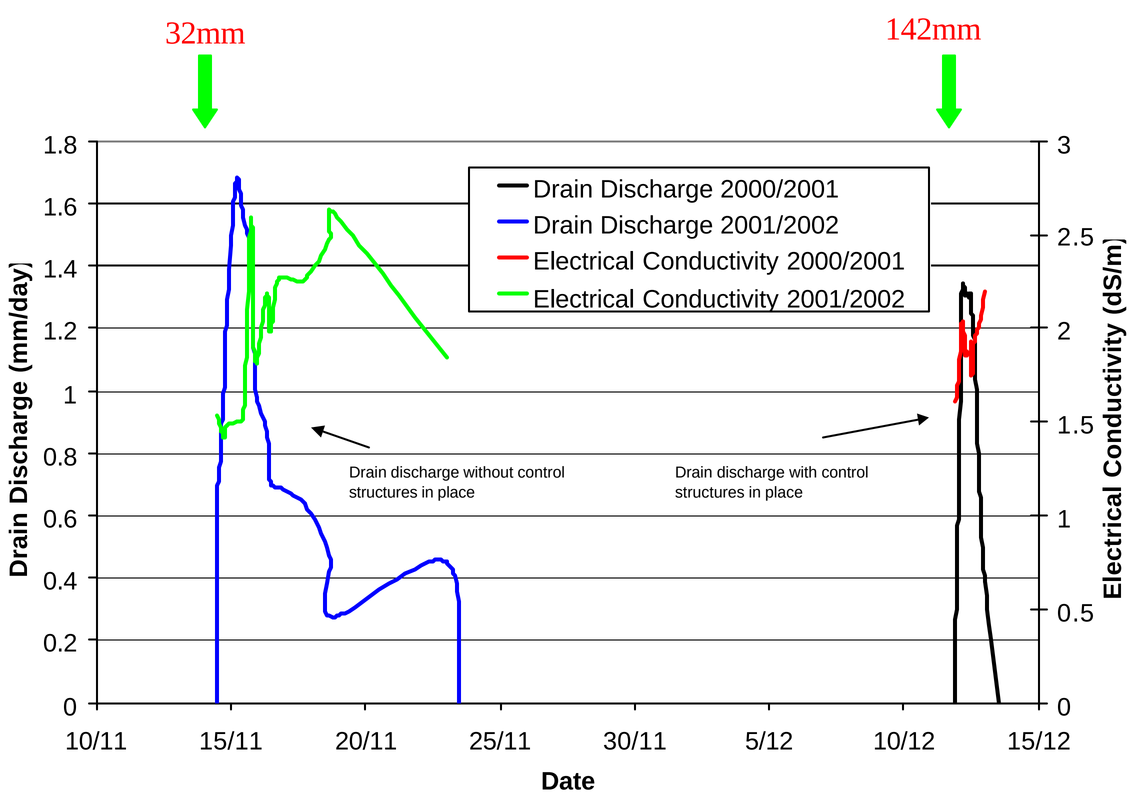


Figure 7-46. Drain discharge and electrical conductivity for the C1 treatment over the experimental period

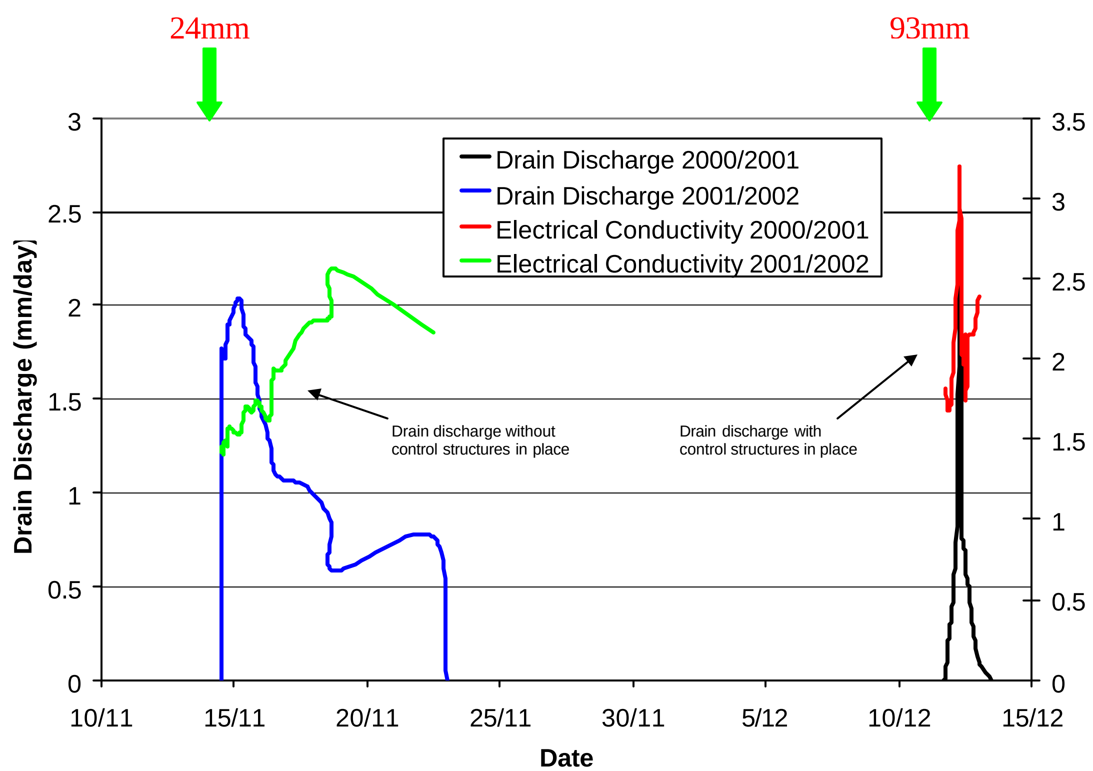


Figure 7-47. Drain discharge and electrical conductivity for the C2 treatment over the experimental period

Table 7-9. Water applied and drained for the C1 and C2 treatments during controlled and uncontrolled periods

Treatment	Drainage Status	Irrigation Applied (mm)	Drainage (mm)	Leaching Fraction (%)	Salt Applied (kg/ha)	Salt Removed (kg/ha)
C1	Controlled	142	1	1	90	12
	Uncontrolled	32	2	6	20	22
C2	Controlled	93	0.8	1	60	13
	Uncontrolled	24	2	8	15	26

It can be seen from Table 7-9 the control structures had a significant effect on reducing the drain flow and subsequently the amount of salt removed from the drainage system. During controlled periods drainage volumes were reduced by approximately 50% even though water applied was significantly higher than during uncontrolled periods.

Average mid-drain water table response under the C1 and C2 treatments for the controlled and uncontrolled periods are shown in Figure 7-48.

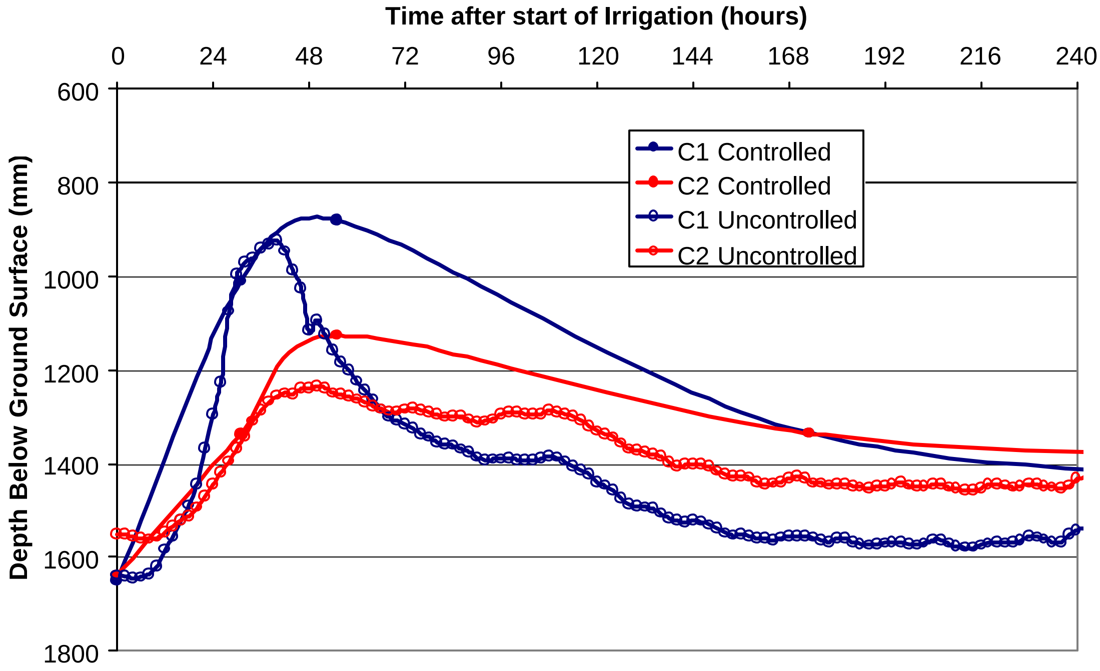


Figure 7-48. Average mid-drain spacing water table height during controlled and uncontrolled drainage periods

It can be seen that during controlled periods the water table was higher than uncontrolled periods, however the peak water table heights do not appear to be significantly higher, hence the potential for problems associated with waterlogging of the crop would not be increased significantly with the use of controlled drainage.

Total drained amounts and the volume of salt removed from the treatments during each of the irrigation seasons is shown in Table 7-10 for the three treatments. Salt volumes were calculated based on the relationship of 1dS/m = 640mg/L (Tanji 1991) for the irrigation and drainage waters and salt content of the rainfall was taken as 6.9mg/L based on studies undertaken by Blackburn and McLeod (1983) in the Griffith area.

Table 7-10. Drainage volumes and salt loads for the three treatments over the experimental period

Treatment	Irrigation Season	Water Applied (mm) Rainfall (mm)	Irrigation (mm)	Drainage (mm)	Salt Applied (kg/ha)	Salt Removed (kg/ha)	Ratio
F	**2000/2001**	292	348	21	332	428	1.3
	2001/2002	172	290	13	272	180	0.66
C1	**2000/2001**	292	340	1	325	12	0.04
	2001/2002	172	354	1.8	329	22	0.07
C2	**2000/2001**	292	317	0.8	304	13	0.04
	2001/2002	172	348	2	324	26	0.08

It can be seen that the free drainage treatment (F) had significantly higher drainage volumes and subsequently salt loads than the controlled drainage treatments (C1 and C2). Drainage volumes measured during the experimental period were considerably lower than those typically found in subsurface drained fields in the area. This was largely due to significantly lower volumes of irrigation water applied to the treatments than is generally considered normal. For the free drainage treatment drainage volumes were only 3 and 2 % of total water applied to the treatment over the 2000/2001 and 2001/2002 irrigation seasons and this is well below values reported in previous studies. Previous monitoring of tile drainage systems in the area reported by Christen and Skehan (2000), Christen and Skehan (2001) and van der Lely (1993) measured drainage volumes between 14-22% of applied water. The large differences between these studies and results shown above were due to firstly irrigation volumes being considerably less in this study <350mm compared to 600 to 1000mm for the previous studies and secondly average rainfall during the experimental period (322mm for 2001 and 208mm for 2002) was well below average (396mm). The lower irrigation volumes applied to the treatment were due to high costs of available irrigation water and low returns for the Cabernet Sauvignon vine grapes grown on the free drainage treatment during the course of the experimental period.

However, considering this it can be seen by monitoring individual recharge events as shown above that the controlled drainage treatments were able to significantly lower drainage volumes and subsequently lower salt loads generated, which ultimately need to be disposed.

It can be clearly seen that the controlled drainage was effective in increasing water table heights in the controlled drainage treatments and the structural modification of the drainage system was successful in achieving this aim. This reduction in drainage had the benefit of reducing disposal problems due to the decreased drainage volumes and subsequent lower salt loads. However, two issues are therefore raised considering the suitability of controlled drainage. These are firstly, if controlled drainage management is to be successful then it relies on the crop being able to successfully use water from the water table in order for it to meet part of its evapotranspiration requirements. The next section addresses this question and investigates the potential of Vitis Vinifera (grapevines) to use shallow groundwater to meet part of the evapotranspiration requirements.

Secondly, it can be seen from Table 7-10 that salt accumulation occurred in the controlled drainage treatments. Therefore, the effects of controlled drainage on soil salinity levels need to be thoroughly investigated in order to determine the sustainability of the system.

7.2.3 Contribution of a Shallow Water Table to Crop Evapotranspiration

In order to determine the contribution of a shallow saline water table in meeting crop evapotranspiration needs, water balance studies were undertaken on the free drainage (F) and controlled drainage treatments (C1 and C2). Previous studies have shown the contribution of a shallow water table to plant evapotranspiration to be strongly related to water table salinity, hence the three drainage treatments were further divided into three blocks representing water table salinity levels. These blocks were areas of low salinity groundwater, medium salinity groundwater and high salinity groundwater and are shown Figure 4-16.

A water balance was then undertaken for each of the nine blocks in order to determine the contribution of capillary rise from the groundwater to crop evapotranspiration. This approach has been used by a number of authors for estimating the contribution of capillary rise to crop evapotranspiration (Ayars et al. 1999; Eching et al. 1994 & Wallender et al. 1979). The water balance equation can be given as:

$$\mathbf{ET_c = I + R + C - D \pm \Delta W} \qquad \textbf{Equation 7-1}$$

Where ET_c = Crop Evapotranspiration (mm)

I = Irrigation Application (Irrigation applied – Surface runoff) (mm)

R = Rainfall (mm)

C = Capillary Rise from the water table (mm)

D = Drainage (mm)

ΔW = Change in soil water storage (mm)

Each of the water balance components used to determine the capillary rise from each of the blocks are outlined in the following sections.

7.2.3.1 Evapotranspiration (ET_c)

In order to calculate evapotranspiration from the study area Bowen Ratio instrumentation was used to develop crop coefficients for the two grape varieties at the site during the 2001/2002 irrigation season. The controlled drainage treatments both had Semillon variety wine grapes whereas the free drainage treatment had Cabernet Sauvignon wine grapes. Plant water use of the two varieties is different due to the physiological characteristics of the varieties. The Semillon wine grapes have a higher evapotranspiration demand than the Cabernet Sauvignon wine grapes.

Crop coefficients were determined by the following relationship:

$$k_c = \frac{ET_c}{ET_o}$$ **Equation 7-2**

where k_c = Crop Coefficient

ET_c = Evapotranspiration of the crop measured with the Bowen Ratio instrumentation

ET_o = Reference crop evapotranspiration

The reference crop evapotranspiration was determined from the CSIRO weather station using the modified Penman formula, with Meyer wind function coefficients (Meyer, 1998). This weather station is situated approximately 4 km from the experimental site and was considered suitable due to the general homogeneous of the area.

During the 2001/2002 irrigation season the Bowen Ratio instrumentation was situated in the Semillon wine grape area (as shown in Figure 4-16) in the center of block C1M to directly measure crop evapotranspiration. For a one week period from the 29/10/2001 to 5/11/2001 it was placed in the Cabernet Sauvignon wine grapes in the center of block FM for determination of early season crop coefficient and for a three week period from 22/02/2002 to 14/03/2002 for determination of a mid season crop coefficient.

Figure 7-49 shows the calculated k_c for the Semillon wine grapes for the 2001/2002 irrigation season. It can be seen that there are two distinct periods in which the crop coefficient is different. This being an initial period (k_{ini}) from Budburst to leaf separation in which the crop coefficient is on average 0.7 and during the major part of the growing season (k_{mid}) in which the crop coefficient is on average 0.85. The variation (noise) associated with the calculated k_c values is expected. ET_o estimates based on the Penman method are generally not reliable for daily calculation of the ET due to the uncertainties of soil heat flux diurnal variation and other small discrepancies between measured parameters and terms used in the equation. The Penman equation lacks the inclusion of a term to account for heat storage, however this shortcoming tends to average out over an extended period of time (week to ten days) (Faulkner, 1996). Therefore this explains the noise associated with the calculated k_c values when using Equation 7-2. Also shown in Figure 7-49 are the irrigation application dates and significant rainfalls (>30mm). It can be seen that there is a strong relationship of the k_c with irrigation application, with a general decrease in k_c occurring after irrigation and rainfall events. Similar results have been reported by Stevens and Harvey (1996) who investigated the relationship between soil water depletion rates and ET_o values on Colombard grape vines on Ramsey rootstocks at Loxton, South Australia, under similar irrigated conditions. The authors observed similar trends between the relationship of soil water storage and ET_o, with the ratio of change in soil water storage/ET_o decreasing linearly with declining soil water availability over the soil tension range 8-100 kPa. A similar pattern can be seen in Figure 7-49 with the highest evapotranspiration occurring immediately after irrigation and then declining linearly with time due to the decrease in soil moisture between irrigations.

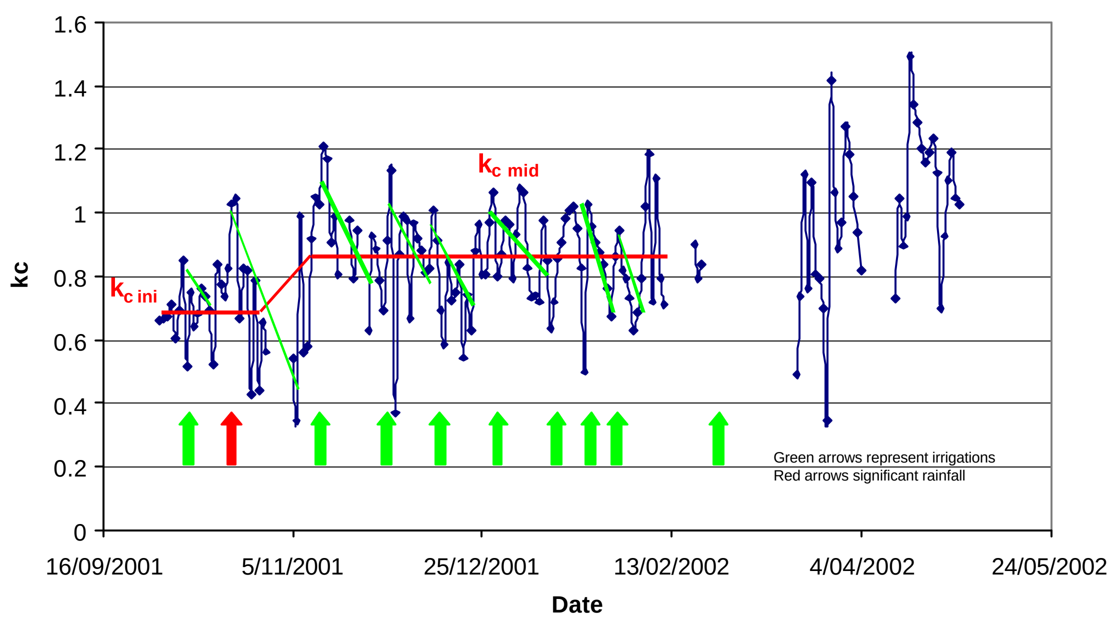


Figure 7-49. Calculated crop coefficient for the Semillon vines during the 2001/2002 irrigation season

The higher k_c values after April are due to inter row growth of grass after the irrigation season when the vines become dormant during the winter period.

The effect of interrow vegetation in vineyards has been studied by Yunusa, Walker and Guy (1997) in Red Cliffs, South Australia. Evapotranspiration components of the grapevines, cover crop and soil evaporation were measured for two irrigation seasons on sultana vines with rye grass and white clover establishing between the vine rows. Transpiration from the vines was measured with sap flow sensors and transpiration of the cover crop determined with mini-lysimeters. Soil evaporation was then determined from subtraction of these two terms from ET. The results showed that the cover crop contributed on average 33% of the measured evapotranspiration over the two monitoring periods, hence the increased k_c values shown in Figure 7-49 are most likely due to the establishment and growth of inter-row grasses which were a mixture of rye grass and native grasses.

Calculated crop coefficients for the Semillon vines appear to be representative and in general agreement with work undertaken by previous authors. Stevens and Harvey (1996) for similar white grape varieties however found much lower crop coefficients particularly during the early season with k_c values of 0.1,0.3,0.5,0.7,0.8,1.0,1.0,0.9 for the months from September to April respectively. This may have again been due to inter-row vegetation, which was not controlled under vine rows. Only the area between vine rows was ploughed and during the initial part of the season when the crop canopy of the vines was small grass was present in the vine row areas.

Recently, Williams et al. (2003) reported on water use of mature Thompson Seedless grapevines in the San Joaquin Valley of California. The four year study used lysimeters to determine crop coefficients and developed the following equation for determination of the crop coefficient based on degree days:

$$k_c = \frac{0.96}{\left(1 + e^{\frac{-(DD-373}{169}}\right)}$$

Equation 7-3

Where:

K_c = Crop Coefficient (unitless)

DD = Degree Days greater than 10^0c from 50% budbreak (^{0}C)

Williams et al. (2003)

Figure 7-50 shows a comparison between calculated crop evapotranspiration based on Stevens and Harvey (1996), Williams et al. (2003) and the data collected from the Energy Balance Instrumentation.

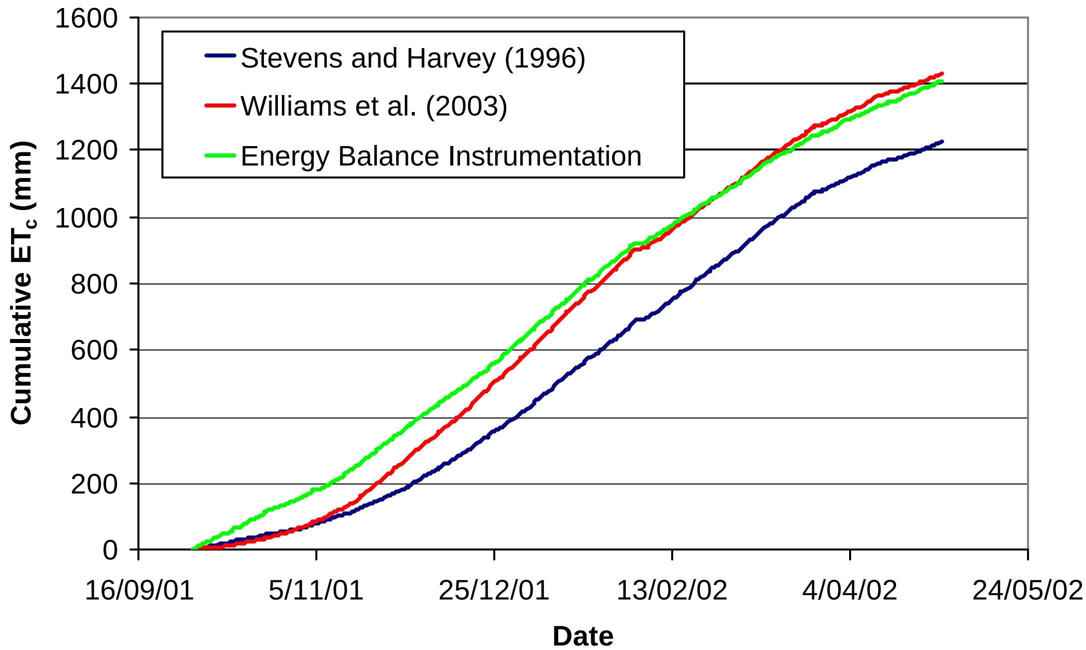


Figure 7-50. Vine water use for the Semillon vines predicted using the methods developed by Stevens and Harvey (1996), Williams et al. (2003) and that measured directly in this study during the 2001/2002 irrigation season

It can be seen that there is good agreement with the predictions made using crop coefficients developed by Williams et al. (2003) and that measured in the field, particularly during the later parts of the irrigation season. However, during the initial periods cumulative ET_c calculated with the Stevens and Harvey (1996) and Williams et al. (2003) crop coefficients are below that measured with the energy balance instrumentation. This is most likely due to the presence of grass growing beneath the vines, as stated earlier.

Figure 7-51 shows the calculated k_c for the Cabernet Sauvignon vines during the two periods when the Bowen Ratio instrumentation was present.

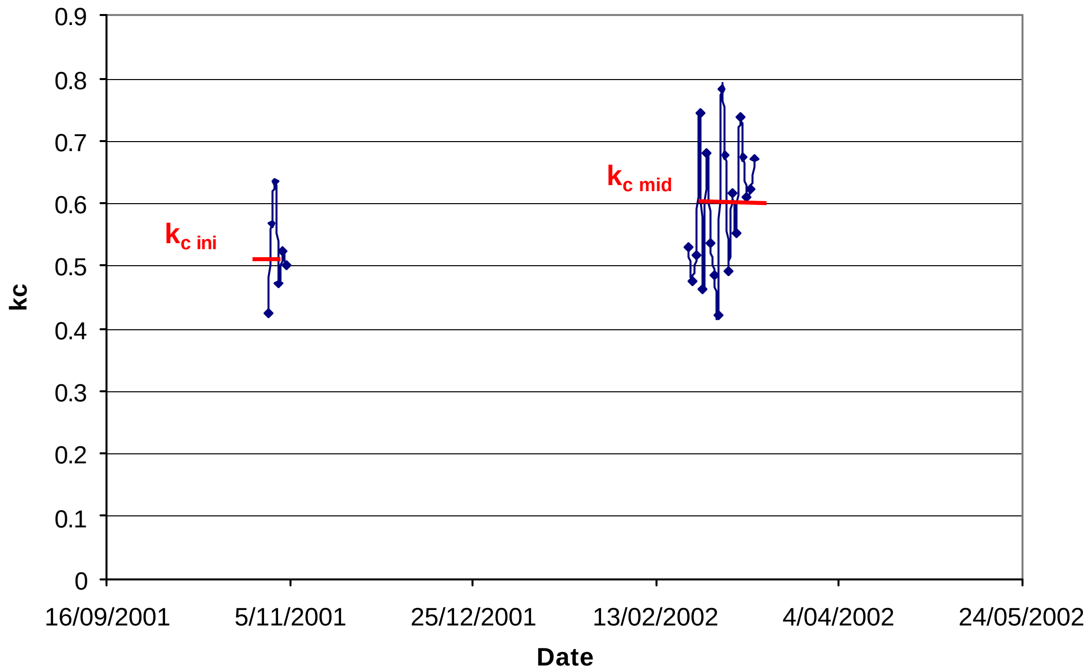


Figure 7-51. Calculated crop coefficient for the cabernet Sauvignon vines during the 2001/2002 irrigation season

The initial crop coefficient was measured as 0.52 and the mid season crop coefficient as 0.6. It must be remembered however that these calculated crop coefficients have been based on minimal data, particularly the initial crop coefficient which was only determined on a seven day period. However, data collected on Cabernet Sauvignon by Williams (2001) for similar vineyard layouts in California supports these calculated crop coefficients. He measured a mid season crop coefficient of 0.5.

It can be seen that the water requirements of the Semillon wine grapes located in the controlled drainage treatments (C1 and C2) had a much higher water demand than the Cabernet Sauvignon wine grapes located in the free drainage treatment (F).

Cumulative ET_c for the Cabernet Sauvignon and Semillon vines as measured in blocks FM and C1M respectively are shown in Figure 7-52 for the 2000/2001 and 2000/2002 irrigation season. In the case of the Semillon vines in the 2000/2001 irrigation season and the Cabernet Sauvignon vines in both 2000/2001 and 2001/2002 irrigation seasons ET_c was calculated using the crop coefficients determined above with the energy balance instrumentation and ET_o data from the CSIRO weather station. ET_c for the Semillon vines in the 2001/2002 irrigation season is that directly measured with the energy balance instrumentation.

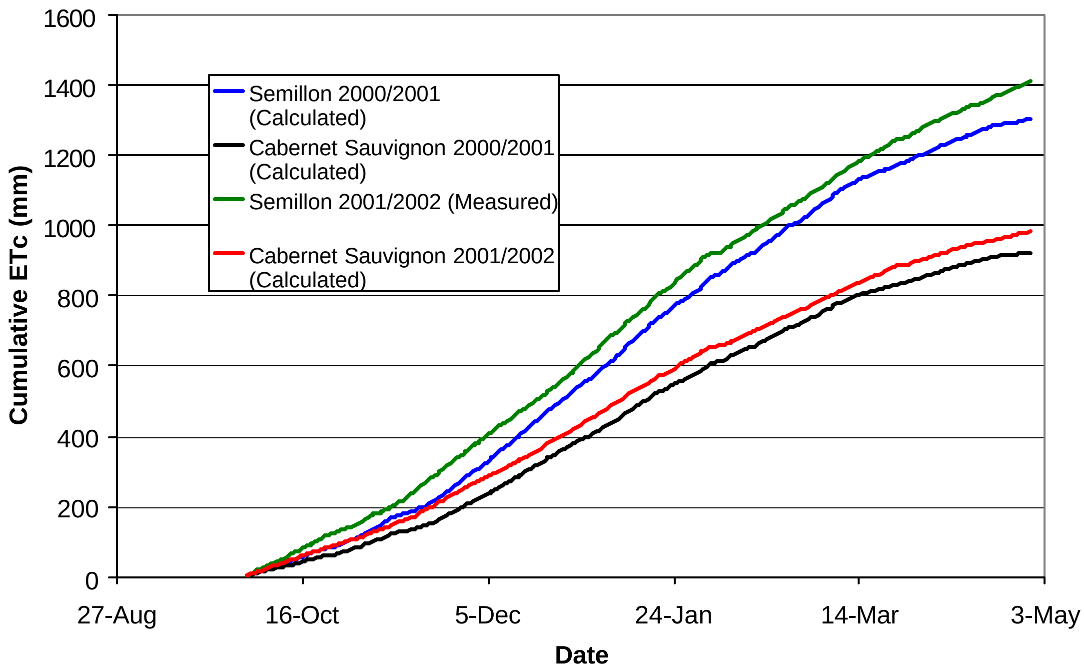


Figure 7-52. Cumulative water use over the 2000/2001 and 2001/2002 irrigation seasons for the Semillon and Cabernet Sauvignon vines

While these values of ET_c provide a realistic measure of ET_c when there are no other limiting factors such as diseases, pests or salinity it was apparent that in a number of blocks, particularly those in the high salinity areas, that ET_c were considerably less than these values. In order to determine ET_c in these blocks a water production function relating relative yield to relative ET_c was used. On blocks in which yields were lower than that measured in the C1M and FM blocks the crop coefficients where determined with the energy balance instrumentation, then ET_c was determined based on the water production function developed by Grimes and Williams (1990). The relationship was given by:

$$ET_{adj.} = 1.02459 ET_{max.} \left(\frac{Y_{adj.}}{Y_{max.}} \right)^{2.44498778}$$

Equation 7-4

Where:

$ET_{adj.}$ = ET_c associated with $Y_{adj.}$ (mm)
$ET_{max.}$ = ET_c associated with maximum yield (mm)
$Y_{adj.}$ = Yield measured at specified area (kg/ha)
$Y_{max.}$ = Yield measured at maximum ET_c

The yields were determined at three positions in each of the blocks and the average yield used to determine an estimate of ET_c in blocks that had lower yields than those measured in the FM and C1M blocks. The assumption was made that blocks that produced higher yields than the FM and C1M blocks still had the same ET_c as that measured in the FM and C1M blocks. This assumption was based on the fact that the water production function developed by Grimes and Williams (1990) had a maximum yield of 30t/ha (18.36 kg/vine equilivalent) and the higher yields were above this figure, and secondly at higher relative yields approaching values of 0.8 to 1.1 the relationship was not as strong as can be seen from Figure 7-53 taken from Grimes and Williams (1990). So addition of extra water after maximum yield is reached gives no extra yield.

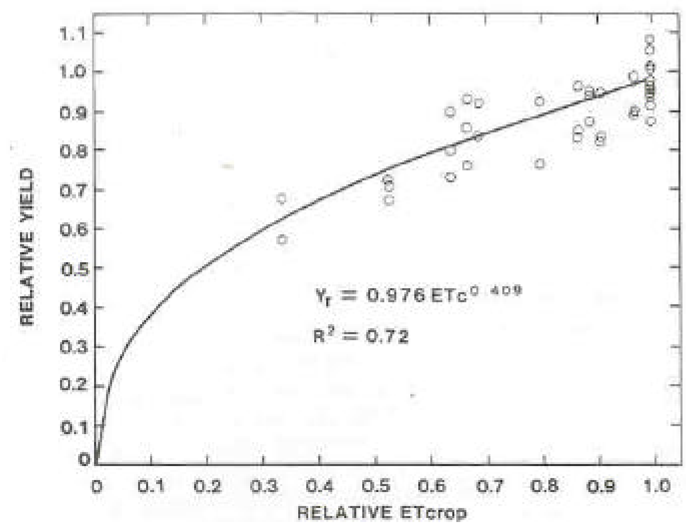


Figure 7-53. Water production function relating relative yield (Observed yield / maximum yield) to relative crop evapotranspiration (Observed evapotranspiration / maximum evapotranspiration), after Grimes and Williams (1990)

ET_c determined for each of the blocks during both the 2000/2001 and 2001/2002 irrigation season are shown in Table 7-13. It can be seen that variation in ET_c was large throughout the blocks and this was influenced by the crop cover in each of the blocks.

This method using crop yield to determine ET_c has been used by a number of authors for determining ET_c (Ayars et al. 1999; Eching et al. 1994; Soppe 2000 & Wallender 1979) in water balance studies for determining the contribution of capillary rise to crop evapotranspiration.

7.2.3.2 Water Applied

Water applied to the treatments was measured using circular flumes (Samani, Jorat & Yousaf 1991). Three furrows in each treatment were monitored and the water applied determined. In order to investigate the distribution of the water down the furrow, which was non-uniform, due to the long length of the furrow (618m) the SIRMOD model (Walker, 1999) was used. Previous studies undertaken by Hornbuckle (1999) and Hornbuckle, Christen and Faulkner (2003) have shown the model to adequately simulate furrow irrigation events on the soil types and management conditions typically found in the area. Inputs into the model are given in Table 7-11. Infiltration characteristics for the treatments were determined using advance data taken on each of the furrows during irrigation events and the Infiltv5 program (McClymont and Smith 1996) used to calculate the Kostiakov-Lewis infiltration parameters, which are used in the SIRMOD model.

Table 7-11. Field characteristics used in the SIRMOD model for determination of applied water

Field Geometry/Topography	Manning n	0.06-0.02
	Slope	0.0005
	Field Length (m)	618
	Field Width (m)	242
Furrow Cross Section	Top Width (m)	0.5
	Middle Width (m)	0.35
	Bottom Width (m)	0.15
	Maximum Depth (m)	0.15

Simulations for each irrigation event were undertaken for both the 2000/2001 and 2001/2002 irrigation seasons and average depth of applied water taken from the three furrows in each treatment is shown in Figure 7-54.

It can be seen that during the 2000/2001 irrigation season both the F and C1 treatments had similar amounts of applied water, however distribution uniformity was marginally improved in the C1 treatment. The C2 treatment had less water applied then the F and C1 treatments until a distance of 510m down the furrow when the improved distribution uniformity of the C2 treatment increases the volume of applied water above the F treatment. The improved distribution uniformity can be attributed to the irrigation method of the C2 treatment, which in three of the irrigations used higher furrow inflow rates (1.7-1.9L/s) compared to the other treatments (0.75-0.95 L/s), which saw an improved distribution uniformity.

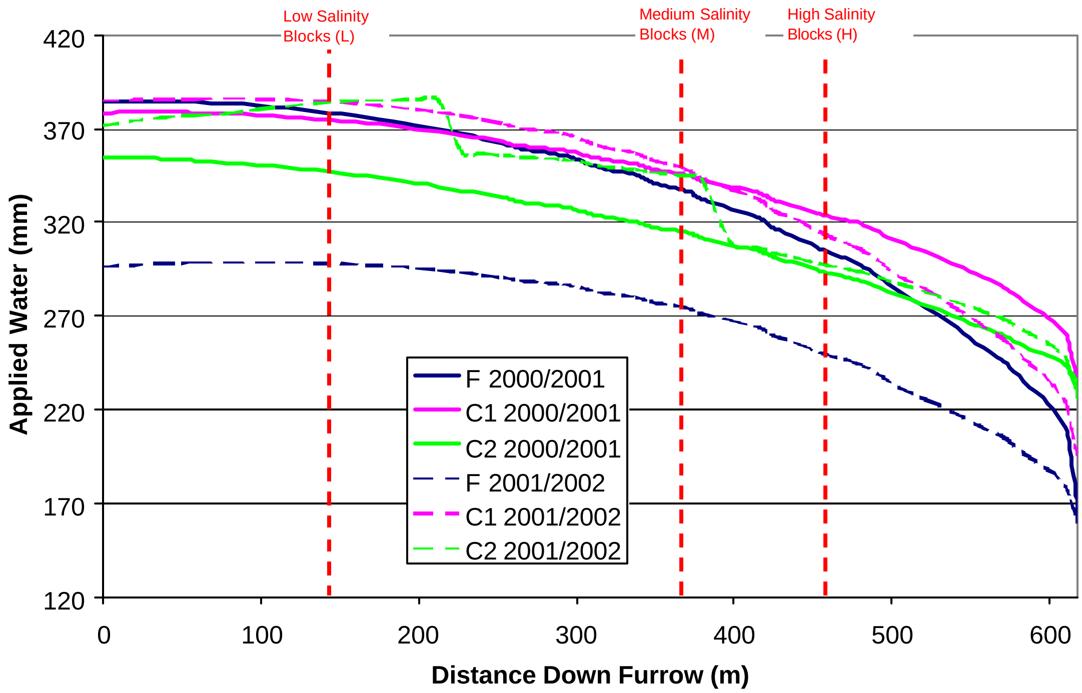


Figure 7-54. Cumulative applied water for each of the treatments for the 2000/2001 and 2001/2002 irrigation seasons as a function of distance down the furrow, also shown are high, medium and low salinity blocks in each treatment

During the 2001/2002 irrigation season a drop in price of Cabernet Sauvignon wine grapes and a general lack of water due to drought conditions resulted in the farmer reducing the volume of water applied to the F treatment.

The step like nature of the cumulative applied water in the C2 treatment in 2001/2002 was due to two additional irrigations being applied to this treatment in partial blocks with the first block extending to a distance 200m down the treatment, and the second block extending a distance 386m down the treatment. Blocked end furrows were used and this explains the slight increase in water applied down the treatment until a 200m distance, where the blocked end furrows were situated for the additional irrigation. Applied irrigation water amounts as taken from Figure 7-54 for each of the blocks is given in Table 7-13 along with rainfall measured with a tipping bucket gauge rain gauge.

7.2.3.3 Soil Moisture

Change in soil moisture during the experimental period was monitored in blocks using neutron probe measurements in the F and C2 treatments. In the C2 treatment where no access tubes were installed gravimetric soil water contents were determined by soil coring and converted to volumetric soil moisture contents. One 1.2m core was taken in each block next to the test well at mid-drain spacing and gravimetric water content determined. These readings were then converted to volumetric soil moisture contents and change in soil water calculated for a 0-2.0m depth. Results are presented in Table 7-12.

In both the 2000/2001 and 2001/2002 irrigation season there was a loss in available water for each of the blocks ranging from 45mm to 93mm.

Table 7-12. Change in soil moisture over the 2000/2001 and 2001/2002 irrigation seasons

Treatment	Soil Layer	Depth of Sample	2000/2001		2001/2002		2000/2001	2001/2002
			$q_{Initial}$	q_{Final}	$q_{Initial}$	q_{Final}	D Available Water	D Available Water
	(m)	(m)					(mm)	(mm)
FL	**0-0.35**	0.25	0.39	0.30	0.38	0.23	29	50
	0.35-0.75	0.5	0.38	0.31	0.39	0.32	26	26
	0.75-1.0	0.9	0.34	0.29	0.33	0.29	11	10
	1.0-2.0	1.1	0.38	0.37	0.37	0.36	16	7
	0-2.0						**83**	**93**
FM	**0-0.35**	0.25	0.35	0.29	0.34	0.30	20	15
	0.35-0.75	0.5	0.39	0.31	0.37	0.30	31	28
	0.75-1.0	0.9	0.36	0.32	0.37	0.32	9	13
	1.0-2.0	1.1	0.35	0.35	0.34	0.30	5	35
	0-2.0						**65**	**90**
FH	**0-0.35**	0.25	0.38	0.33	0.36	0.34	19	8
	0.35-0.75	0.5	0.37	0.34	0.38	0.36	10	8
	0.75-1.0	0.9	0.36	0.33	0.35	0.36	8	-4
	1.0-2.0	1.1	0.37	0.34	0.36	0.32	28	42
	0-2.0						**65**	**55**
C1L	**0-0.35**	0.25	0.35	0.27	0.31	0.24	28	25
	0.35-0.75	0.5	0.34	0.31	0.36	0.30	12	25
	0.75-1.0	0.9	0.33	0.28	0.36	0.32	12	9
	1.0-2.0	1.1	0.36	0.33	0.38	0.34	34	35
	0-2.0						**87**	**94**
C1M	**0-0.35**	0.25	0.37	0.28	0.37	0.29	33	28
	0.35-0.75	0.5	0.38	0.27	0.36	0.32	44	16
	0.75-1.0	0.9	0.30	0.33	0.36	0.33	-7	7
	1.0-2.0	1.1	0.34	0.32	0.39	0.37	23	20
	0-2.0						**93**	**71**
C1H	**0-0.35**	0.25	0.42	0.31	0.40	0.27	39	43
	0.35-0.75	0.5	0.37	0.33	0.36	0.29	15	28
	0.75-1.0	0.9	0.33	0.32	0.30	0.29	3	3
	1.0-2.0	1.1	0.38	0.37	0.38	0.37	10	7
	0-2.0						**67**	**82**
C2L	**0-0.35**	0.25	0.38	0.28	0.39	0.27	35	41
	0.35-0.75	0.5	0.38	0.31	0.39	0.34	26	19
	0.75-1.0	0.9	0.34	0.30	0.36	0.34	11	3
	1.0-2.0	1.1	0.38	0.35	0.38	0.35	22	28
	0-2.0						**94**	**91**
C2M	**0-0.35**	0.25	0.39	0.31	0.38	0.27	29	39
	0.35-0.75	0.5	0.37	0.29	0.36	0.31	32	23
	0.75-1.0	0.9	0.33	0.32	0.37	0.29	2	19
	1.0-2.0	1.1	0.37	0.35	0.38	0.39	15	-9
	0-2.0						**78**	**72**
C2H	**0-0.35**	0.25	0.38	0.30	0.36	0.29	27	23
	0.35-0.75	0.5	0.37	0.31	0.34	0.30	24	15
	0.75-1.0	0.9	0.35	0.30	0.38	0.29	12	23
	1.0-2.0	1.1	0.34	0.32	0.36	0.33	18	25
	0-2.0						**81**	**86**

It appeared that larger reductions in available water occurred in the less saline areas. There did not appear to be large differences between seasons in the available water loss for given blocks.

7.2.3.4 Subsurface Drainage

Subsurface drainage was measured from each of the treatments and the assumption made that drainage was equivalent for each of the blocks within the treatment. Drainage volumes are as shown previously in Table 7-10. While in reality this assumption would most likely not be the case, the relatively small amounts of drainage measured during the experimental period would only have a very small effect on the water balance equation and subsequent determination of capillary rise contribution to crop evapotranspiration. This is particularly true in the C1 and C2 treatments where controlled drainage was implemented and drainage volumes were very small.

7.2.3.5 Crop Water Use from the Watertable

Each of the above components of the water balance is shown in Table 7-13. The capillary rise contribution to crop evapotranspiration was then determined based on water balance closure and results shown in Table 7-13.

Table 7-13. Water balance for each irrigation season on the treatments over the experimental period

Treatment	Grape Variety	Evapotranspiration (mm)		Irrigation (mm)		Rainfall (mm)		Soil Water (mm)		Drainage (mm)		Capillary Rise (mm)		% ETc from Capillary Rise	
		2000/2001	2001/2002	2000/2001	2001/2002	2000/2001	2001/2002	2000/2001	2001/2002	2000/2001	2001/2002	2000/2001	2001/2002	2000/2001	2001/2002
FL	**Cab. Sav.**	676	983	368	297	292	172	83	93	21	13	-46	434	0	44
FM	**Cab. Sav.**	923	983	335	274	292	172	65	90	21	13	252	460	27	47
FH	**Cab. Sav.**	209	175	311	248	292	172	65	55	21	13	-438	-287	0	0
C1L	**Semillon**	1301	1409	370	380	292	172	87	94	1	1.8	553	765	43	54
C1M	**Semillon**	1301	1409	324	337	292	172	93	71	1	1.8	593	831	46	59
C1H	**Semillon**	1040	831	285	302	292	172	67	82	1	1.8	397	277	38	33
C2L	**Semillon**	1301	1409	340	385	292	172	94	91	0.8	2	576	763	44	54
C2M	**Semillon**	370	415	303	308	292	172	78	72	0.8	2	-302	-135	0	0
C2H	**Semillon**	402	171	282	292	292	172	61	45	0.8	2	-232	-336	0	0

The water balance was assumed to start on the 1/10 and close on the 1/5, a total growing period of 212 days. It can be seen that there was a wide variation in evapotranspiration over the treatments. The more saline areas had restricted vegetative growth reducing transpiration rates and hence lowering evapotranspiration. Based on these results water table contribution to crop evapotranspiration varied between 0 % and 59 % over the experimental period. Larger contributions were present during the 2001/2002 irrigation season, this was due to higher evapotranspiration during the irrigation season and lower rainfall. What can be seen from the water balance studies was that drainage was a very small component of the water balance having little effect on the calculated contribution of capillary rise to evapotranspiration for the period measured in the study.

The largest component of the water balance equation was clearly the evapotranspiration hence accurate determination of this component is important as it has a large effect in the determination of the capillary rise when using a closure of the water balance. In assessing the contribution of capillary rise from a shallow water table to crop evapotranspiration it must be understood that a number of assumptions are taken within the water balance approach and it is difficult to adequately calculate all components of the water balance, indeed calculation of ET_c is a critical component of the water balance and in this study an effort was made to directly measure this component rather than use ET_c estimates. However, due to the high cost of such instrumentation a water production function relating yield and evapotranspiration was used to determine evapotranspiration in unmeasured areas. A number of authors (Ayars et al. 1999; Eching et al. 1994 & Wallender et al. 1979) have used this approach for determining the water table contribution to crop evapotranspiration. However, this can often lead to inaccuracies, particularly where there is a shallow watertable and a large amount of evapotranspiration occurring from soil evaporation. This factor could account for the large negative capillary rise values (recharge) calculated in Table 7-13. Considering there was very little drainage occurring from the treatments and these values may be related to the water production function not adequately representing ET_c in these areas.

Inaccuracies also exist in using the water balance method due to the complication of measuring each of the water balance components, and errors associated with measurement of the individual components of the water balance tend to be cumulative. Therefore, the values of capillary rise contribution to crop evapotranspiration should only be considered an estimate and not a definitive absolute value. What can be concluded from Table 7-13 is that there is potential for wine grapes to ultilise shallow saline water tables.

In considering the inaccuracies associated with the water balance model it is evident that a physical determination of the crop water use from the water table needs to be investigated, especially considering the large contributions determined with the water balance shown in Table 7-13. In order for these large estimates of crop water use from the water table to occur the water table needs to be at depth where it is available for the plant to use, and also at a salinity level that does not induce totally adverse osmotic stresses for the plant. The following section outlines water table and soil moisture responses that provide supporting evidence that such large contributions to crop evapotranspiration were achievable.

7.2.4 Water Table and Soil Moisture Responses

Water table response was measured over the experimental period in a total of 39 test wells installed in the field and also with four deep piezometers located outside the experimental area to investigate regional influences on water table. Positioning of the test wells is shown in Figure 4-16. There were 12 test wells installed in each treatment with five continuously monitored wells in each treatment.

Water table levels taken from the continuously monitored test wells in each treatment are shown in Figure 7-55 to Figure 7-59.

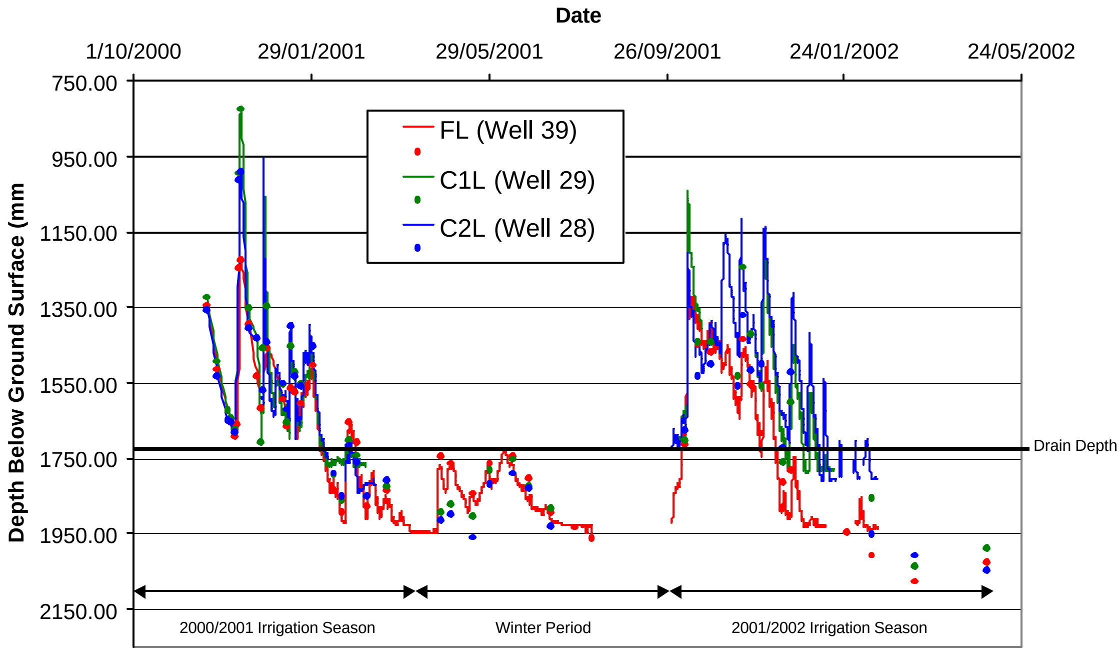


Figure 7-55. Water table level as measured in test wells 39, 29 and 28 over the experimental period, corresponding to near drain positioning at the supply end

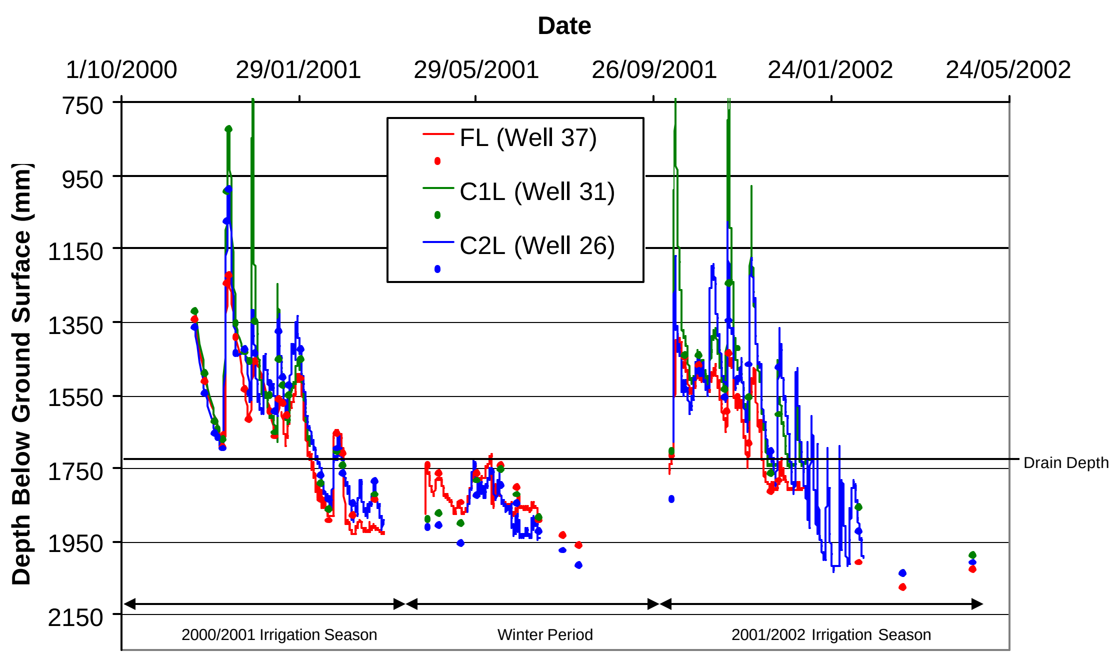


Figure 7-56. Water table level as measured in test wells 37, 31 and 26 over the experimental period, corresponding to mid drain positioning at the supply end

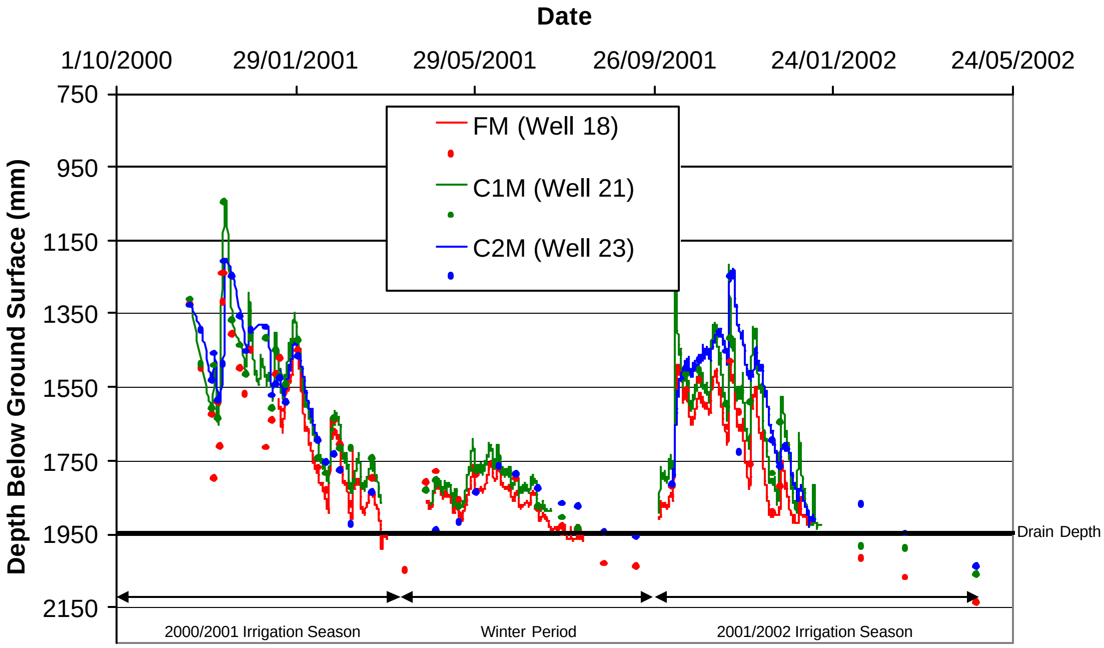


Figure 7-57. Water table level as measured in test wells 18, 21 and 23 over the experimental period, corresponding to mid drain positioning in the center of the treatment

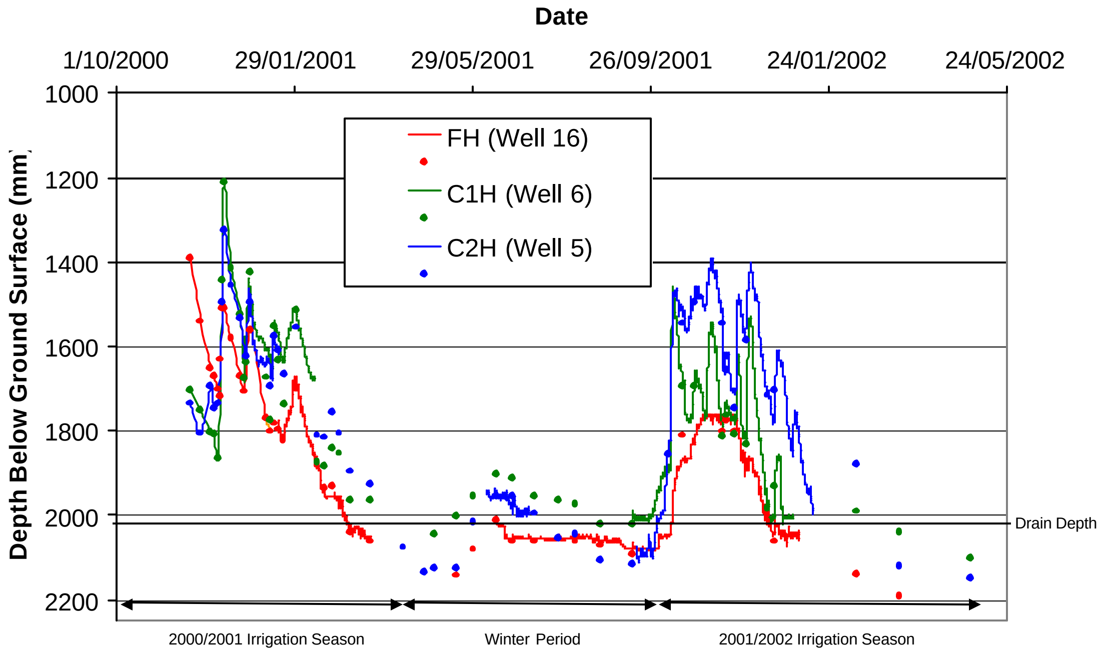


Figure 7-58. Water table level as measured in test wells 16, 6 and 5 over the experimental period, corresponding to near drain positioning at the outlet end

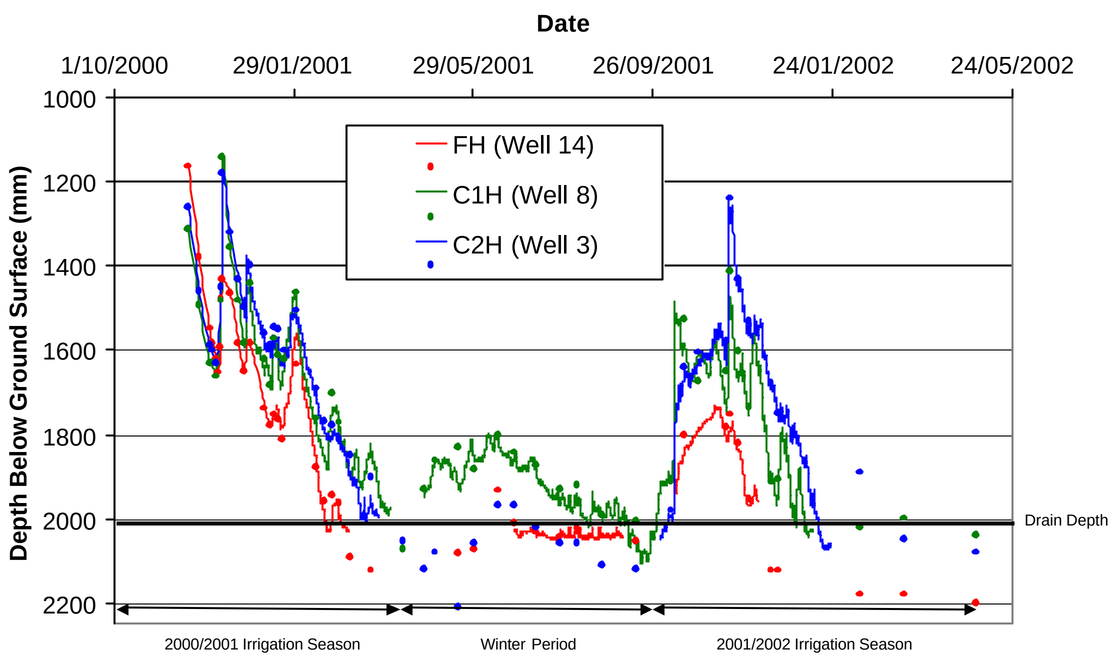


Figure 7-59. Water table level as measured in test wells 14, 8 and 3 over the experimental period, corresponding to mid drain positioning at the outlet end

It can be seen from Figure 7-55 to Figure 7-59 that the greatest differences between water table treatments occurred at the outlet end of the field (Figure 7-58, Figure 7-59), with smaller differences between treatments occurring at the supply end of the treatments. This is due to the drain depth varying from 1.65 to 2.2m from the supply end to the outlet end of the treatments. Hence, lowering of the water table occurs to a much greater depth at the outlet end of the treatment, and results in a much greater difference between the depth of the water table in the F treatment compared to the C1 and C2 treatments. Greater differences were also found, as expected, when comparing water table depths near the drain to those at mid spacing between the treatments. A larger difference was found between the F and C1 and C2 treatments near the drain than at mid spacing in the L and H blocks. This can be explained by an increased mid spacing water table height which occurs with the FL treatment where the drains have been allowed to flow freely. An essentially parabolic water table shape occurred with the free drainage treatment, F, and a flat water table shape under the controlled drainage treatments, C1 and C2.

Table 7-14 shows the average depth to water table for each of the blocks determined using well data collected from the well at mid-drain spacing in each of the treatment blocks. It can be seen that for the controlled drainage treatments there was very little difference in water tables depths for each of the treatment blocks. There was, however, a larger variation in the free drainage treatment particularly in the FH block and this can be attributed to the deeper depth of the drain in this block due to the gradient of the drainage line. Since no control structures were placed on the free drainage treatment then a large drawdown could be expected in the FH block due to a deeper depth to the drain compared to the FM and FL blocks which are up gradient of the drain line (Figure 4-12).

Average depth to water table was higher in the 2000/2001 irrigation season than in the 2001/2002 irrigation season and this may have been due to a greater irrigation deficit in the 2001/2002 causing increased use of the shallow groundwater, hence lowering the water table.

Also shown is the average electrical conductivity of the water table in each block determined from five sampling events taken over the duration of experimental period in the irrigation seasons.

Table 7-14. Average depth to water table during each of the irrigation seasons determined from mid-drain water table height in each block and average electrical conductivity of the water table

	Average Depth to Water Table (mm)		Average EC (dS/m)	
Block	**2000/2001**	**2001/2002**	**2000/2001**	**2001/2002**
FL	1.54	1.72	2.2	2.4
FM	1.55	1.78	1.5	1.3
FH	1.62	1.95	5.96	8
C1L	1.54	1.78	1.8	1.7
C1M	1.49	1.69	0.9	1.2
C1H	1.5	1.57	4	4
C2L	1.55	1.7	1.8	1.8
C2M	1.48	1.67	7.6	5.9
C2H	1.51	1.67	13.8	11.6

Since there was not a particularly large variation in water table depths under each of the blocks, apart from the FH block, the salinity level of the ground water is most likely the major factor contributing to the potential of vines to use a saline groundwater resource in this field situation.

Figure 7-60 shows the relationship between the percentage contribution of capillary rise to crop evapotranspiration as measured over the two irrigation seasons.

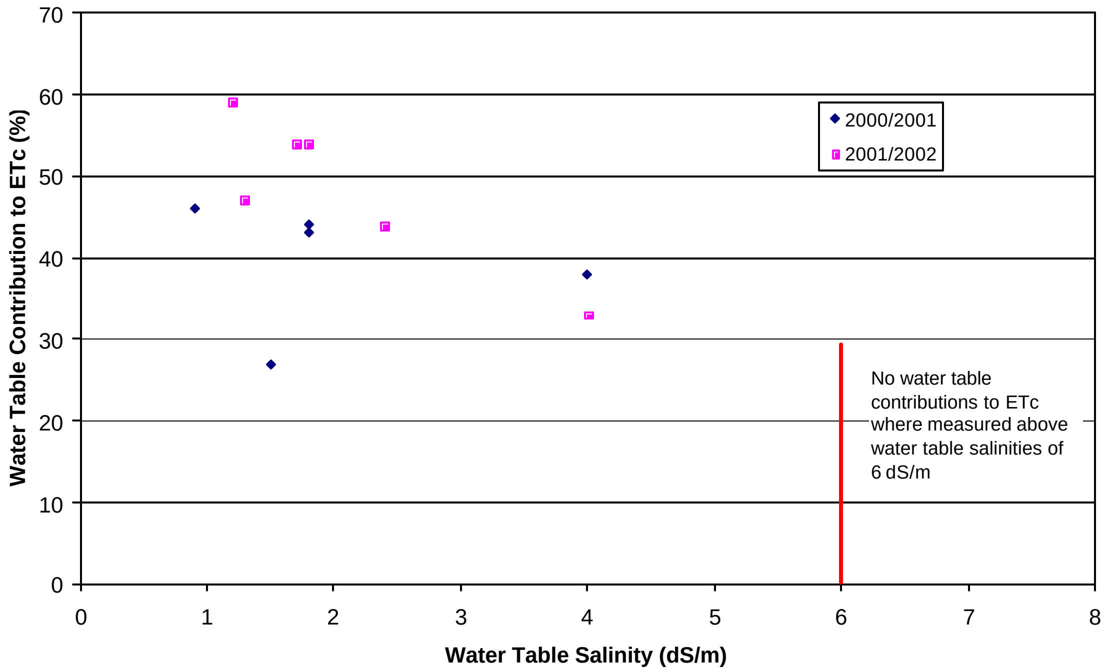


Figure 7-60. Relationship between groundwater use and salinity of the water table

It can be seen that there appears to be a relationship between the water table salinity and contribution of capillary rise to crop evapotranspiration, with water table contribution to evapotranspiration decreasing steadily until approximately 4 dS/m and then declining rapidly to zero after 6 dS/m. No contribution of capillary rise to evapotranspiration was calculated in this experiment at groundwater salinity levels above 4 dS/m. This relationship is expected as an increase in water table salinity will essentially reduce plant vigour and hence lead to smaller canopy sizes and reduced evapotranspiration demands. Based on the data in Figure 7-60 it appears that contributions to vine evapotranspiration can occur from shallow water tables at groundwater salinity levels up to approximately 6 dS/m. However, at levels above 4 dS/m the potential for vine water use from a shallow saline water table appears to decrease significantly with no contributions being measured at water table salinities above 6 dS/m.

It can also be seen from Figure 7-55 to Figure 7-59 that the change in water table over the irrigation seasons is in the order of 500mm to 1000mm, depending on the treatment, with a general trend of decreasing water table height as the irrigation season progresses.

Considering the water table decline was between 500 to 1000mm then the contribution this would have to crop evapotranspiration would be in the order of 25 to 50mm considering an air filled porosity of 0.05%. Hence, in order for the water table to be contributing the significant volumes of water to evapotranspiration as calculated with the water balance approach, external sources of groundwater must be supplying water to the water table during the irrigation season.

Regional ground water levels were monitored over the experimental period at Department of Water Resources (DWR) Bores, which form part of the regional water table monitoring network. The bores were 9.5 and 11.3m deep for Bore DWR 205 and DWR 206 respectively and were screened over the bottom 1m. Figure 7-61 shows the ground water levels as measured in the bores over the irrigation seasons along with the water table level measured in well 21 located in the centre of the experimental field. It can be seen that the bores were considerably higher than the field water tables over the duration of the experiment particularly during the irrigation periods. This provides support for the theory that the ground water contribution to crop evapotranspiration occurred due to regional pressures, which maintained the water table and hence allowed capillary rise to supply a significant portion of the crop evapotranspiration. It can be seen that the regional bores followed the trend of decreasing pressures over the winter period, when irrigation was not occurring, and increasing pressures with the start of the irrigation season. During the irrigation season a gradual decrease in pressure occurred with the progression of the irrigation season.

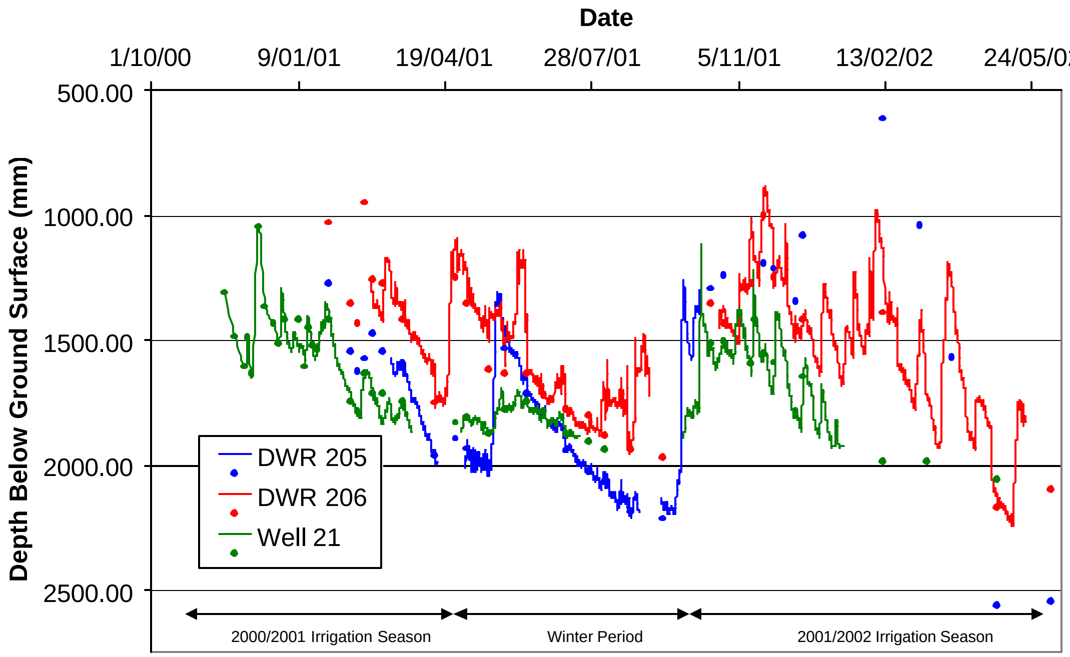


Figure 7-61. Regional water table level measured in deep piezometers surrounding the experimental site

Data was also available for the DWR bores from 1995 onwards which is shown in Figure 7-62. Bores DWR 696 and DWR 697 are located approximately 1 and 1.5 km away from the experimental site respectively. Although the regional bores are only monitored during September and March of each year, which may not include the periods of the highest pressures, it does show that during the course of the experimental period there was a general trend of decreasing groundwater pressures in the area. The reasons for this decrease are due to a number of factors including relatively dry periods from 2000 onwards plus a lack of rice growing in the area, which was present before1998.

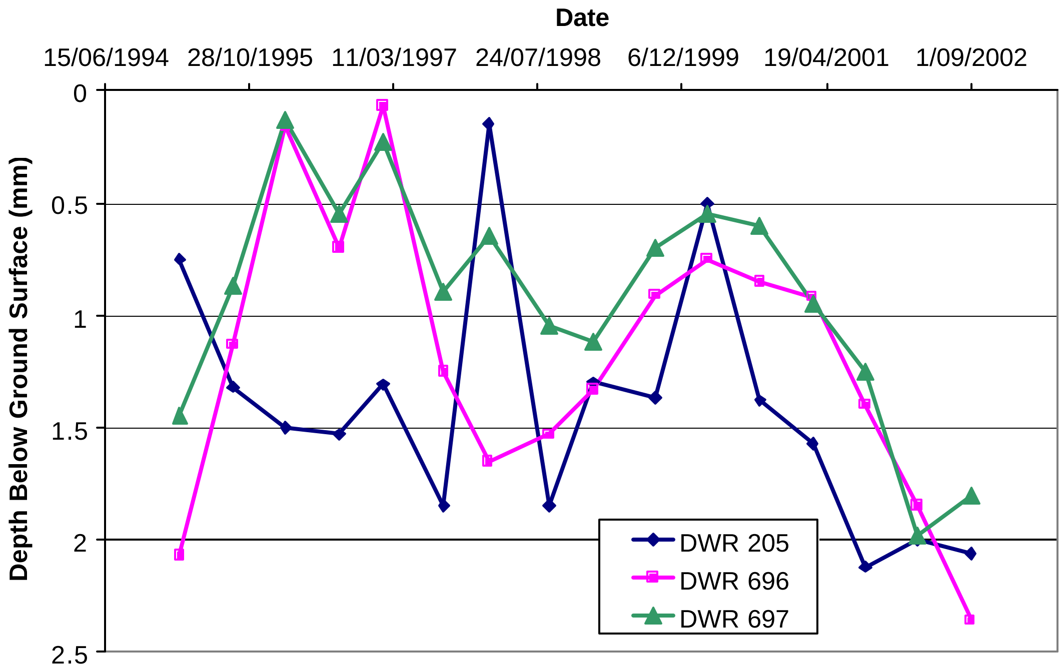


Figure 7-62. Regional ground water levels for the experimental area from 1995 to 2002

These factors all have consequences when aiming to maximize ground water contribution to crop evapotranspiration. Also due to regional influences there may be periods in which external sources of groundwater are not sufficient to the meet the needs of crop evapotranspiration, particularly when external sources of groundwater are not at sufficiently high levels to provide capillary rise into the plant rootzone to meet evapotranspiration. However, during the experimental period Figure 7-61 provides evidence that sufficient water would be available from the regional groundwater source to meet part of the evapotranspiration requirements of the vines.

Further evidence that the shallow groundwater was able to supply significant water to the vines can be seen from soil moisture measurements. Continuously logged watermark gypsum blocks were installed during the 2001/2002 irrigation season. Four depth intervals were monitored at positions in the block corresponding to on the drain and mid-drain spacing. Unfortunately, during the irrigation season there were periods when the dataloggers failed, during these periods tensiometer readings were used to fill in missing data. Tensiometer data, however, was only available for the 0.25, 0.5 and 0.9m depths, no 1.1m deep tensiometers were installed and periods when 1.1m depth soil moisture tensions are not shown correspond to the periods when tensiometer data was used. This data was collected on a less frequent basis (1-2 weeks) compared to the watermark data (1/2 hour intervals). Figure 7-63 and Figure 7-64 show the soil water tension measured in the C2L block at positions on the drain and at mid-drain spacing respectively.

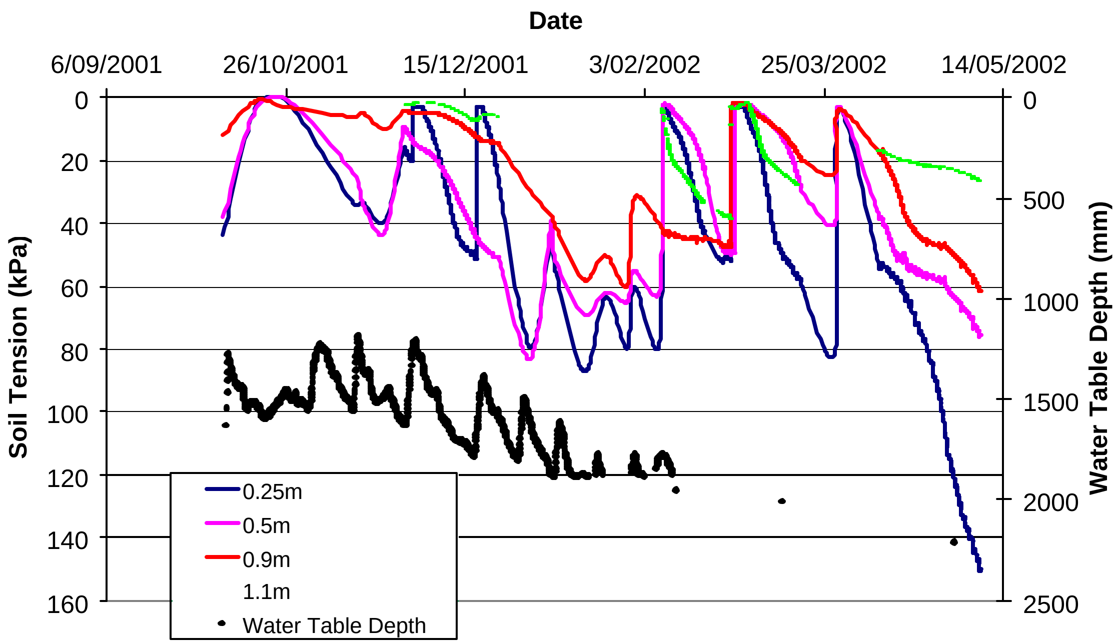


Figure 7-63. Soil water tension measured on the drain in the C2L block during the 2001/2002 irrigation season

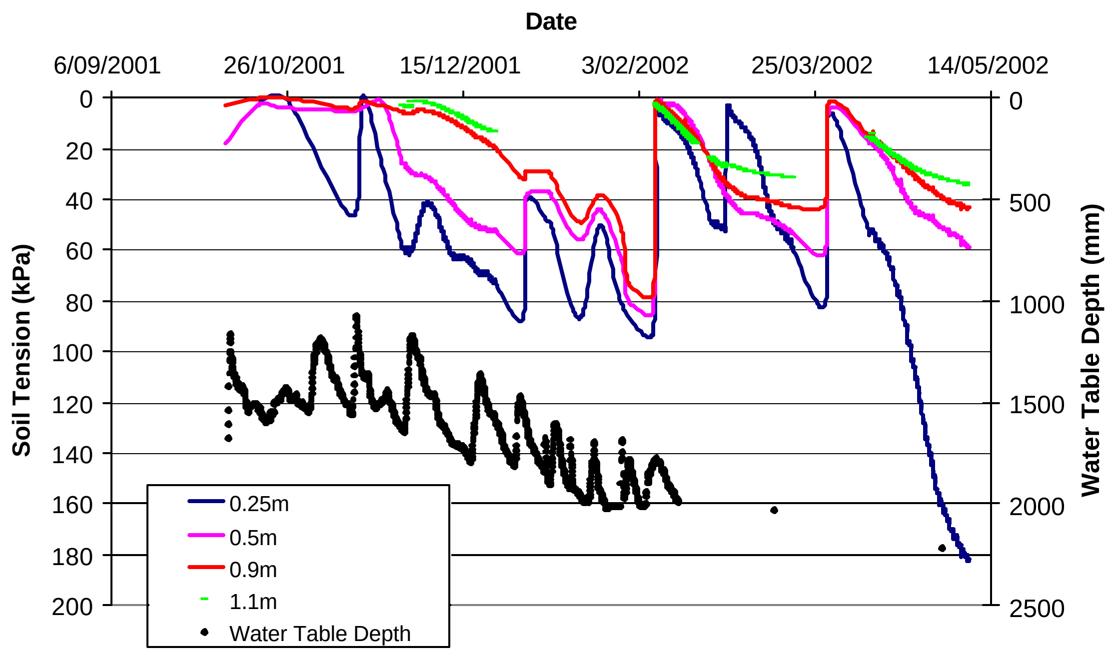


Figure 7-64. Soil water tension and water table depth measured at mid-drain spacing in the C2L block during the 2001/2002 irrigation season

It can be seen that even though there was a large deficit between crop evapotranspiration and water applied to the field (Table 7-13), soil water tensions are still relatively low throughout the duration of the irrigation season. It is only during the latter stages of the irrigation season that the soil tension gradually increases to high levels and this only occurs in the 0.25m depth where there would be little influence from a water table. At the deeper depths tensions remain above 60 kPa indicating an external source of water is maintaining these low tensions. This large increase in soil tension at the end of the irrigation season corresponds with the decline of the water table under the block as shown in Figure 7-55 and Figure 7-56. Unless there was a contribution from the water table then such large irrigation deficits should have caused a considerable increase in soil moisture tension, well above those measured during the experimental period. Indeed, at depths greater than 0.5m there were no periods when soil tension increased above 80 kPa. Considering the large irrigation deficit (Table 7-13) then soil moisture tensions should have been well above these levels.

7.2.5 Effects of Controlled Drainage Practices on Vine Yields and Soil Salinity

The previous sections have outlined the effect of controlled drainage on water tables, drainage flows and salt loads, and showed that there are considerable environmental benefits with using controlled drainage practices. It has also been shown that wine grapes have the potential to use significant amounts of water from a shallow groundwater resource, therefore the aims of controlled drainage of maintaining higher water table levels to promote water use from the water table and hence improve irrigation water use efficiency are valid. However, what still needs to be assessed is the effect of controlled drainage practices on yields and soil salinity which will determine the long-term sustainability of such options.

7.2.5.1 Effect on Yield

Yield was monitored during both irrigation seasons with hand harvesting undertaken over the test well between two vines. Three positions in each block corresponding to positions on the drain, ¼ drain spacing and ½ drain spacing were used in the yield determination. Berry weights were determined by randomly selecting 50 berries at each sample site and then averaging. Ten leaves selected from the first fully developed leaf on the cane were collected and oven dried and ground for determination of leaf chloride. Table 7-15 shows the yield, berry weight and leaf chloride changes over the two irrigation seasons.

Table 7-15. Yield, berry weight and leaf chloride changes over the two irrigation seasons

Treatment	Well No.	Yield (kg/Vine) 2000/2001	Yield (kg/Vine) 2001/2002	Berry Weight (g) 2000/2001	Berry Weight (g) 2001/2002	Leaf Chloride (mmol/kg) 2000/2001	Leaf Chloride (mmol/kg) 2001/2002	Change Between Seasons (%) Yield	Change Between Seasons (%) Berry Weight	Change Between Seasons (%) Cl^-
FL	37	10.5	20.9	1.2	1.3	79.0	78.0	98.9	10.7	-1.3
	38	7.3	17.7	1.1	1.1	112.0	91.0	142.5	-0.1	-23.1
	39	8.8	15.3	1.1	1.2	123.0	78.0	74.3	8.3	-57.7
Average		**8.9**	**18.0**	**1.1**	**1.2**	**104.7**	**82.3**	**105.2**	**6.3**	**-27.4**
FM	17	7.8	12.5	1.3	1.6	81.0	70.0	59.6	24.1	-15.7
	17b	15.2	25.4	1.5	1.7	84.0	53.0	67.1	12.1	-58.5
	18	7.9	12.1	1.8	2.7	87.0	75.0	51.8	47.0	-16.0
Average		**10.3**	**16.6**	**1.5**	**2.0**	**84.0**	**66.0**	**59.5**	**27.7**	**-30.1**
FH	14	9.2	10.8	1.1	0.9	154.0	122.0	17.5	-17.9	-26.2
	15	4.4	8.0	0.8	0.8	180.0	116.0	82.8	4.6	-55.2
	16	3.0	2.3	0.6	0.7	191.0	157.0	-23.7	16.8	-21.7
Average		**5.5**	**7.0**	**0.8**	**0.8**	**175.0**	**131.7**	**25.5**	**1.2**	**-34.4**
Treatment Average		**8.2**	**13.9**	**1.2**	**1.3**	**121.2**	**93.3**	**63.4**	**11.7**	**-30.6**
C1L	29	16.6	34.1	2.5	1.9	138.0	83.0	105.7	-24.4	-66.3
	30	16.0	29.4	2.6	1.9	95.0	71.0	83.4	-25.9	-33.8
	31	16.0	29.4	2.5	2.0	87.0	76.0	84.3	-20.0	-14.5
Average		**16.2**	**30.9**	**2.5**	**1.9**	**106.7**	**76.7**	**91.2**	**-23.4**	**-38.2**
C1M	21b	20.2	28.1	2.3	2.3	149.0	68.0	39.1	-2.8	-119.1
	21a	15.8	26.9	2.3	1.9	104.0	93.0	69.9	-18.2	-11.8
	21	11.0	19.6	2.4	2.3	123.0	67.0	78.2	-3.6	-83.6
Average		**15.7**	**24.9**	**2.3**	**2.2**	**125.3**	**76.0**	**62.4**	**-8.2**	**-71.5**
C1H	6	12.2	16.5	1.4	1.8	188.0	217.0	35.8	31.2	13.4
	7	10.4	14.5	1.2	2.0	163.0	165.0	39.6	66.6	1.2
	8	19.5	27.8	1.7	1.6	157.0	149.0	42.9	-4.6	-5.4
Average		**14.0**	**19.6**	**1.4**	**1.8**	**169.3**	**177.0**	**39.4**	**31.1**	**3.1**
Treatment Average		**15.3**	**25.1**	**2.1**	**2.0**	**133.8**	**109.9**	**64.3**	**-0.2**	**-35.5**
C2L	28	12.8	25.6	2.5	1.9	73.0	82.0	100.4	-25.7	11.0
	27	20.0	28.4	2.3	2.1	104.0	86.0	41.8	-12.0	-20.9
	26	18.8	27.6	2.5	1.9	73.0	100.0	46.5	-26.0	27.0
Average		**17.2**	**27.2**	**2.4**	**1.9**	**83.3**	**89.3**	**62.9**	**-21.2**	**5.7**
C2M	22	12.6	17.5	1.3	1.9	132.0	82.0	39.0	45.3	-61.0
	23	8.5	7.4	1.1	1.1	149.0	114.0	-12.4	1.5	-30.7
	23a	6.5	9.4	1.2	1.6	121.0	112.0	44.6	35.8	-8.0
Average		**9.2**	**11.4**	**1.2**	**1.5**	**134.0**	**102.7**	**23.7**	**27.5**	**-33.2**
C2H	5	3.5	9.2	1.3	1.5	118.0	186.0	166.7	18.4	36.6
	4	9.3	7.1	1.1	0.9	143.0	128.0	-23.8	-22.2	-11.7
	3	5.7	1.9	0.6	0.8	138.0	193.0	-67.5	29.8	28.5
Average		**6.1**	**6.0**	**1.0**	**1.1**	**133.0**	**169.0**	**25.1**	**8.6**	**17.8**
Treatment Average		**10.8**	**14.9**	**1.5**	**1.5**	**116.8**	**120.3**	**37.3**	**5.0**	**-3.3**

* Average district yields were the equivalent of 11.5 and 11.2 kg/vine for Semillon during 2000/2001 and 2001/2002 seasons respectively and 8.1 and 11.1 kg/vine for Cabernet Sauvignon for the 2000/2001 and 2001/2002 irrigation season respectively (Harry Creey, Pers. Comm.)

It can be seen from Table 7-15 that there was a general decrease in yield from the supply end of the treatments to the outlet end. This can be explained by a number of factors including the water application, which increased down the length of the treatments, the soil salinity and the groundwater salinity, which also generally increased down the length of the furrow from the low salinity blocks (L) to the high salinity blocks (H). Variation in yield was also markedly increased during the 2001/2002 irrigation season and this may have been attributed to a large application of Urea 150 kg N/ha during the second irrigation of 2001/2002 season, which was not applied in the 2000/2001 irrigation season. Yield increases as measured over the entire field through grape deliveries were 35 % for the Semillon vines (17.9-23.9 T/ha) and 58% for the Cabernet Sauvignon vines (10-15.8 T/ha). It is difficult to drawn conclusions based on the yield data over such a short period of time. Prior, Grieve and Cullis (1992a,b) found that yield response of grapevines were related to previous salinity levels the plant was exposed to. During a six year experiment it was found that tissue ion content (Na and Cl) had a significant effect on grapevine yield for periods of four years or more, hence it is difficult to make robust conclusions based on the treatment effects on yield data with only a two year monitoring period.

What can be seen is that in the less-saline areas yields were significantly higher than the district averages. While the district averages include both young and extremely old vines which have lower yields the significant increases in yields over the district average measured indicate that increased levels of water use from the water table most likely occurred to produce these increased yields. Average irrigation water use for grapevines grown in the area was 4.05 ML/ha for the 2000/2001 irrigation season and 4.88 ML/ha for the 2001/2002 irrigation season (Murrumbidgee Irrigation, Pers Comm.). These figures are approximately 0.3-2.4 ML/ha higher than the irrigation volumes applied to the experimental treatments, hence the significant increases in yields measured in some treatments at the experimental site are most likely due to the increased use of shallow groundwater.

It appeared that the major limitation affecting yield was related to stress caused by salinity. Airborne infrared imaging undertaken in January of 2002 showed that high levels of stress were occurring particularly in the high salinity treatment blocks. Crop water stress index determined from the infrared imaging is shown in Figure 7-65 just before irrigation and three days after irrigation.

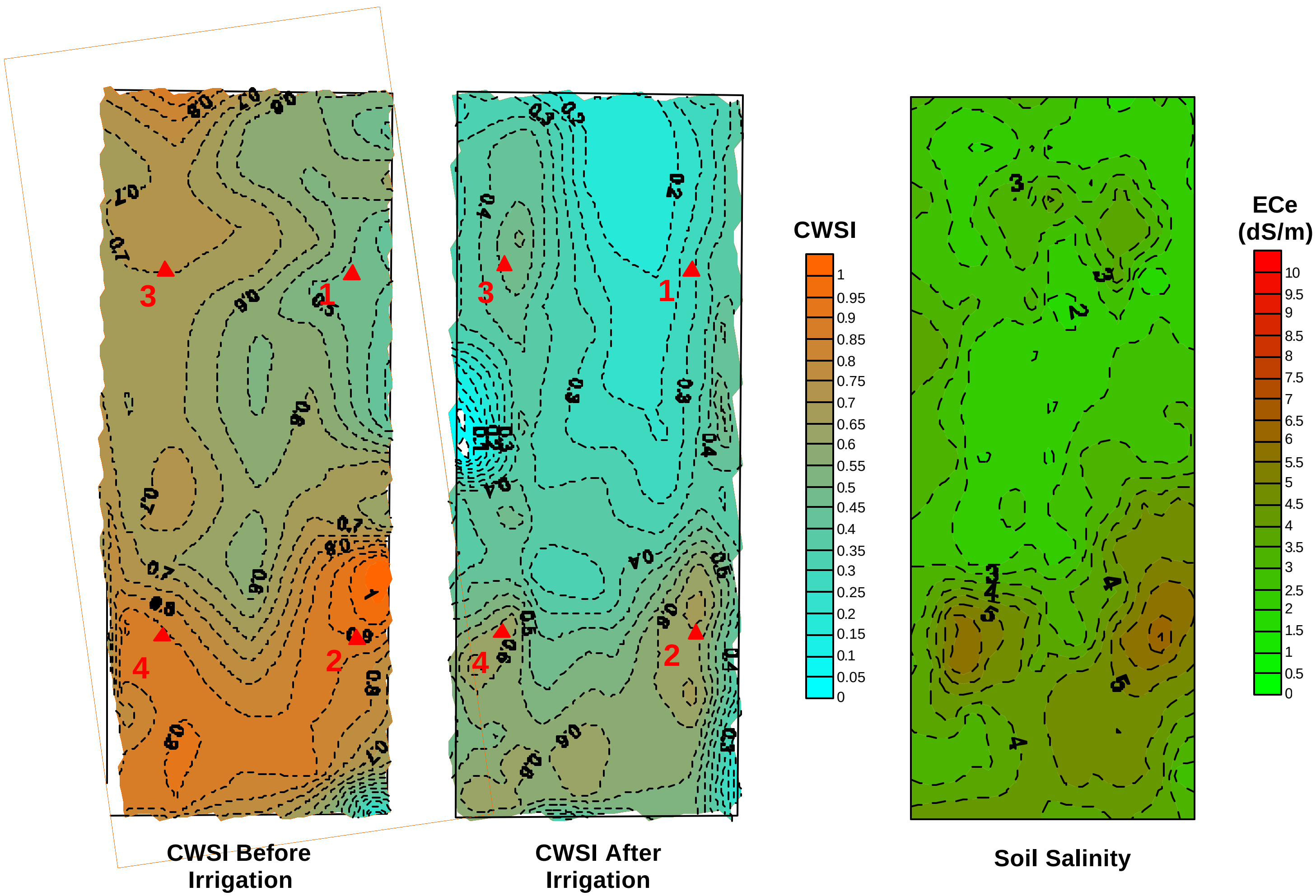


Figure 7-65. Crop Water Stress Index (CSWI) before and after irrigation and soil salinity. Red Triangles indicate soil moisture monitoring points

The CWSI before irrigation is high particularly in the lower outlet end of the field. This is due largely to the elevated salinity levels in this region of the field which can be seen by Figure 7-65, which shows average soil salinity in the rootzone determined through EM38 soil surveying.

Soil moisture monitoring was undertaken at the same time the 'before irrigation' CWSI image was taken at positions marked 1 to 4 in Figure 7-65 respectively and results are shown in Figure 7-66.

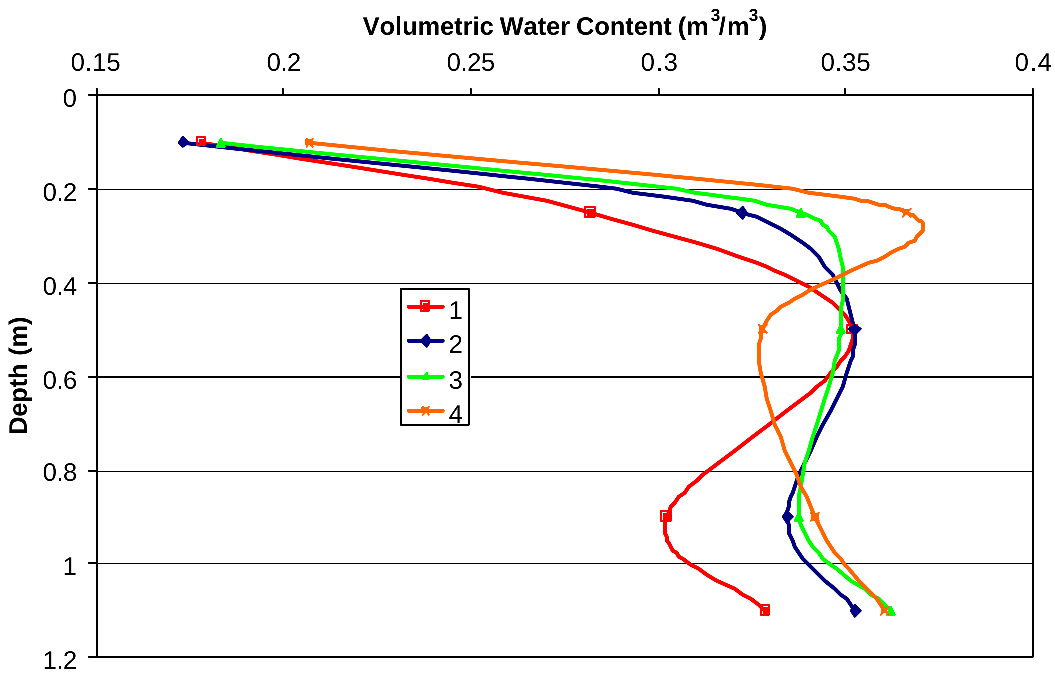


Figure 7-66. Volumetric water contents determined with a neutron probe taken in conjunction with the CWSI measurements

It can be seen that the results from the soil moisture monitoring indicate that the vines should be roughly at the same stress levels, as the moisture contents are relatively similar. However, in the main root zone between 0.2-0.4m, moisture levels in the low salinity blocks are the lowest and yet the vines are least stressed, and in the high salinity blocks soil moisture contents are higher yet these vines are the most stressed. This indicates that the reduced yields from the high salinity blocks are most likely due to salinity effects rather than a lack of available water.

It appears that the treatments had little effect on leaf chloride levels even though soil chloride levels in the treatments showed a general increasing trend over the course of the experiment (Section 7.2.5.2). On average in all treatments leaf chlorides declined from the 2000/2001 to the 2001/2002 irrigation season. This may have been due to a reduction in transient waterlogging during the 2001/2002 irrigation season compared with the 2000/2001 irrigation season. Subsurface drainage was not installed until the 8/11/2000 and there may have been transient periods of waterlogging during this early part of the 2000/2001 irrigation season. During periods of waterlogging in the plant rootzone the uptake of chloride is increased (Stevens and Walker, 2002) and this may explain the decrease in levels in the 2001/2002 irrigation season.

Prior, Grieve and Cullis (1992b) found a linear relationship between leaf chloride and vine yield, recommending that leaf chloride levels be keep as low as possible with levels above approximately 100 mmol/kg having a significant effects on yield.

Due to the large differences in yields and leaf chlorides measured over the two year period it is difficult to draw conclusions based on the long-term effects of controlled drainage practices on vineyard yields. What does appear apparent from the data is that the yields have been affected from the salinity levels present rather than from a lack of available water. Therefore, the groundwater salinity and associated soil salinity appear to be the limiting factors contributing to the reduction in yield.

7.2.5.2 Soil Salinity

Soil salinity was monitored over the experimental period using EM38 surveys, ground truthed with soil coring undertaken at selected well positions. The ESAP software program (Lesch, Rhoades and Corwin 2000) was then used to create spatial maps of soil salinity for the field. A general trend was observed over the entire field of increasing soil salinity and this can be attributed to the upflux of water from the groundwater table, which occurred to meet crop water demands. Figure 7-67 to Figure 7-70 shows soil salinity changes as measured at three periods during the course of the experiment.

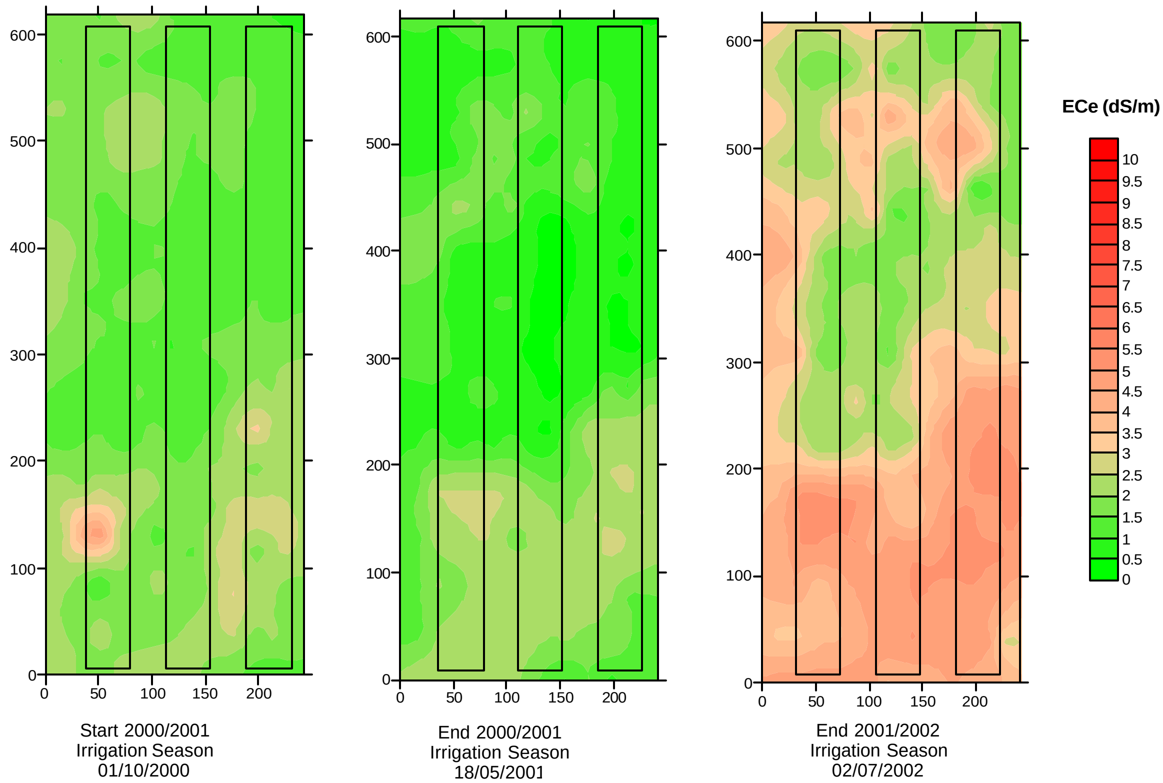


Figure 7-67. Soil salinity in the 0-0.3m layer over the course of the experiment

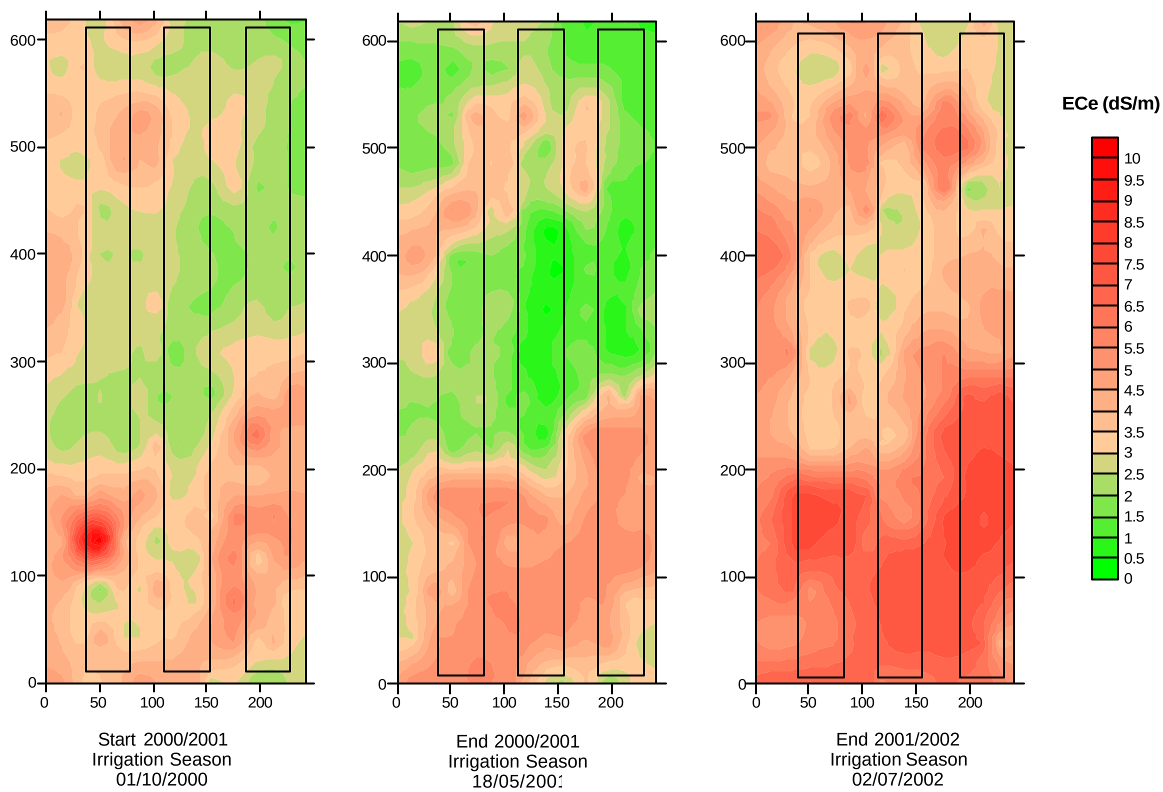


Figure 7-68. Soil salinity in the 0.3-0.6m layer over the course of the experiment

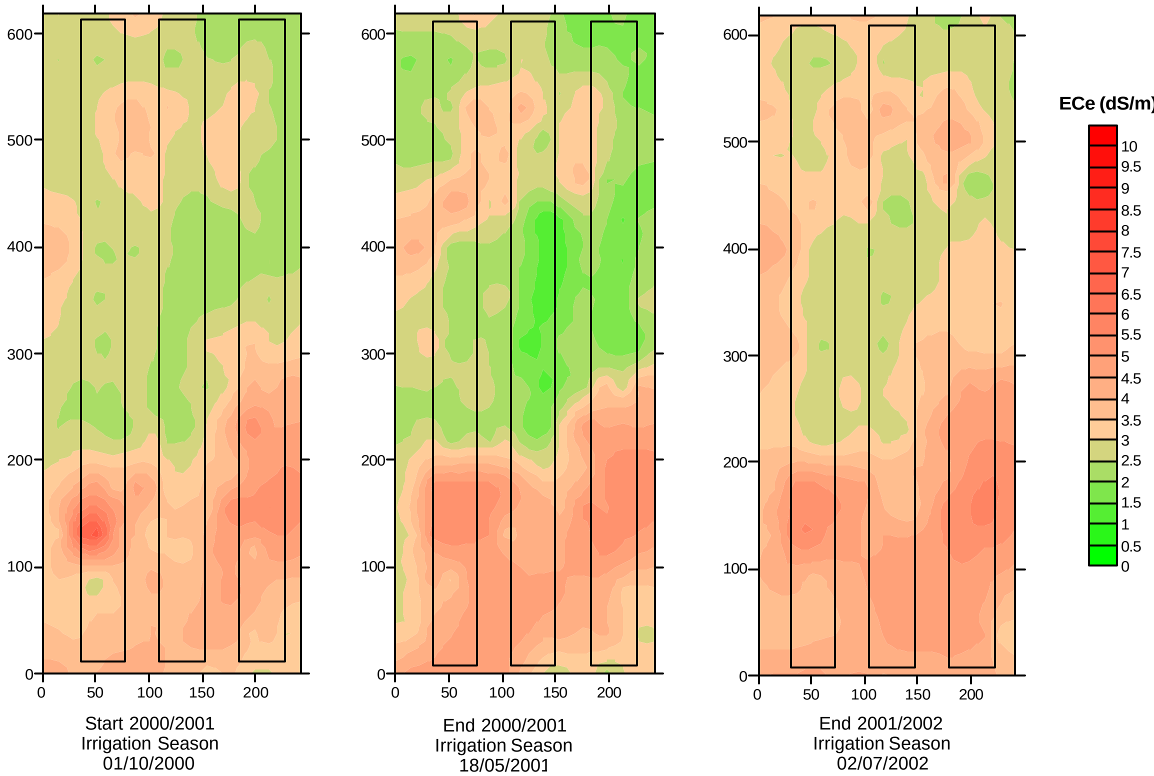


Figure 7-69. Soil Salinity in the 0.6-0.9m layer over the course of the experiment

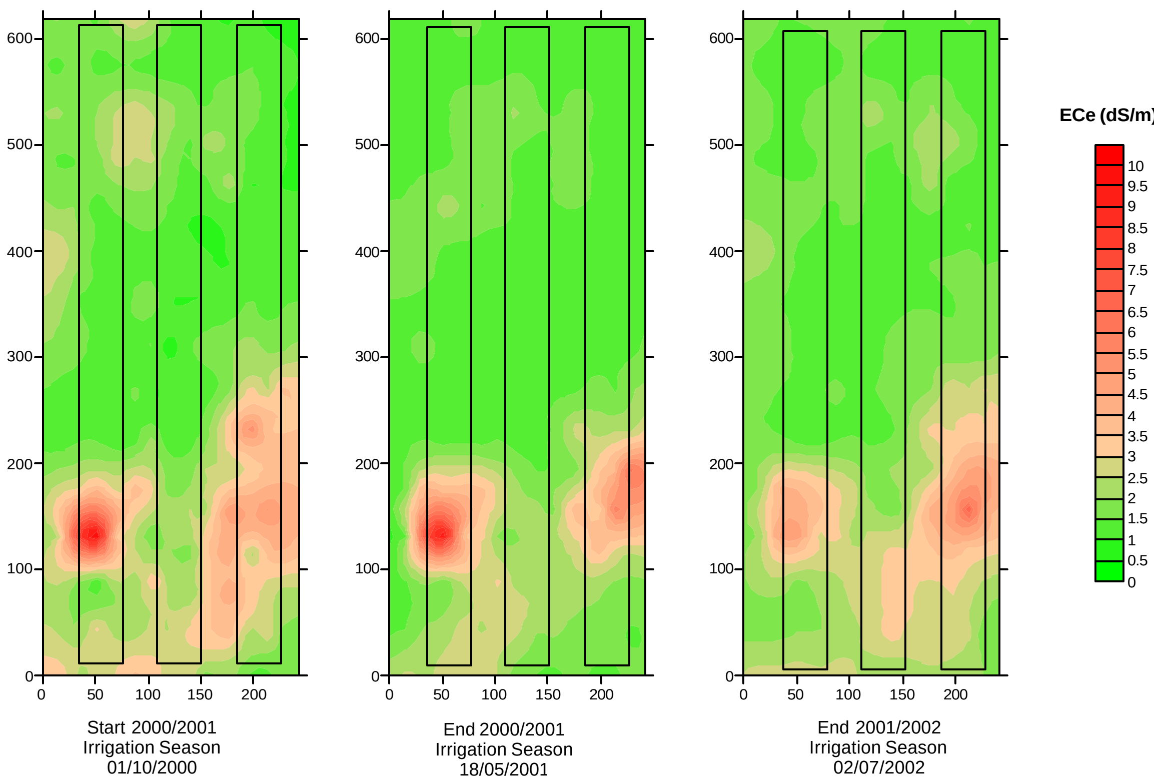


Figure 7-70. Soil salinity in the 1.5-1.8m layer over the course of the experiment

The increasing trend of soil salinity in the rootzone layers can be seen, while at deeper depths below the active rootzone (1.5-1.8m) the change in soil salinity was marginal. While the increases in soil salinity did not reduce the measured yields, it is apparent that sustainability issues will need to be carefully considered when implementing controlled drainage. Both the free drainage and controlled drainage areas experienced an increase in soil salinity over the experimental period, and this is due to the large irrigation deficits that were present. Even the free drainage treatment had a general increase in soil salinity during the experimental period.

Therefore, any implementation of strategies which aim to increase plant water use from a shallow saline groundwater source will need to carefully consider soil salinity increases and implement appropriate monitoring to ensure that soil salinity does not increase to harmful levels. While the increase in soil salinity is a drawback associated with controlled drainage mitigation of its effects may be possible with careful management and is discussed later.

7.2.6 Conclusions

Considering the objectives of the field experiment which are given in Chapter 4 and based on the experimental findings at the controlled water table management site it can be concluded that:

1. Water table regimes are significantly changed under controlled drainage management. Controlled drainage results in higher water table levels in the field than with free drainage (uncontrolled), however the severity of waterlogging in the rootzone does not appear to be increased

2. Controlled drainage management results in significant reductions in drainage volumes and subsequently salt loads which are generated by the drainage system compared to free drainage. Drainage volumes under controlled drainage management were reduced by approximately 90 % and salt loads by approximately 95 % compared to free drainage with no management

3. Grapevines (Vitis Vinifera) have the potential to use significant quantities of shallow saline groundwater for meeting evapotranspiration requirements. Estimates of groundwater use using a water balance approach indicate that this could be as high as 50% of total evapotranspiration for non-limiting saline groundwaters. Contributions to evapotranspiration from groundwater was found at salinity levels up to 4 dS/m

4. Implementing controlled drainage for increasing plant water use from a saline groundwater source has the potential to significantly increase rootzone soil salinisation, during the experimental period salinity levels were found to increase under controlled drainage management, however increases were also found under free drainage management

These results indicate the that both the Cabernet Sauvignon and Semillon wine grapes have the potential to use water from a shallow saline water table to varying degrees. The largest contributions were found in the Semillon variety where controlled drainage was implemented. In blocks where there was no water use from the water table this was largely due to the reduced crop canopy and subsequent reduced evapotranspiration in these blocks and was strongly related to how saline the blocks were.

8 General Discussion

8.1 Multi-level Subsurface Drainage System

8.1.1 Drainage Flow and Salt Loads

Based on the findings from the multi-level drainage experiment it can be seen that a subsurface drainage system, which incorporates both shallow and deep drains, has significant benefits in relation to reduction in drainage disposal volumes. While the salt loads in the multi-level drainage system were only slightly smaller than the single-level drainage system, if the spacing of the deep drains was increased salt loads generated from the system could be significantly reduced when compared to a conventionally designed single-level drainage system. Salt loads from the shallow drain discharge water were significantly lower than that from the deep drains. At the experimental site there was an average difference in drain water salinity of 27 dS/m between the deep and shallow drains in the multi-level drainage treatment, with the shallow drains having an average electrical conductivity of 4.7 dS/m compared to 31.7 dS/m for the deep drains. While the experimental site was extremely saline and such large differences may not be seen at other sites due to less saline conditions it can clearly be seen that a properly designed multi-level drainage system which incorporates shallow drains has the potential to reduce drainage salt loads.

Earlier work by Christen and Skehan (2001) using mole drainage at a single shallow depth also showed similar significant improvements in drainage water salinity reduction. However, the shallow drain system appeared to be susceptible to salinisation of the rootzone due to the water table remaining just below mole drain depth for significant periods. This capillary flow from the saline water table results in salinisation of the plant rootzone. Ghaemi and Willardson (1992) also found similar problems with shallow drainage systems and concluded that while the shallow drains were effective at waterlogging prevention they did not provide effective control of soil salinity in the longer term. However, soil salinity was only measured at two intervals before and after the irrigation season, which may not be a sound foundation to base such conclusions on. Indeed shallow drains may not be particularly suitable for long-term salinity control due to the effect of capillary upflow and resalinisation if the water table remains just below drain depth. Nevertheless, based on the findings with the multi-level subsurface drainage treatment shallow drains do appear to be successful in rapidly removing salt from the rootzone evidenced by the rapid reductions in shallow drain water salinities, which occurred throughout the experiment. After each successive irrigation event there was generally a noticeable decline in drain water salinity, which tends to indicate that the shallow drains were effective in reducing salinity levels in the rootzone. However, the reduction in the rootzone salinity levels may not be permanent. Capillary upflow and resalinisation may occur over longer-term periods, rather than during short intervals between irrigations. Therefore, shallow drainage systems alone are not particularly well suited to manage rootzone soil salinities over the longer term, where capillary upflow is a major transport mechanism for salt accumulation in the rootzone. In a multi-level subsurface drainage system the deeper drains have the capability to lower the water table to a safe depth to prevent salinisation by capillary upflow. The multi-level subsurface drainage system essentially has two distinct drainage periods, which are characteristic of the system. These periods are a high drainage discharge period and rapid water table draw down when the water table is above the shallow drains and irrigation or rainfall events are occurring, and a reduced discharge period when the water table falls below the shallow drain depth and only the deep drains are active. Such a system is therefore to a degree self controlling with drainage rates being a maximum during periods of high recharge when waterlogging occurs, and low discharge once waterlogging of the rootzone has been removed. This has the advantage of providing excellent waterlogging protection to the crop while at the same time minimizing salt loads from the system.

In this study the presence of a reduced hydraulic conductivity layer and the formation of a perched water table also affected shallow drain behaviour and it is difficult to assess what effect the absence of such features would have had on the performance of the multi-level drainage system. Without the presence of a restrictive layer the reductions in soil salinity in the upper profile above the restrictive layer, particularly in the upper 0.4m depth may not have been as great. Furthermore at the deeper depths there may have been a further increase in the reduction of salt due to increased water flow through these layers.

8.1.2 Soil Salinity Control

The multi-level drainage system was more successful in reducing soil salinity in the rootzone than the single-level drainage system, hence it can be assumed that the general health of the vines and yields in the multi-level drainage system should be improved to a greater extent than with the single-level treatment over the longer term. The incidence of waterlogging was also significantly reduced in the multi-level drainage system and it is during these periods that there is accelerated uptake of chloride (West and Taylor 1984; Stevens and Prior 1994). Considering these factors the multi-level drainage system provides improved benefits to the crop in relation to both mitigation of rootzone soil salinity problems and waterlogging over existing single-level drainage systems.

8.1.3 Drainage Discharge Management

The multi-level drainage system has the potential to allow a greater degree of drainage discharge management than traditional single-level drainage systems. While it was not undertaken in this trial, the potential exists for further reduction in drainage water and salt loads through actively managing the drainage system. Such options may include limiting deep drain discharges to certain periods of the year, using only the shallow drainage system for waterlogging control. This type of management would be particularly useful during periods in which disposal of subsurface drainage water was an issue, e.g. when there is little water for dilution. With operation of the shallow drains, drain flow volumes would be significantly reduced, although waterlogging protection would still be provided along with a degree of salinisation protection in the short term. During periods where salt discharge is not an issue, the shallow drains in combination with the deep drains would rapidly remove salt accumulated in the rootzone.

8.1.4 Limitations of the Analytical Solution and Multi-level Drainage Design Criteria

No specific design criteria or design methodology for a multi-level drainage system has been given in this investigation. While analytical solutions for the ponded water condition have been developed in Chapter 6, further investigation and field comparison of the solution are needed before a robust design methodology can be formulated, based on this solution. At the experimental site a number of assumptions, which were made in the development of the analytical solution, were not always met under field conditions, hence validation of the analytical solution with field data could not be undertaken.

At the field site it was clear that a fully saturated soil profile did not occur during periods of irrigation application, hence verification of the analytical solution with field data proved difficult. Soil heterogeneity was also present at the field site and hence it was difficult to apply the analytical solution to the field data. In homogenous soils which are not layered and do not have preferential flow these problems may not exist. What can be seen from the analytical solution for the multi-level drainage system when comparing results with single-level drainage system under the same conditions is that spacing of deep drains can be significantly increased when there is the presence of a shallow drainage system. Maximum flow rates from the multi-level drainage system where found to be considerably higher than the single level drainage system during high recharge periods in the field site and support the results from the analytical solution that deep drain spacings can increased when there is a shallow drainage system present.

Therefore it can be seen that the analytical solution has a number of limitations and while it can be considered a useful tool for initial investigations into system behaviour a more complex modelling approach needs to be undertaken for comprehensive coverage of the design of a multi-level drainage system which overcomes the limitations associated with the analytical approach presented in this thesis. Possible use of a numerical based model may overcome these limitations, however it would also increase dramatically the amount of input information required to model such situations and may not be practical at the field level. Further work on the analytical solution could be undertaken to overcome some of the limitations which are present with the analytical solutions presented in

Chapter 6 and address issues such as layered soils which were a problem at the experimental site.

8.2 Controlled Drainage

8.2.1 Reduction in Drainage Volume

The research undertaken at the controlled drainage site has been able to demonstrate that controlled drainage practices can offer significant reductions in drainage volumes and subsequently salt loads over conventionally managed drainage systems. This finding supports previous investigations, which have been undertaken in other semi-arid irrigated areas throughout the world (Ayars 1999; Ayars et al. 1999; Christen and Skehan 2001; Day, Gartung & Lord 1998; Eching et al. 1994). While it is difficult to place an absolute value on the reduction of drainage volumes, which could be expected, with implementation of controlled drainage practices, due to the extremely dry period in which the experiment was undertaken it can be seen that it was significant when comparing individual irrigation events. For the largest recharge event there was a 8-fold reduction in drainage volumes through the use of controlled drainage practices. Over the entire duration of the experiment the controlled drainage reduced drainage discharges by 90% compared to the uncontrolled treatment.

Therefore, it can be judged that the implementation of controlled drainage practices in the Murrumbidgee Irrigation Area would have the potential to significantly reduce salt loads and hence reduce drainage disposal problems.

8.2.2 Grapevine Water Use from a Shallow Water Table

The use of controlled drainage also has the potential to improve water use efficiency (both irrigation and rainfall). It was seen that both white (Semillon) and red (Cabernet Sauvignon) wine grape varieties had the potential to use significant volumes of water from a shallow water table to meet crop evapotranspiration. This improves water use efficiency and makes use of a resource (the shallow water table), which is often ignored.

The contribution of capillary rise to crop evapotranspiration was found to vary between 0-60% and depended largely on the salinity of the water table. These estimates were determined using a water balance approach hence care must be taken when interpreting the results. The largest source of error using such an approach is likely to be the estimate of crop evapotranspiration as this is the largest component of the water balance. (Soppe 2000) has shown that this will have the greatest effect on determination of capillary upflow when using a water balance approach and closure of the water balance equation to determine capillary upflow. To reduce error in this component this study directly measured crop evapotranspiration. Trambouze, Bertuzzi and Voltz (1998) in comparing methods of estimating evapotranspiration in a vineyard found the energy balance method (as used in this experiment) the most accurate method, more reliable than methods based on a soil water balance. While the soil water balance method has been used by many other authors this method was not suitable for use at the experimental site as there was capillary rise from the water table.

An alternative approach to the water balance approach is through use of a chloride mass balance. The chloride mass balance approach is also difficult to apply in situations such as that found at the experimental site. Furrow irrigation does not see a uniform application of water over the whole surface hence chloride transfer occurs three dimensionally and secondly recharge of fresh irrigation water to the water table will affect the estimate of capillary upflow essentially lowering the calculated value. Grismer, Bachman and Powers (2000) who compared groundwater recharge estimates in an avocado and citrus orchard in semi-arid California, using both a water balance and chloride mass balance approach, found the water balance method to give acceptable results, however where possible the authors recommended the use of multiple methods, however this was not possible due to the conditions present at the experimental site. Indeed, in the majority of field based studies the closure in the water balance term has been the accepted methodology (Ayars et al. 1999; Ayars 1999; Eching et al. 1994 & Wallender et al. 1979) to estimate capillary upflow from the water table to meet crop evapotranspiration, however it must be understood that the values calculated using this approach are basically estimates with a wide source of errors. Therefore results presented in this study of contributions from capillary upflow must be considered as approximate amounts not absolute values.

The experimental data has shown that significant quantities of shallow groundwater can be used by grapevines to meet evapotranspiration requirements. Whilst this has been shown previously on annual crops this study has been the first to measure such contributions to a perennial horticultural crop in a field situation. Experimental data from the study indicated that there was potential for vines to use water from a shallow saline water table of up to 4 dS/m. At higher water table salinities there may still be the possibility of groundwater contribution if the grapevines are growing vigorously. This observation is based on the finding at the experimental site, that areas that had high water table salinity levels also had high soil salinity levels that had affected vine growth. It is feasible that there could exist situations in the Murrumbidgee Irrigation Area, particularly where regional groundwater influences are large, that rootzone soil salinities are low and water table salinities are high. Recently, in reviewing the resource potential of shallow groundwaters in irrigated agriculture Ayars et al. (in press) noted that generally cotton crops are capable of using significant qualities of shallow groundwater of up to 3 to 4 times greater salinity than the Maas Hoffman threshold. Based on the findings of this work it would appear that grapevines have the potential to use saline water from a groundwater source up to 2.5 times the Maas Hoffman threshold (1.5 dS/m Rhoades and Loveday 1990) slightly less than the magnitude increase reported by Ayars et al. (in press) when high quality irrigation water is used. The difference may be related to cotton being more naturally tolerant to salinity than grapevines, with cotton classed as tolerant and grapevines as moderately sensitive to salinity. It can also be seen that the high water use figures from a shallow groundwater source come from plots which were at or below the Maas Hoffman salinity thresholds for grapes and it would appear that the contribution of vine evapotranspiration from a shallow saline water table was limited by factors other than the salinity of the water table at these low values.

Taking a simplified approach and treating the irrigation water and groundwater as a conjunctive source of water to the vine then approximations can be made regarding the contribution from a saline groundwater source and at what salinity such a source would prove detrimental to the vines. It can be seen from Rhoades (1974) that the leaching requirement assuming steady state conditions is given by:

$$LR = \frac{ECcw}{ECdw} \qquad \textbf{Equation 8-1}$$

Where ECcw is the combined irrigation/groundwater EC

ECdw is the drainage water EC and is given by ECdw = 5ECse – ECcw

ECse is the saturated paste electrical conductivity of the soil

Using an irrigation water at 0.1 dS/m and assuming soil ECse of 1.5 dS/m for no yield loss, then the maximum contributions from the groundwater source and the required leaching fractions for no yield loss are shown in Figure 8-1.

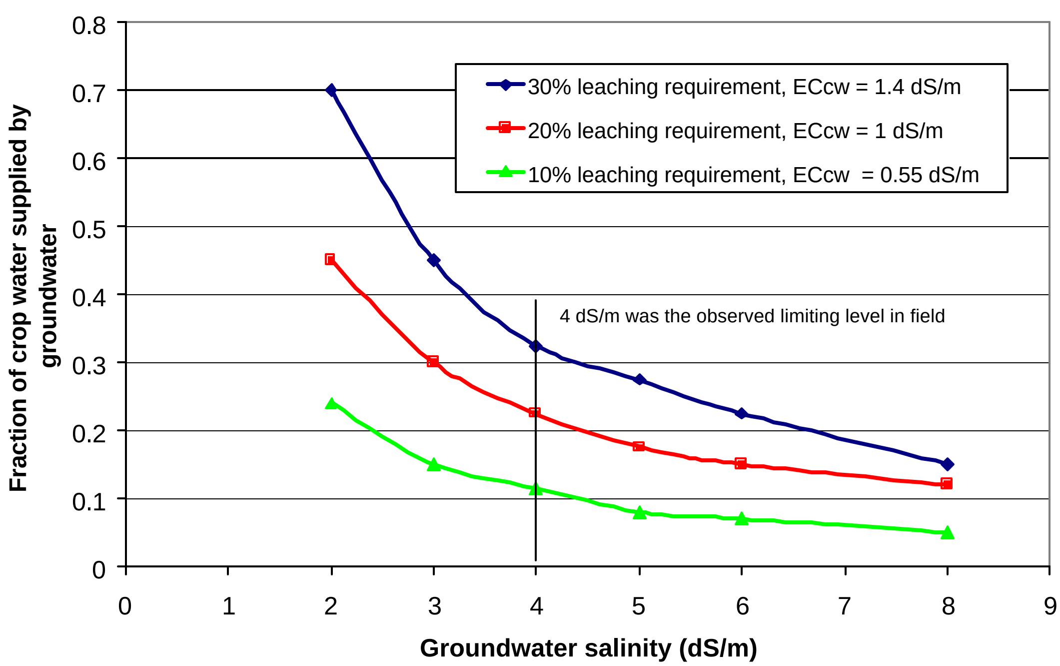


Figure 8-1. Fraction of groundwater that can be used by vine for no yield loss at given leaching fractions

It can therefore be seen that theoretically with high leaching requirements there may be potential for grapevines to use groundwater at levels above 4 dS/m, however it can also be seen from Figure 8-1 that the fraction of groundwater usage becomes rather small at groundwater salinities above 4 dS/m for leaching requirements generally found in field situations, e.g. 10-20%.

Considering this then the potential for water use from a saline water table in practical field based situations by grapevines would rely on the groundwater salinity being at or below approximately 4 dS/m.

The high crop water use figures from shallow saline water tables measured in this study may be attributed to the characteristics of grapevines. While other studies have been undertaken on annual crops which require time for development of the rootzone to a depth were they can use water from the water table, perennial crops such as vines already have an established root system from the beginning of the irrigation season and hence do not require time for the root system to develop as in the case of annual crops before use from the water table can occur. It is also generally found in most field situations where shallow water tables are present that the shallowest period of the water table occurs early in the irrigation season (Ayars et al. 1999; Christen and Skehan 2001; Hornbuckle, Christen and Faulkner 2002) hence during this time perennial crops such as vines have the advantage over annual crops in that they already have a well established root system and can therefore use water from a shallow water table in the early stages of the irrigation season. Perennial crops such as grapevines also develop larger canopy areas earlier in the growing season than annual crops and hence have high initial evapotranspiration earlier in the growing season than many annual crops, hence the potential for water use from the water table on perennial crops can be considered much greater than with annual crops.

8.2.3 Regional Impacts on Controlled Drainage

In implementing controlled drainage for maximizing groundwater use other factors than salinity also need to be considered. The results of the controlled drainage experiment showed that the regional groundwater played an important role in supplying water used by the grapevines. What must be considered when controlled drainage management is to be implemented is the source of the water, which has caused the shallow water table to develop. If the source is through inefficient irrigation then the benefits of controlled drainage can also be obtained through improved management of the irrigation system and an improvement in irrigation efficiency. Hence, if the source of the high water table is the result of poor irrigation practices on the field then the amount of water available to the crop is limited if irrigation efficiency is improved as recharge to the water table will be reduced. If the sources of recharge to the water table are through rainfall or preferential flow such irrigation efficiency improvements will not reduce the available water from the water table. The maximum potential benefit of controlled drainage management will be associated with areas in which regional groundwater levels are high and the source of the recharge is external to the farm e.g. irrigation channels, prior streams, neighboring poor irrigation practices. At the experimental site regional groundwater was a large source of the water which contributed to the shallow water table, hence when implementing controlled drainage careful attention needs to be given to assessing whether the regional sources of water to the water table will be able to maintain the high water table levels in the field to meet crop evapotranspiration needs, hence the potential use of groundwater will need to be carefully scheduled into the irrigation management to make maximum use of the resource. It can be seen from Figure 7-62 that regional groundwater levels have varied rather dramatically, hence controlled drainage management would need to consider these factors and realize that high contributions to crop evapotranspiration from shallow water tables may not be possible in all seasons or all years due to differences in regional groundwater levels which are essentially supplying this water and maintaining the water table level at a depth were it can be used by the crop.

8.2.4 Salinity Control

It is evident from the experimental results that any management decision to implement controlled drainage will require that rootzone salinity levels are carefully monitored. It is obvious that groundwater use by a crop from a shallow saline water table will result in salt accumulation in the soil profile, which has the potential to eventually retard crop growth and yields unless careful management is undertaken. Such management will need to ensure periods of adequate leaching to maintain a rootzone salt balance. In some areas such as California, annual crops have relied on pre-plant irrigations, which typically have high recharge and allow adequate leaching on a yearly basis. However, in the case of perennial crops such pre-plant irrigations are not a characteristic of the management system, hence incorporation of a specific leaching period may be needed. Christen and Hutchinson (2002) have shown that in many vineyards in the MIA large irrigations early in the irrigation season produce large volumes of drainage water, hence these periods could be used to allow periods of uncontrolled drainage for salt leaching. This would ensure that rootzone salinity levels were low at the beginning of the irrigation season and each season the processes could be repeated.

While winter rainfall during the experimental period was limited this may also provide an opportunity for leaching to occur, and control structures should be removed during the winter period. Another possibility may be in removing control structures for periods during the irrigation season to allow leaching to occur. While this was done in the 2001/2002 irrigation season for a two week period not enough drainage occurred to allow an adequate amount of salt leaching from the rootzone. Longer periods with the control structures removed or larger irrigation applications when the control structures are removed would provide improved leaching of the rootzone. Such practices would only have to be implemented periodically, hence the benefits associated with controlled drainage would still occur, albeit at a reduced level. Leaching periods may also be undertaken during optimal periods when environmental consequences of disposal of saline effluent are at their lowest. This could be during high river flow periods or early in the irrigation season to allow time for evaporation of drainage water to occur in evaporation basins over the irrigation season.

Considering the importance of maintaining low rootzone salinity levels than techniques incorporating high spatial resolution such as EM38 should be used. Such monitoring is already offered as a consultancy service in many irrigated areas in Australia and its high spatial resolution provides an excellent method for monitoring rootzone salinity levels. Its use in assessing the performance of subsurface drainage has recently been reported by Ayars, Christen and Hornbuckle (In press) using data collected at the ML site. It can be seen from the monitoring undertaken at the controlled drainage site that this methodology is extremely useful in monitoring rootzone soil salinity. This technique could therefore be used to base management decisions on when controlled drainage practices should or should not be implemented.

9 Conclusions

The overall aim of this research was to investigate alternative design and management practices for subsurface drainage to reduce environmental problems associated with the disposal of saline drainage water. It was identified that two broad areas could be improved. These were firstly changing the design of new systems and secondly modification and management of existing systems.

9.1 Design Alternatives of Subsurface Drainage Systems

An alternative subsurface drainage design was developed known as a 'Multi-level drainage System' that incorporated a series of both shallow and deep subsurface drains. This design configuration aimed to reduce drainage salt loads compared to conventional systems while still providing adequate crop protection from waterlogging and salinisation and remaining cost effective. Investigation of the new system design showed that:

1. The analytical model showed that the spacing of deep drains in a multi-level drainage system could be increased significantly over a single-level system. Therefore mitigating the extra costs of installing a multi-level drainage system.

2. Analytical modelling showed that flow paths were shown to be shallower in the multi-level drainage system hence drainage water salinities should be reduced when such a system is installed in soil profiles which show increased soil salinity with depth.

3. Field investigations showed drainage water salinity from shallow drains (0.8m) in a multi-level system were found to be markedly lower than those found in deeper drains (1.65m) confirming the assumptions from the theoretical modelling study.

4. Total salt load from a multi-level drainage system were lower than those of a single-level drainage system, hence reducing problems associated with disposal of

saline drainage effluent. There could be further reductions in salt loads by wider spacing of the deep drains.

5. The efficiency of salt removal from the rootzone is higher with a multi-level drainage system than with a single-level drainage system.

6. Increased waterlogging protection is provided by a multi-level drainage system over a conventional single-level system.

Considering these findings it can be concluded that development of drainage designs, which incorporate the impacts of saline drainage water disposal can have benefits to both the drained area as well as the receiving water body of the drainage discharge. The multi-level drainage system provides a design approach that begins to incorporate and address the problems associated with disposal of saline drainage effluent. The design aims to minimize the extraction of excess saline drainage water from below the rootzone that does not offer any benefit to the crop. This investigation has shown that these aims are achievable at the field scale.

9.2 Drainage Management of Subsurface Drainage Systems

Management of existing drainage systems was also investigated to reduce drainage salt loads. Active management of the drainage system was undertaken through the use of controlled drainage. Based on the results of the field investigation it can be concluded that:

1. Controlled drainage can significantly reduce drainage volumes, thereby reducing salt loads. This significantly reduces the problems associated with disposal of saline drainage effluent and reduces environmental impacts associated with subsurface drainage.

2. Water table heights are significantly increased with the use of controlled drainage, yet the incidence of waterlogging is not increased significantly. Therefore, the impacts on agronomic production are minimised.

3. Grapevines have the potential to use significant quantities of water from a shallow saline groundwater resource if managed correctly. This has the benefit of improving water use efficiency through beneficial use of the resource, which is often the result of inefficient irrigation measures.

4. Rootzone soil salinity was found to increase under controlled drainage. Therefore, the potential for root zone salinization will be a major consideration when developing management practices to ensure the sustainability of controlled drainage. Careful monitoring and management will be required when implementing controlled drainage. Periodic leaching will be required either by rainfall or specific irrigation periods e.g. large initial irrigations of the season.

It can therefore be concluded that controlled drainage has significant potential to reduce drainage salt loads when implemented on existing subsurface drainage systems. It has been shown that these reductions in drainage salt loads can be achieved with little impacts on agronomic production provided careful management is implemented.

9.3 Future Research Needs

9.3.1 Multi-level Drainage System

Future research should focus on further investigation into the interaction of water flow paths and drain water salinity. This could be undertaken using a modeling approach with a package such as Hydrus-2D (Simunek, Sejna and van Genuchten 1999). Field data collected in this investigation could be used to initially calibrate the model through inverse modeling. Predictions could then be made using the model and optimal drainage design investigated for various parameter combinations. This would also allow quantification on salt loads for various configurations of shallow and deep drains to be developed for numerous situations commonly incounted in field settings, such as heterogeneous soil profiles and preferential flow.

9.3.2 Controlled Drainage

Future research to develop techniques to incorporate groundwater contributions into irrigation scheduling procedures are needed. While this study has shown there is potential for significant use of shallow groundwater by perennial horticultural crops, such as grapevines, it has not developed robust techniques which can be used by farm manages to incorporate these benefits. Research needs to be undertaken on developing irrigation scheduling techniques and monitoring equipment, which allow the potential benefits of crop water use from a shallow water table to be maximized.

10 References

Abbaspour, K.C., Kohler, A., Simunek, J., Fritsch, M., and Schulin, R. 2001 'Application of a two-dimensional model to simulate flow and transport in a macroporous agricultural soil with tile drains', *European Journal of Soil Science*, September, 52:433-447

Anderson, J.J., and Guitjens, J.C. 2000 'Hydrodynamic modeling to optimize irrigation efficiency', In *Challenges Facing Irrigation and Drainage in the New Millennium*, Proceedings of 2000 USCID International Conference, Eds Deason, Gates, Zimblelman and Anderson, Denver, Colorado

Arnold, J.G., Boast, C.W., and Lembke, W.D. 1984 'Evaporation and non-tile seepage during water table drawdown', *Winter Meeting of American Society of Agricultural Engineers*, Hyatt Regency, New Orleans, Louisiana, December 11-14, Paper No. 84-2562

Ayars, J.E. 1996a 'Alternatives for Managing Shallow Groundwater in Arid Irrigated Areas', *North American Water and Environment Congress*, ASCE

Ayars, J.E. 1996b 'Managing irrigation and drainage systems in arid areas in the presence of shallow groundwater: Case studies', *Irrigation and Drainage Systems*, Vol. 10: 227-224, Kluwer Academic Publishers

Ayars, J.E., and McWhorter, D.B. 1985 'Incorporating crop water use in drainage design in arid areas', *Proc. Spec. Conf. Irrig. And Drain. Div*., ASCE, New York, Eds Keyes, C.G., and Ward, T.J., 380-389

Ayars, J.E. and Soppe, R.W. 2001 *Integrated Management of Irrigation and Shallow Ground Water in the Presence of Drains*, Final Report, Water Management Research Laboratory, USDA-ARS, Fresno, C.A.

Ayars, J.E., Christen, E.W. and Hornbuckle, J.W. Inpress 'Drainage Performance Assessment in Salinity Control for a New Vineyard – A Case Study', In *Performance Assessment and Potential Indicators for Drainage Systems*, Eds. Vincent, B., Vlotman W.F. & Zimmer, D., ICID – CIID

Ayars, J.E., Grismer, M.E., and Guitjens, J.C. 1997 'Water quality as design criterion in drainage water management systems', *Journal of Irrigation and Drainage Engineering*, Vol. 123, No.3, 154-158

Ayars, J.E., Christen, E.W., Soppe, R.W. and Meyer, W.S. Inpress 'The resource potential of shallow groundwater in irrigated agriculture – a review', *Irrigation Science*

Ayars, J.E., Schoneman, R.A., Dale, F., and Shouse, P. 1996 'Shallow Ground Water Management with a Modified Subsurface Drainage System', *North American Water and Environment Congress*, ASCE

Ayars, J.E., Hutmacher, R.B., Schoneman, R.A., Soppe, R.W.O., Vail, S.S., and Dale, F. 1999 'Realizing the potential of integrated irrigation and drainage water management for meeting crop water requirements in semi-arid and arid areas', *Irrigation and Drainage Systems*, Vol 13: 321-347, Kluwer Academic Publishers

Beltran, J.M 1999 'Irrigation with saline water: benefits and environmental impact', *Agricultural Water Management*, 40:183-194

Blackburn, G. and S. McLeod 1983 'Salinity of Atmospheric Precipitation in the Murray-Darling Drainage Division, Australia', *Australian Journal of Soil Research*, **21**, 411-434.

Blackwell, J., Biswas, T.K., Jayawardane, N.S. & Townsend, J.T. 2000 'Irrigation – Getting the Edge', *GRDC Irrigation Update*, Mathoura Bowling Club, NSW, 16 August

Boast, C.W, and Kirkham, D. 1971 'Auger hole seepage theory', *Soil Science Society of America* 35(3):365-373

Bonython, C.W. 1956 'The salt of Lake-Eyre – its occurrence in Madigan Gulf and its possible origin', *Royal Society of South Australia Transactions*, 79: 66-90

Borland, A-M., Jerie, P.H., Mitchell, P.D., Irvine, J.L. and Nardella, N. 1996 'The effect of a saline and non-saline water table on peach tree water use, growth, productivity and ion uptake', *Australian Journal of Agricultural Research*, Vol. 47, P. 121-139

Bouwer, H. 1965 'Developing design requirements for parallel drains', *Drainage for Efficient Crop Production Conference*, Am. Soc. Agr. Eng., Proc. Pp. 62-65

Boumans, J.H. 1986, *Drainage in Arid Regions*, In Proc. 25th Int. Course on Land Drainage, 25 years of Drainage, Wageningen, The Netherlands, 24-28 Novemeber, ILRI, Wageningen, The Netherlands

Bowen, L. 1926. 'The Ratio of Heat Losses by Conduction and by Evaporation from any Surface', *Physical Reviews*, Vol. 27, pp. 779-789

Bowmer, K.H., Korth, W., Scott, A., McCorkelle, G. and Thomas, M. 1998 *Pesticide Monitoring in the Irrigation Areas of South Western NSW 1990-1995*, CSIRO Land and Water, Technical Report 17/98

Brown, C.M. and Stephenson, A.E. 1991 *Geology of the Murray Darling Basin, South Eastern Australia,* Aust. Bureau of Min. Res. Bulletin 235, Canberra

Bulter, B.E. & Hutton J.T. 1956, 'Parna in the Riverine Plain of south eastern Australia and soils thereon', *Australian Journal of Agricultural Research*, Vol. 7, pp. 536-553

Cassel, D.K. & Klute, A. 1986 'Water Potential: Tensiometry', In *Methods of Soil Analysis Part 1 – Physical and Mineralogical Methods*, Second Edition, Eds Klute A.,American Society of Agronomy Inc, Madison, Wisconsin USA

Chivas, A.R., Andrew, A.S., Lyons.,Bird, M.I. and Donnelly, T.H. 1991 'Isotopic constraints on the orgin of salt in Australian playas. 1. Sulphur', *Palaeography Palaeoclimatology Palaeoecology*, 84:309-331

Christen, E.W. 1994, *The Feasibility of using Mole Drainage to Control Waterlogging in Irrigated Agriculture*, Unpublished PhD thesis, Silsoe College, Cranfield University

Christen, E.W., and Hornbuckle, J.W. 2001 *Subsurface Drainage Design and Management Practices in Irrigated Areas of Australia*, Irrigation Insights No.2, NPIRD

Christen, E.W. and Hutchinson, P. 2002 'Vineyard leakiness – Monitoring methods and current evidence', In *Vineyard Leakiness,* Proceedings of a Workshop held at Waite Campus Adelaide, January 24-25 2002, Eds Bramley, R.G.V and Lanyon, D.M, Final Report on GWRDC Project No. GWR01/04, CSIRO Land and Water

Christen, E.W., and Skehan, D. 1999 *Design and Management of Subsurface Drainage for Improved Water Quality: a Field Investigation*, CSIRO Land and Water, Griffith, Technical Report 6/99

Christen, E.W., and Skehan, D. 2000 *Design and Management of Subsurface Pipe Drainage to Reduce Salt Loads,* CSIRO Land and Water, Griffith, Consultancy Report 22-00

Christen, E.W., and Skehan, D. 2001 'Design and Management of Subsurface Horizontal Drainage to Reduce Salt Loads', *Journal of Irrigation and Drainage Engineering*, Vol. 127, No.3

Christen, E.W. & Spoor, G. 1999, 'Controlling Irrigation Water Flow to Mole Drains', *Journal of Irrigation and Drainage Engineering Division*, ASCE, Vol. 125, No.2, pp. 59-63

Christen, E.W., Ayars, J.E., and Hornbuckle, J.W. 2001 'Subsurface drainage design and management in irrigated areas of Australia', *Irrigation Science*, 21:35-43

Chu, S.T., and DeBoer, D.W. 1976 'Field and laboratory Evaluation of Bi-level drainage theory', *Transaction of the ASCE,* Paper No. 75-2045, pp. 478-481

Cooinda Ceramics Pty Ltd. 126 Canterbury Road, Bayswater, Victoria, Australia

Cook, F.J., and Rassam, D.W. 2002 'An analytical model for predicting water table dynamics during drainage and evaporation', *Journal of Hydrology*, Vol. 263, pp.105-113

Cox, S. 1995 *Soil Water Conditions and Root Distributions under Grape Vines with Drips, Riverina Twin Furrow and Flood Irrigation*, CSIRO Division of Water Resources, Project DDEA Irrigation and Drainage Management Horticulture, Vac. Stud. Rep. Nov-Mar. 1995

Cresswell, H.P. 1993 'Evaluation of the Portable Pressure Transducer Technique for Measuring Field Tensiometers', *Australian Journal of Soil Research*, 31, 397-406

CSIRO 1965 *Tile Drainage in the MIA*, Rural Research in CSIRO 50

Dataflow Systems Pty Ltd, "Gopher" Place, 13 Jarrah Street, PO Box 93 Cooroy 4563, Queensland Australia, www.soilmoisture.com.au

Day, M.J., Gartung, J.L. & Lord, J.M. 1988, 'Subsurface Drainage Reduction Through Irrigation Management and Controlled Drainage', *Paper – American Society of Agricultural Engineers*, No. 88-2590

DeBoer, D.W., and Chu, S.T. 1975 'Bi-level subsurface drainage theory', *Transactions of the ASCE*, Paper No. 72-731, pp. 664-667

De Vos, J.A., Raats, R.A.C., and Feddes, R.A. 2000 'Chloride transport in a recently reclaimed Dutch polder', *Journal of Hydrology*, 257:59-77

Deverel, S.J. and Fio, J.L. 1991 'Groundwater flow and solute movement to drain laterals, Western San Joaquin Valley, California 1. Geochemical Assessment', *Water Resources Research*, Vol. 27, No 9, 2233-2246

Doering, E.J., Benz, L.C., and Reichman, G.A. 1982 'Shallow-water table concept for drainage design in semi-arid and subhumid regions', *Advances in Drainage*, Proceedings of 4th National Drainage Symposium, ASAE Publication 12-82, ASAE, St Joseph, Mich., 34-41

Donnan, W.W., Aronovici, V.S. and Blaney, H.F. 1947 *Report on Drainage Investigations in Irrigated Areas of Imperial Valley, California*, Mimeographed report, U.S. Department of Agriculture

Dougherty, T.C. and Hall, A.W. 1995 'Environmental Impact Assessment of Irrigation and Drainage Projects', *FAO Irrigation and Drainage Paper no. 53,* FAO, Rome

Drainage Manual, 1993 U.S. Department of Interior, Denver, Colorado

Dumm, L.D. 1954 'Transient-Flow Concept in Subsurface Drainage: Its Validity and Use', *Trans. Am. Soc. Agric. Eng.*, 7(2):142-146

Dumm, L.D. 1968 'Subsurface drainage by transient-flow theory', *Journal of Irrigation and Drainage Division*, ASCE, 94(4):505-519

Eching, S.O., Hopmans, J.W., Wallender, W.W., MacIntyre, J.L., and Peters, D. 1994 ‘Estimation of local and regional components of drain-flow from an irrigated field’, *Irrigation Science*, Vol. 15, 153-157

Evans, R.O., Gilliam, J.W., and Skaggs, R.W. 1991 *Controlled drainage management guidelines for improving drainage water quality*, Bulletin AG-443, Cooperative Extension Service, Raleigh, N.C

Evans, R.O., Skaggs, W.R., and Gilliam, J.W. 1995 ‘Controlled versus conventional drainage effects on water quality’, *Journal of Irrigation and Drainage Engineering*, Vol 121, No.4, pp. 271-276

Evans, R.S. 1989 ‘Saline water disposal options in the Murray Basin’, *Journal of Australian Geology and Geophysics*, 11:167-185

Faulkner, R.D. 1992 ‘Field determination of crop evapotranspiration from the energy balance’, *Transactions of the Zimbabwe Scientific Association*, 66:18-24

Faulkner, R.D. and Jones, M.J. 1996 *An Introduction to Irrigation Engineering*, Hydrology and Water Management Series 2. Department of Resource Engineering. University of New England

Fio, J.L. 1994 *Calculation of water budget and delineation of contributing sources to drainflows in the western San Joaquin Valley, California*, U.S. Geological Survey, Open-File Report 94-95, Sacramento, California

Fio, J.L. and Deverel, S.J. 1991 ‘Groundwater flow and solute movement to drain laterals, Western San Joaquin Valley, California 2. Quantitative Hydrologic Assessment’, *Water Resources Research*, Vol.27, No.9, 2247-2257

Fio, J.L. and Leighton, D.A. 1994 *Effects of ground-water chemistry and flow quality of drainflow in western San Joaquin Valley, California*, U.S. Geological Survey, Open-File Report 94-72, Sacamento, California

Fry, R.K., Sinai, G.S., and Spoor, G. 1984 'Machinery for the installation of small diameter pipes at shallow depths', *Agricultural Water Management*, 9: 23-36

Gamet Equipment Pty Ltd, 215 Mann St. Armidale, 2350, Australia

Garcia, L.A., Manguerra, H.B., and Gates, T.K. 1995 'Irrigation-Drainage Design and Management Model: Development', *Journal of Irrigation and Drainage Engineering*, Vol. 121, No. 1, pp. 71-82

GARMIN, GARMIN International, Inc, 1200 E.151st Street, Olathe, KS 66062 U.S.A www.garmin.com

Ghaemi, A.A., and Willardson, L.S. 1992 'Salt movement in a shallow drained soil with an artesian pressure', In *Land reclamation: Advance in research and technology*, Proceedings of the International Symposium, Eds, Younos, T., Diplas, P., and Mostaghimi,S., 14-15 December 1992, Nashville, Tennessee, ASCE

Grimes, D.W. and Williams, L.E. 1990 'Irrigation effects on plant water relations and productivity of Thompson seedless grapevines', *Crop Sciences*, Vol. 30, pp.255-260

Grismer, M.E. 1993 'Subsurface drainage system design and drain water quality', *Journal of Irrigation and Drainage Engineering*, Vol. 119, No.3, 537-543

Grismer, M.E., Bachman, S.B. and Powers, T. 2000 'Field determination of groundwater recharge from irrigated and non-irrigated areas of avocado/citrus orchards using chloride mass balance, soil moisture monitoring and soil-water balance methods', *Hydrological Processes*, Vol. 14 (14), pp. 2527-2543

Guitjens, J.C., Ayars, J.E., Grismer, M.E., and Willardson, L.S. 1997 'Drainage design for water quality management: Overview', *Journal of Irrigation and Drainage Engineering*, Vol. 123, No. 3, 148-153

Hager, W 1988 'Mobile Flume for Circular Channel', *Journal of Irrigation and Drainage Engineering*, Vol. 114, No.3, August, ASCE

Hanson, B.R., and Kaita, K. 1997 'Response of electromagnetic conductivity meter to soil salinity and soil-water content', *Journal of Irrigation and Drainage Engineering*, Vol. 123, No.2

Harris Pty Ltd, 136 Worcester street, Christchurch, New Zealand, www.gpselogger.com

Hathoot, H.M. 1998 'Theory of pipe drainage assisted by mole drainage', *Irrigation and Drainage Engineering*, Vol. 124, No.2, pp. 102-233

Herczeg, A. L. and Lyons, W. B. 1991. 'A chemical model for the evolution of Australian sodium chloride salt lake brines Paleogeography', *Paleoclimatology*, Paleoecology, (Special issue: Palaeoenvironments of salt lakes), Vol.84, pp. 43-53

Herczeg, A.L., Dogramaci, S.S., and Leaney F.W. 2001 'Origin and evolution of solutes in a large, semi-arid, regional multi-aquifer system: Murray Basin, for Australia', *Mar. Freshwater Res. Mar. Freshwater Res*., Vol. 52, pp. 41-52.

Hermsmeier, L.F. 1973, 'Shallow Drain Performance in a Heavy Soil', *Transactions of the ASAE*, Vol. 39(5), pp.92-96

Hillel, D. 2000, *Salinity Management for Sustainable Irrigation, Integrating Science, Environment and Economics*, Environmentally and Socially Sustainable Development, Rural Development, World Bank, Washington, D.C.

Hoffman, G.J. 1990 ‘Leaching fraction and rootzone salinity control’, In *Agricultural Salinity Assessment and Management*, Ed. Tanji, K.K., ASCE, New York, pp.237-261

Hornbuckle, J.W. 1999 *Modelling furrow irrigation on heavy clays, high water tables and tiled drained soils using SIRMOD in the Murrumbidgee Irrigation Area,* Environmental Engineering Department, University of New England, unpublished Honours thesis

Hornbuckle, J.W. and Christen, E.W. 1999 *Physical properties of soils in the Murrrumbidgee and Coleambally Irrigation Areas*, CSIRO Land and Water, Technical Report No. 17/99

Hornbuckle, J.W., Christen, E.W and Faulkner, R.D 2002 ‘Preliminary Investigations of a Multi-level Subsurface Drainage System for Improving Drainage Water Quality’, *Irrigation 2002*, Irrigation Association of Australia Conference, 21-23 May 2002, Sydney.

Hornbuckle, J.W., Christen, E.W., & Faulkner, R.D 2003 ‘Improving the Efficiency and Performance of Furrow Irrigation using Simulation Modeling in South-Eastern Australia’, *International Workshop on Improved Irrigation Technologies and Methods: Research, Development and Testing*, ICID, 18-19 September, Montpellier, France

Hooghoudt, S.B. 1940 ‘Bijdragen tot de kennis van eenige natuurkundige grootheden van den grond’, 7*, Algemeene beschouwing van het probleem van de detail ontwatering en de infiltratie door middle van parallel loopende drains, greppels, slooten, en kanalen*. Versl. Landbouwk. Ond., 46:515-707

Hutmacher, R.B., Ayars, J.E., Vail, S.S., Bravo, A.D., Dettinger, D. and Schoneman, R.A. 1996 ‘Uptake of shallow groundwater by cotton: growth stage, groundwater salinity effects in column lysimters’, *Agricultural Water Management*, 31:205-223

Jack, R.L. 1921 ‘The salt and gypsum resources of South Australia’, *Geological Survey of South Australia Bulletin*, No. 8, 118pp.

Johnson, M. 1979 *The origin of Australia’s salt lakes*, NSW Geological Survey Technical Report No. 19(2), 221-266

Jury, W.A. 1975a ‘Solute travel-time estimates for tile-drained fields: I. Theory’, *Soil Science Society of America Proceedings*, 39:1020-1023

Jury, W.A. 1975b ‘Solute travel-time estimates for tile-drained fields: II. Application to experimental studies’, *Soil Science Society of America Proceedings*, 39:1024-1028

Kacimov, A.R. 1998 ‘Theory of Pipe Drainage Assisted by Mole Drainage, Discussion by A.R. Kacimov’, *Journal of Irrigation and Drainage Engineering*, July/August pp.231-233

Kamra, S.K., Singh, K.V., Rao, G.K., and Van Genuchten, M.Th. 1991 ‘A semidiscrete model for water and solute movement in tile-drained soils 1. Governing equations and solutions’, *Water Resources Research*, 27:2439-2447

Khan, S., and Rushton, K.R. 1996 ‘Reappraisal of flow to tile drains 1. Steady state response’, *Journal of Hydrology*, 183:351-366

Kirkham, D. 1949 ‘Flow of ponded water into drain tubes in soil overlying an impervious layer’, *Trans. Am. Geophys*. Union, 30:369-385

Kirkham, D. 1951 ‘Seepage into drain tubes in stratified soil’, *Transaction of the American Gepphysical Union*, Vol. 32, pp. 422-442

Kirkham, D. 1957, ‘III. The Ponded Water Case, Theory of Land Drainage’, In *Drainage of Agricultural Lands*, (Ed) J.N. Luthin, American Society of Agronomy, Madison, Wisconsin, USA

Kirkham, D. 1958 ‘Seepage of steady rainfall through soil into drains’, *Trans. Am. Geophys. Union*, 39:892-908

Kirkham, D. 1966’ Steady-State Theories for Drainage’, *Journal of the Irrigation and Drainage Division*, Proceedings of the American Society of Civil Engineers, IR1, pp. 19-39

Kirkham, D. 1967 ‘Explanation of Paradoxes in Dupuit-Forchheimer Seepage Theory’, *Water Resources Research*, Vol. 3, No. 2. pp. 609-622

Kirkham, D., and Powers, W.L. 1984 *Advanced Soil Physics*. Wiley-Interscience. Reprint. Ed. Krieger Publ.Co., Melbourne (Malabar), Florida

Kirkham, D., van der Ploeg, R.R., and Horton, R. 1997 ‘Potential theory for dual-depth subsurface drainage of ponded land’, *Water Resources Research*, Vol. 33, No. 7, pp. 1643-1654

Kohler, A,. & Hager, W.H. 1997 ‘Mobile Flume for Pipe Flow’, *Journal of Irrigation and Drainage Engineering*, Vol. 123, No.1, January/February, ASCE

Kohler, A., Addaspour, K.C., Fritsch, M., van Genuchten, M.Th., Schulin, R. 2001 ‘Simulating unsaturated flow and transport in a macroporous soil to tile drains subject to an entrance head: model development and preliminary evaluation’, *Journal of Hydrology*, 254:67-81

Kruse, E.G., Young, D.A. and Champion, D.F. 1985 'Effects of saline water table on corn irrigation', In *Development and Management Aspects of Irrigation and Drainage Systems*, Eds C.G. Keyes and T.J. Ward, pp. 444-453, ASCE, New York

Ladanay-Bell, J.R.W., and Acworth, R.L. 2002 'Salinisation processes in the Irrigation Environment Riverine Plain, Murray Darling Basin', *Irrigation Australia 2002 Conference, Irrigation: Conservation or Conflict*, 21-23 May Sydney, 2002

Leeds-Harrison, P., Spoor, G. and Godwin, R.J 1982 'Water flow to mole drains', *Journal of Agricultural Engineering Research*, Vol. 27, No. 81-91

Lesch, S.M., Herrero, J., and Rhoades, J.D. 1998 'Monitoring for temporal changes in soil salinity using electromagnetic induction techniques', *Soil Sci. Soc. of Am. J.*, 62: 232-242

Lesch, S.M., Rhoades, J.D. and Corwin, D.L. 2000 *ESAP-95 Version 2.01R User Manual and Tutorial Guide*, Research Report No. 146, USDA, ARS, Riverside, Califorina

Luthin, J.N. 1966 *Drainage Engineering*, John Wiley and Sons Inc, New York

Luthin, J.N. 1978 *Drainage Engineering*, R.E Krieger Publ. Co. Hungtington, N.Y

Maas, E.V. 1986 'Salt tolerance of plants', *Applied Agricultural Research*, Vol. 1, p. 12-26

Maas, E.V. 1990 'Crop salt tolerance', In *Agricultural Salinity Assessment and Management*, Ed. Tanji, K.K., ASCE, New York, pp. 237-261

Maasland, M. 1956 *The relationship between permeability and the discharge, depth and spacing of tile drains*. Bull. No.1, Water Conservation and Irrigation Commission, New South Wales

Maasland, M. 1959 'Water Table Fluctuations Induced by intermittent recharge', *Journal of Geophysical Research*, Vol. 64, No.5, pp. 549-559

Maasland, M. 1964 'Water Table Fluctuations Induced by Irrigation', *Transactions of the ASCE*, Vol. 128, Part 3, Paper No. 3423, pp. 142-161

Maasland, M., and Haskew, H. 1958 *The auger hole method of measuring the hydraulic conductivity of soil and its application to tile drainage problems*, Bulletin No. 2, Groundwater and Drainage Series, Water Conservation and Irrigation Commission, New South Wales

Manguerra, H.B., and Garcia, L.A. 1997 'Field strategy for agricultural drainage and water-quality management', *Journal of Irrigation and Drainage Engineering*, Vol. 123, No.1, 37-44

Mazor, E., Geogre, R. 1992 'Marine airbourne salts applied to trace evaporation, local recharge and lateral groundwater flow in Western Australia', *Journal of Hydrology*, 139:63-77

McClymont, D., and Smith R. 1996. 'Infiltration Parameters from Optimization on Furrow Irrigation Advance Data', *Irrigation Science,* Vol. 17, pp.15-22

M^c^Intyre D.S. and Loveday, J. 1974a 'Bulk Density', In *Methods for Analysis of Irrigated Soils*, Ed Loveday, J, Technical Communication No.54 of the Commonwealth Bureau of Soils, ISBN 0 85198 302 2

M^c^Intyre, D.S. and Loveday, J. 1974b 'Particle Size Analysis', In *Methods for Analysis of Irrigated Soils*, Ed Loveday, J, Technical Communication No.54 of the Commonwealth Bureau of Soils, ISBN 0 85198 302 2

McNeil, J.D. 1986 *Rapid, accurate mapping of soil salinity using electromagnetic ground conductivity meters*, Tech. No. TN-18, Geonics Limited, Ontario, Canada

M[c]Whorter, D.B. 1977 'Drain spacing based on dynamic equilibrium', *Journal of Irrigation and Drainage Division*, ASCE, Vol. 103(2), pp. 259-271

Mead, R.M., Soppe, R.W.O. and Ayars, J.E. 1996 'Capacitance Probe Observations of Daily Soil Moisture Fluctuations', *Evapotranspiration and Irrigation Scheduling*, Proc. of the Int. Conf., Nov. 3-6, eds Camp, C.R., Sadler, E.J. and Yoder, R.E., ASAE, San Antonio, Texas, pp. 916-923

Meron, M., Tsipris, J. and Charitt, D. 2003 'Remote mapping of crop water status to assess spatial variability of crop stress', *4th European Conference on Precision Agriculture,* Berlin, Germany

Meyer, W.S. 1992 *Neutron and Gamma probe calibration and calculation of plant available water for wheat field 100W*, Farm 459, CSIRO Griffith, NSW, Technical Memorandum, 1992

Meyer, W.S. 1998 *Standard Reference Evaporation Calculation for Inland, South Eastern Australia*, Technical Report, CSIRO Land and Water, Griffith, NSW

Meyer, W.S., White, B. and Smith, D. 1996 'Water use of Lucerne over shallow water tables in Australia', In *Proceedings of International Conference, Evapotranspiration and Irrigation Scheduling*, Eds C.R. Camp, E.J. Sadler and Yoder, R.E., Nov. 3-6, 1996, San Antonio, Texas, ASCE, St. Joseph, MI, pp. 1140-1145

MIA and Districts LWMP Working Group, 1998, *MIA and Districts Community Land and Water Management Plan*, July 1998

Muirhead, W.A., Humphreys, E., Jayawardane, N.S. and Moll, J.L. 1996 'Shallow subsurface drainage in an irrigated vertisol with a perched water table', *Agricultural Water Management*, Vol. 30, 261-282

Murphy, A. 2001 *GPS Utility Software*, www.gpsu.co.uk

Namken, L.N., Weigand, C.L., and Brown, R.O. 1969 'Water use by cotton from low and moderately saline static water tables', *Agronomy Journal*, Vol 61 p. 305-310

Nieber, J.L., and Feddes, R.A. 1999 'Solutions for Combined Saturated and Unsaturated Flow', In *Agricultural Drainage*, Eds, Skaggs and van Schilfgaarde, American Society of Agronomy, Madison, Wisconsin, USA

Northcote, K.H. and Skene, J.K.M. 1972. *Australian soils with saline and sodic properties,* CSIRO Soil Publication, No. 27, CSIRO, Melbourne

Nour el-Din, M.M., King, I.P., and Tanji, K.K. 1987 'A salinity management model: 1. Development', *Journal of Irrigation and Drainage Engineering*, Vol. 113, No. 4, pp. 440-453

Onset Computer Corporation 470 MacArthur Blvd. Bourne, MA 02532, www.onsetcomp.com

Pandey, R.S., and Gupta, S.K. 1990 'Drainage Design Equation with Simultaneous Evaporation from Soil Surface', *ICID Bulletin*, Vol. 39, No. 1, pp. 19-25

Pels, S. & Stannard, M.E. 1977, 'Environmental Changes due to Irrigation Development in Semi-arid parts of Australia', *Arid Land Irrigation in Developing Countries: Environmental Problems and Effects*, (Ed.) E. Worthington, pp. 171-183

Pickens, J.F., Gillham, R.W., and Cameron, D.R. 1979 'Finite element analysis of the transport of water and solutes in tile-drained soils', *Journal of Hydrolog*y, 40:243-264

Polkinghorne, C. 1992. 'Tile Drainage in the MIA', *Farmers Newsletter*

Prior, L.D., Grieve, A.M. and Cullis, B.R. 1992a 'Sodium chloride and soil texture interactions in irrigated field grown Sultana grapevines 1. Yield and fruit quality', *Australian Journal of Agricultural Research,* Vol 43, pp. 1051-1066

Prior, L.D., Grieve, A.M. and Cullis, B.R. 1992b 'Sodium chloride and soil texture interactions in irrigated field grown Sultana grapevines 2. Plant mineral content, growth and physiology', *Australian Journal of Agricultural Research,* Vol 43, pp. 1066-1083

Ragab. R. 2002 'A holistic generic integrated approach for irrigation, crop and field management: the SALTMED model', *Environmental Modelling and Software*, 17:345-361

Rassam, D.W. and Cook, F.J. 2002 '2. Numerical simulations of water flow and solute transport applied to acid sulfate soils', *Journal of Irrigation and Drainage Engineering,* Vol. 128, No.2, 107-115

Rassam, D.W., Cook, F.J., and Gardner, E.A. 2002 '1. Field and Laboratory studies of acid sulfate soils', *Journal of Irrigation and Drainage Engineering*, Vol. 128, No.2, 100-106

Reeve, R.C. 1986 'Water Potential: Piezometry', In *Methods of Soil Analysis Part 1 – Physical and Mineralogical Methods,* Second Edition, Eds Klute A.,American Society of Agronomy Inc, Madison, Wisconsin USA

Replogle J.A. n.d. *Measuring Agricultural Drain-Line Flows*

Rhoades, J.D. 1974 'Drainage for salinity control', *Drainage For Agriculture,* Ed. Van Schilfgaarde, J., American Society of Agronomy, Wisconsin, USA

Rhoades, J.D., Chanduvi, F., and Lesch, S.M. 1999 *Soil Salinity Assessment: Methods and Interpretation of electrical conductivity measurements*, FAO Irrigation and Drainage Paper #57, Food and Agricultural Organisation of the United Nations, Rome, Italy

Rhoades, J.D. & Loveday, J. 1990. 'Salinity in Irrigated Agriculture', In *Irrigation of Agricultural Crops*, Eds Steward, B.A. & Nielsen, D.R., Amercian Society of Agronomy, No. 30 in Agronomy Series, Madison, Wisconsin USA

Richards, L.A. 1931 'Capillary conduction of liquids in porous mediums', *Physics*, 1:318-333

Richards, L.A. 1954 *Diagnosis and Improvement of Saline and Alkali Soils*, United States Salinity Laboratory, Agriculture Handbook No. 60

Samani, Z., Jorat, S., & Yousaf, M 1991 'Hydraulic Characteristics of Circular Flume', *Journal of Irrigation and Drainage Engineering*, Vol. 117, No.4, July/August, ASCE

Schultz, B and Wrachien, D.D 2002 'Irrigation and drainage systems research and development in the 21st Century', *Irrigation and Drainage*, 51:311-327

Sentek Pty Ltd, 77 Magill Road, Stepney South Australia 5069, www.sentek.com.au

Simunek, J., Sejna, M. & van Genuchten, M. Th. 1999. *The Hydrus-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably saturated media*, Version 2.0, IGWMC – TPS – 53, International Ground Water Modeling Centre, Colorado School of Mines, Golden, Colorado

Skaggs, R.W., Breve, M.A. and Gilliam, J.W. 1994 'Hydrologic and water quality impacts of agricultural drainage', *Critical Reviews in Environmental Science and Technology*, 24(1):1-32

Skaggs, W.R. n.d. 'Models for simulating hydrology and water quality on drained soils', *Irrigation and Drainage Systems*, pp. 549-557

Slavich, P.G. 1990 'Determining ECa depth profiles from electromagnetic induction measurements', *Australian Journal of Soil Research*, 28:443-452

Slavich, P.G. n.d. *EM-38 Operator Manual*, NSW Agriculture

Slavik, B. 1974 'Methods of studying plant water relations', *Ecological Studies* No. 9, Chapman and Hall Limited, London, ISBN 0 412 13230 3

Smedema, L.K. & Rycroft, D.W. 1983. *Land Drainage: Planning and Design of Agricultural Drainage Systems*, Cornell University Press, Ithaca, New York

Smedema, L.K., Adbel-Dayem, S., and Ochs, W. 2000 'Drainage and agricultural development', *Irrigation and Drainage Systems*, 14:223-235

Soppe, R.W. 2000 *Optimising shallow saline groundwater use by crops*, PhD Dissertation, University of California, Davis, unpublished

Stace, H.C.T., Hubble, G.D., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulcahy, M.J. & Hallsworth, E.G. 1968. *A Handbook of Australian Soils*, Glenside, South Australia

Standard Methods for the Examination of Water and Wastewater, 1992. 18th Edition, Eds, Greenberg, A.E., Clesceri, L.S., and Eaton, A.D., Amercian Public Health Association, American Water Works Association and Water Environment Federation, Washington, D.C.

Stannard, M.E. 1970. *Morphological Descriptions of Soils Occuring in Colemabally Irrigation Area,* Water Conservation and Irrigation Commission, Sydney, Australia

Stevens, R.M. and Prior, L.D. 1994 'The Effect of Transient Waterlooging on the Growth, Leaf Gas Exchange, and Mineral Composition of Potted Sultana Grapevines', *Amercian Journal of Enology and Viticulture,* Vol. 45, No. 3, pp285-290

Stevens, R.M. and Harvey, G. 1996 'Soil water depletion under large grapevines, *Australian Journal of Grape and Wine Research,* Vol 2. pp. 155-162

Stevens, R.M. & Walker, R.R. 2002. 'Response of grapevines to irrigation-induced saline-sodic soil conditions', *Australian Journal of Experimental Agriculture,* Vol. 42, pp. 323-331

Talsma, T. 1963 *The Control of Saline Groundwater*, Department of Physics and Meteorology, Agricultural University, Wageningen, Netherlands

Talsma, T. 1967 'Leaching of Tile-Drained Saline Soils', *Australian Journal of Soil Research,* Vol. 5, pp. 37-46

Talsma, T., and Haskew, H. 1959 'Investigation of Water-Table Response to Tile Drains in Comparison with Theory', *Journal of Geophysical Research*, Vol. 64, No. 11, pp. 1933-1944

Tanji, K.K. 1990 *Agricultural salinity assessment and management*, ASCE Manuals and Reports on Engineering Practice No. 71, American Society of Civil Engineers, 345 East 47th street, N.Y. 10017

Taylor, B.A. & Hooper, P.D. 1938. *A Soil Survey of the Horticultural Soils in the Murrumbidgee Irrigation Areas, New South Wales,* Bulletin No. 118, CSIR, Melbourne

Thomas, D.L., Hunt, P.G., and Gilliam, J.W. 1992 'Water table management for water quality improvement', *Journal of Soil Water Conservation*, 47(1):65-70

Thompson, S.J. and Armstrong, C.F. 1987 'Calibration of the watermark model 200 soil moisture sensor', *Applied Engineering in Agriculture*, Vol.3, No.2 pp. 186-189

TPS Pty Ltd, 4 Jamberoo Street, Springwood, Brisbane, Australia, 4127, www.tps.com.au

Trambouze, W., Bertuzzi, P. and Voltz, M. 1998 'Comparison of methods for estimating actual evapotranspiration in a row-cropped vineyard, *Agricultural and Forest Meterology*, Vol. 91, Issue 3-4, pp. 193-208

Tucker, B.M. and Beatty, H.J. 1974 'pH, Conductivity and Chlorides', In *Methods of Analysis of Irrigated Soils*, Ed. Loveday, J., Technical Communication No. 54 of the Commonwealth Bureau of Soils, ISBN 0 85198 302 2

Van Beers, W.F.J. 1958 *The Auger Hole Method – A field measurement of the hydraulic conductivity of soil below the water table*, International Institute for Land reclamation and Improvement, The Netherlands

Van der Lely, A.1978 'Artifical Subsurface Drainage in the MIA', In The *Hydrologeology of the Riverine plain of South East Australia*, Eds. Storrier and Kelly, Australian Society of Soil Science Inc, Riverina Branch

Van der Lely, A. 1984 *Options for salt management in the MIA – Principles, Requirements, Consequences, Constraints*, Water Resources Commission Report, Griffith

Van der Lely, A., and Ellis, R.L. 1974 'Water from tile drainage systems in the MIA – Salinity Aspects', In *Agricultural Engineering Conference*, Sydney, NSW, IE Australian Agricultural Engineering Branch, University of New South Wales

Van der Lely, A., and Tiwari, A. 1995 *Evaluation of Watertable control options*, Appendix 4, Support Document to the MIA LWMP

Van der Ploeg, R.R., Horton, R., and Kirkham. D. 1999 'Steady flow to drains and wells', In. *Agricultural Drainage*, Eds. Skagg, R.W. and van Schilfgaarde, J., American Society of Agronomy, Madison, Wisconsin, USA

Van Dijk, D.C. 1958. *Soils of Portion of the Coleambally Irrigation Area, NSW*, CSIRO Soil Publication No. 11, Melbourne

Van Dijk, D.C. 1961. *Soils of the Southern Portion of the Murrumbidgee Irrigation Areas*, CSIRO Soils and Land Use Series, No. 40

Van Schilfgaarde, J. 1965 'Transient design of Drainage Systems', *Journal of the Irrigation and Drainage Division*, ASCE, IR3, pp.9-22

Van Schilfgaarde, J. 1974 'Irrigation management for salt control', *Journal of the Irrigation and Drainage Division*, Vol. 100, No. IR3, September, p. 321-338

Verma, A.K., Gupta, S.K., Singh, K.K., and Chauhan, H.S. 1998 'An analytical solution for design of bi-level drainage systems', *Agricultural Water Management*, 37:75-92

Walker, W. 1998 *SIRMOD* – Surface Irrigation Modeling Software. Utah State University

Wallender, W.W., Grimes, D.W., Henderson, D.W. and Stromberg, L.K. 1979 'Estimating the contribution of a perched water table to the seasonal evapotranspiration of cotton, *Agronomy Journal*, Vol. 71, pp. 1056-1060

Wenyan,W., Bing, S., and Zhilu, L. 1994 'Drain-Spacing Calculation Considering Influence of Evaporation', *Journal of Irrigation and Drainage Engineering*, Vol. 120, No. 3, pp. 563-572

Wesseling, J. 1964 'A comparison of the steady state drain spacing formulas of Hooghoudt and Kirkham in connection with design practice', *Journal of Hydrology*, Vol2: 25-32

West, D.W. and Taylor, J.A. 1984 'Response of Six Grape Cultivars to the Combined Effects of High Salinity and Rootzone Waterlogging', *Journal of American Society of Horticultural Science*, 109(6): 844-851

Westcot, D.W. 1988 *Reuse and disposal of higher salinity subsurface drainage water – A review*, Elsevier Science Publishers, B.V

Williams, L.E. 2001, 'Irrigation of winegrapes in California', Practical Winery. Retrieved 29 April from http://www.practicalwinery.com/novdec01p42.htm

Williams, L.E., Phene, C.J., Grimes, D.W. and Trout, T. 2003 'Water use of mature Thompson seedless grapevines in California, *Irrigation Science*, Vol. 22 (1), pp. 11-18

Wolfram, S. 1991. *Mathematica*, A system for doing Mathematics by Computer, Addison-Wesley, Redwood City, California

Wopfner, H., and Twidale, C.R. 1967 'The chemical characteristics of lentic surface water in Australia'. In *Australian Inland Waters and their Fauna: Eleven Studies*, Eds A.H. Weatherby, Australian National University Press, Canberra

Youngs, E.G.1999. ‘Non-steady flow to drains’, In: R.W. Skaggs and J. van Schilfgaarde (eds.) *Agricultural Drainage*, Agronomy Monograph No. 38, ASA/CSSA/SSSA, Madison (WI), USA

Yunusia, I.A.M., Walker, R.R. and Guy, J.R. 1997 ‘Partioning of seasonal evapotranspiration from a commercial furrow-irrigated Sultana vineyard, *Irrigation Science*, Vol. 18(1), pp. 45-54

Appendix 1

Theory for Multi-level Subsurface Drainage of Ponded Land

John Hornbuckle
CSIRO Land and Water
PMB No. 3, Griffith, NSW
2680
email: john.hornbuckle@csiro.au
04/03/2003

Introduction

This notebook uses the method of complex variables and multiple drain images to devire equations for the hydraulic head, the stream function and the drain discharge rates for a multi-level drainage system. The work extends on that of Kirkham (1949) and Kirkham et al. (1997) to include an array of shallow drain tubes installed between two deeper drain tubes. The mathematical model presented here will also correctly analyise a single depth drainage system and a dual depth drainage system as described by Kirkham (1949) and Kirkham et al. (1997) by setting m=0 for the case of a single depth drainage system and m=1 for the case of a dual depth drainage system.

User input is enetered in the input parameters section of the notebook below. All other cells have been locked for editing.

```
Off[General::spell1]
```

This line simply turns of the spell checker whcih is not needed

Input Parameters

```
m = 4; r = 0.1; a = 50; d = 4.5; t = 0;
h = 8; δ = 1; ρ = 0.065; k = 1; L = d - h;
```

m number of shallow drains
r is the radius of the deep drain (m)
a is the spacing between deep drains (m)
d is the depth of the deep drains (m)
t is the depth of ponded water on the soil surface (m)
h is the depth to impermeable layer (m)
is the depth of the shallow drain system (m)

is the radius of the shallow drains (m)
k is the hydraulic conductivity of the soil (m/d)

is an expression which represents the shallow drain coordinates in terms of the the x axis

```
ξ = Table[x - g * a / (m + 1), {g, 1, m}]

{-10 + x, -20 + x, -30 + x, -40 + x}
```

cp is an extactly as above but used in the contour plots

```
ξcp = Table[xcp - g * a / (m + 1), {g, 1, m}]

{-10 + xcp, -20 + xcp, -30 + xcp, -40 + xcp}
```

Posmd is the x reference for each of the shallow drains

```
Posmd = Table[(T * a) / (m + 1), {T, 1, m}]

{10, 20, 30, 40}
```

qSD is the hydraulic head coefficient for the shallow drains

```
qSD = Table[q_{SD*g}, {g, 1, m}]

{q_SD, q_{2 SD}, q_{3 SD}, q_{4 SD}}
```

qMLS is the hydraulic head coefficient for the Multi-level drainage system, consisting of the hydraulic head coefficients of the shallow drains and deep drain respectively

```
qMLS = Join[qSD, {qDD}]

{q_SD, q_{2 SD}, q_{3 SD}, q_{4 SD}, qDD}
```

W_{SD} is the summation expression in relation to the shallow drains

```
WSD = Sum[(-1)^n
    Log[(Cosh[(2*Pi (y - d + δ - 2*n*h)) / a] - Cos[2*Pi*ξ / a]) /
      (Cosh[(2*Pi (y - d - δ - 2*n*h)) / a] - Cos[(2*Pi*ξ) / a])], {n, -10, 10}];
```

W_{DD} is the summation expression for the deep drains

```
WDD =
  Sum[(-1)^n Log[(Cosh[(2*Pi (y - 2*n*h)) / a] - Cos[2*Pi*x / a]) /
      (Cosh[(2*Pi (y - 2*d - 2*n*h)) / a] - Cos[(2*Pi*x) / a])], {n, -10, 10}];
```

Expression for the shallow drains

```
ShallowDrains = Apply[Plus, qSD*WSD];
```

Expression for deep drain

```
DeepDrains = qDD*WDD;
```

We now apply the boundary condition I in which $\phi_{MLS} = r$, $y = r$ and $x = 0$

```
y = r; x = 0;
```

```
DDSim = y == DeepDrains + ShallowDrains + d + t
```

$$0.1 == 4.5 - 9.60291\,qDD - 0.169128\,q_{SD} - 0.0266726\,q_{2\,SD} - 0.0266726\,q_{3\,SD} - 0.169128\,q_{4\,SD}$$

```
y = d - δ + ρ; x = Posmd;
```

```
SDSim = DeepDrains + ShallowDrains + d + t
```

$\{4.5 - 0.160667\, qDD - 6.81122\, q_{SD} - 0.0423094\, q_{2\,SD} - 0.00640805\, q_{3\,SD} - 0.00640805\, q_{4\,SD},\ 4.5 - 0.0253722\, qDD - 0.0423094\, q_{SD} - 6.81122\, q_{2\,SD} - 0.0423094\, q_{3\,SD} - 0.00640805\, q_{4\,SD},\ 4.5 - 0.0253722\, qDD - 0.00640805\, q_{SD} - 0.0423094\, q_{2\,SD} - 6.81122\, q_{3\,SD} - 0.0423094\, q_{4\,SD},\ 4.5 - 0.160667\, qDD - 0.00640805\, q_{SD} - 0.00640805\, q_{2\,SD} - 0.0423094\, q_{3\,SD} - 6.81122\, q_{4\,SD}\}$

```
SDEqu = Table[d - δ + ρ, {m}]
```

{3.565, 3.565, 3.565, 3.565}

Hydraulic head coefficients are determined by solving the simulatneous equations above - there is m+1 equations and m+1 unknowns

```
Result = Solve[{SDSim == SDEqu, DDSim}, qMLS]
```

$\{\{q_{SD} \to 0.125512,\ q_{2\,SD} \to 0.133857,\ q_{3\,SD} \to 0.133857,\ q_{4\,SD} \to 0.125512,\ qDD \to 0.45303\}\}$

Next four steps simply get the hydraulic head coefficients for each drain

```
qMLSNum = qMLS /. Result[[1]]
```

{0.125512, 0.133857, 0.133857, 0.125512, 0.45303}

```
qMLSNum
```

{0.125512, 0.133857, 0.133857, 0.125512, 0.45303}

```
qDDNum = qMLSNum[[m + 1]]
```

0.45303

```
qSDNum = Take[qMLSNum, m]
```

```
{0.125512, 0.133857, 0.133857, 0.125512}
```

```
QSD = (qSDNum * 4 * Pi * k)
```

```
{1.57723, 1.68209, 1.68209, 1.57723}
```

```
QSDTotal = Apply[Plus, QSD]
```

```
6.51864
```

```
QDD = qDDNum * 4 * Pi * k
```

```
5.69294
```

```
QMLS = QSDTotal + QDD
```

```
12.2116
```

Summation expression for the deep drain used in contour ploting

$$WDDcp = \sum_{n=-10}^{10} (-1)^n \; Log[(Cosh[(2*Pi\,(ycp - 2*n*h))/a] - Cos[2*Pi*xcp/a])/(Cosh[(2*Pi\,(ycp - 2*d - 2*n*h))/a] - Cos[(2*Pi*xcp)/a])];$$

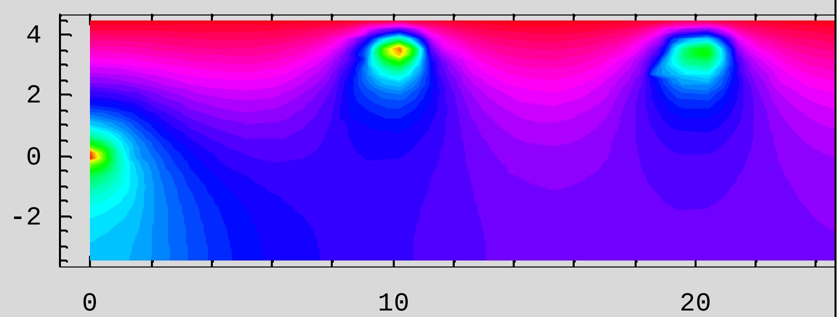
Summation expression for the shallow drains used in contour ploting

$$WSDcp = \sum_{n=-10}^{10} (-1)^n \; Log[(Cosh[(2*Pi\,(ycp - d + \delta - 2*n*h))/a] - Cos[2*Pi*\xi cp/a])/(Cosh[(2*Pi\,(ycp - d - \delta - 2*n*h))/a] - Cos[(2*Pi*\xi cp)/a])];$$

```
Shallowcp = Apply[Plus, qSDNum + WSDcp];
```

Equipotential lines of the drainage system

```
PotlinesML =
 ContourPlot[φ[xcp, ycp] = (qDDNum * WDDcp) + (Shallowcp) + (d + t),
  {xcp, 0.0000001, a}, {ycp, L, d}, PlotPoints → 50,
  Contours → 50, ContourLines → False, ColorFunction → Hue,
  AspectRatio → Automatic, PlotRange → All]
```




```
- ContourGraphics -
```

Summation expression for the deep drain in relation to the stream function

```
ZDDcp = Sum[(-1)^n (ArcTan[
       Tanh[(Pi (ycp - 2 * n * h)) / a] * Cot[(Pi * xcp) / a]] - ArcTan[
       Tanh[(Pi (ycp - 2 * d - 2 * n * h)) / a] * Cot[(Pi * xcp) / a]]), {n, -10, 10}];
```

$$ZDDcp = \sum_{n=-10}^{10} (-1)^n \left(\mathrm{ArcTan}[\mathrm{Tanh}[(\mathrm{Pi}\,(ycp - 2*n*h))/a] * \mathrm{Cot}[(\mathrm{Pi}*xcp)/a]] - \mathrm{ArcTan}[\mathrm{Tanh}[(\mathrm{Pi}\,(ycp - 2*d - 2*n*h))/a] * \mathrm{Cot}[(\mathrm{Pi}*xcp)/a]]\right);$$

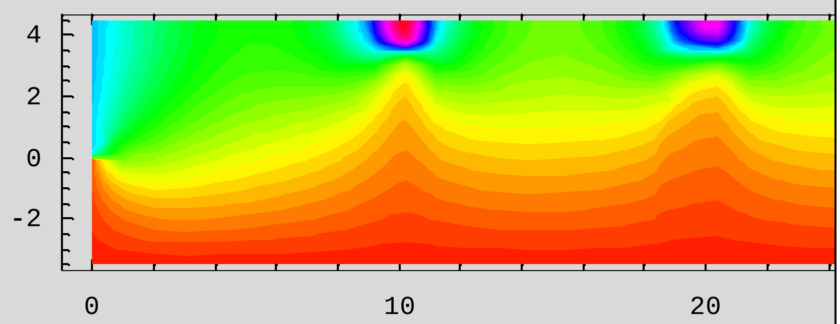
Summation expression for the shallow drains in relation to the stream function

$$ZSDcp = \sum_{n=-10}^{10} (-1)^n \left(\mathrm{ArcTan}[(\mathrm{Tanh}[(\mathrm{Pi}\,(ycp - d + \delta - 2*n*h))/a]) * (\mathrm{Cot}[(\mathrm{Pi}*\xi cp)/a])] - \mathrm{ArcTan}[\mathrm{Tanh}[(\mathrm{Pi}\,(ycp - d - \delta - 2*n*h))/a] * (\mathrm{Cot}[(\mathrm{Pi}*\xi cp)/a])]\right);$$

```
ShallowcpPot = Apply[Plus, Abs[qSDNum] + Abs[ZSDcp]];
```

Streamlines of the drainage system

```
StreamlinesML = ContourPlot[
  ψ[xcp, ycp] = (2 * k * ShallowcpPot) + (2 * k * qDDNum * Abs[ZDDcp]),
  {xcp, 0.0000001, a}, {ycp, L, d}, ContourLines → False,
  AspectRatio → Automatic, PlotPoints → 50,
  Contours → 50, ColorFunction → Hue, PlotRange → All]
```




```
- ContourGraphics -
```