Ghent University

Faculty of Bioscience Engineering

Department of Soil Management

Space-time variability of soil salinity in irrigated vineyards of South Africa

Ruimte-tijd variabiliteit van bodemverzilting in geïrrigeerde wijngaarden van Zuid Afrika

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor (PhD) in Applied Biological Sciences: Land and Forest Management

Academic Year 2008-2009

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Photograph of the farm Broodkraal close to the town Piketberg in the Western Cape Province of South Africa.

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Reference:

de Clercq W.P., 2009. Space-time variability of soil salinity in irrigated vineyards of South Africa. PhD Thesis, Ghent University, 209p.

ISBN 978-90-5989-276-7

ACKNOWLEDGEMENT

In April of 2000, Prof. Dr. Ir. M. Van Meirvenne and Prof. Dr. ir. D. Gabriels visited the Department of Soil Science of the Stellenbosch University as a part of a bilateral program between Flanders and South Africa. During their visit, the idea to start a PhD at Ghent University took shape. Consequently, in October 2001 my proposed project was accepted for a PhD study. I continued the study in Stellenbosch with a number of visits to Ghent University.

I need to express my gratitude first and foremost, to Prof. Dr. ir. M. Van Meirvenne who encouraged me through the whole process.

And to a number of people, and organisations:

Prof. Dr. M.V. Fey and Dr. A. Rozanov, for always encouraging me and reminding me of the urgency in completing the study.

The reading committee, Prof. Dr. D. Gabriels, Prof. Dr. ir. V. Pauwels, Prof. Dr. Ir. T. Toth, whose comments ultimately contributed to a better product.

Students from Ghent, Griet de Smet and Frederik Seghers, who handled some of the fieldwork contained in this study.

Hendrik Engelbrecht (student at Stellenbosch), who also managed some of the fieldwork in my absence.

My always loyal colleague, Kamilla Latief, for her assistance in lowering my workload.

My Heavenly Father for His omnipresence.

The WRC of SA for funding most of this research.

Last but not least, my family, Maryke, Jaco and Jo-Anne.

ABSTRACT

Salts present in the soil and surface waters of the Western Cape Province of South Africa represent a limitation to farming activities. Therefore the management of salinity in the landscape, which includes measuring, mapping and monitoring of its behaviour on a regional scale, is the general subject of this investigation.

Four sites were actively investigated in this study. These are the Robertson experimental farm, Goedemoed farm near Robertson, Broodkraal farm near Piketberg and the Glenrosa farm near Paarl. At the first two, regular point measurements were taken to study the behaviour of salinity in irrigated soils over several irrigation seasons. Frequent sampling of soil and soil water was done. The quality of the irrigation water was recorded and at the Robertson site the quality of the irrigation water was adjusted to six different levels of salinity, between 30 mS m^{-1} and 500 mS m^{-1}. At the Broodkraal and Glenrosa farms, large scale investigations were conducted to estimate salinity over larger areas. Broodkraal farm was a large newly established table grape enterprise offering the opportunity to study the initial change in soil salinity when irrigated with saline water. At the Glenrosa farm, there was an opportunity to characterize the soil even before irrigated vineyards were established.

Detailed point measurements were taken to investigate the salinity distribution in these soil profiles and its dynamics. Suction cup measurements were taken with self-designed and patented lysimeters and used to follow the seasonal soil water salinity changes through the root zone under different salinity regimes. These results were used to characterize an average salt depth trend, which was found to be best

represented by a linear function, and its evolution over time. A method was proposed to reduce the number of samples necessary to determine this salt depth trend and to estimate the quality of the soil water that drains below the rooting zone. One of the important findings was that an EC_e threshold for vines of 100 mS m^{-1} was more suitable than the conventional 150 mS m^{-1} and that the sensitivity of the vines to levels beyond this threshold increased with the number of years of exposure.

The detailed surveys at the Broodkraal and Glenrosa Farms helped the modelling of the regional salinity behaviour. This study allowed to gain a comprehensive understanding of the soil salinity dynamics in an irrigated landscape using saline water.

SAMENVATTING

Zouten aanwezig in de bodems en oppervlaktewaters van de 'Westeren Cape Province' van Zuid Afrika vertegenwoordigen een beperking van de landbouwactiviteiten. Vandaar dat het landschappelijk beheer van verzilting, inclusief het registreren, kartering en monitoren op een regionale schaal, het algemeen onderwerp is van deze thesis.

Vier sites werden actief onderzocht in deze studie. Deze zijn de Robertson experimentele boerderij, de Goedemoed boerderij nabij Robertson, de Broodkraal boerderij nabij Piketberg en de Glenrosa boerderij nabij Paarl. In de eerste twee werden op een regelmatige wijze bodemstalen genomen om het gedrag van zouten in de geïrrigeerde bodem te bestuderen doorheen meerdere irrigatieseizoenen. Regelmatig werden stalen genomen van de bodem en het bodemwater. De kwaliteit van het irrigatiewater werd opgemeten en in de Robertson boerderij werd de kwaliteit van het irrigatiewater aangepast aan zes verschillende zoutniveaus tussen 30 mS m-1 en 500 mS m^{-1}. In de Broodkraal en Glenrosa boerderijen werden grootschalige onderzoeken uitgevoerd om het zoutgehalte over grotere oppervlakten in te schatten. De Broodkraal boerderij bestond hoofdzakelijk uit een nieuw opgericht bedrijf van tafeldruiven, hetgeen de mogelijkheid bood om de initiële veranderingen van bodemzouten te bestuderen tijdens irrigatie met zout water. Bij de Glenrosa boerderij was er zelfs de mogelijkheid om de bodem te karakteriseren voordat er geïrrigeerde wijngaarden werden aangelegd.

Gedetailleerde puntmetingen werden uitgevoerd om de verdeling en veranderingen van zouten doorheen het bodemprofiel te onderzoeken. Daarnaast werden met zelf ontworpen en gepatenteerde 'suction cup lysimeters' de seizoensveranderingen van het zoutgehalte in het

bodemwater gevolgd onder verschillende zout regimes. Deze resultaten werden gebruikt om gemiddelde zout-diepte trends te karakteriseren, deze warden het best weergegeven door een lineaire functie, en hun evolutie doorheen de tijd te volgen. Een methode werd voorgesteld om het aantal stalen dat moet genomen worden om de zout-diepte trend te bepalen, en zo de kwaliteit van het wegdrainerend bodemwater in te schatten, te verminderen. Eén van de belangrijkste vaststelling was dat de drempelwaarde voor de elektrische geleidbaarheid van de verzadigingspasta van de bodem beter op 100 mS m^{-1} gesteld wordt dan de gebruikelijke 150 mS m^{-1}, en dat de gevoeligheid van wijnstokken aan hoge zoutdosissen toeneemt met het aantal jaren dat ze blootgesteld zijn aan zout water irrigatie.

Aldus hielpen de gedetailleerde kartering van de Broodkraal en Glenrosa boerderijen om het regionaal gedrag van verzilting te modelleren. Deze studie liet toe om een alomvattend begrip te krijgen van de dynamiek in bodemverzilting in een geïrrigeerd landschap waarbij verzilt irrigatiewater gebruikt wordt.

LIST OF ACRONYMS

BRC	Berg River Catchment
cdf	Cumulative distribution function
Df	Degrees of freedom
DWAF	Department of Water Affairs and Forestry of SA
EC	Electrical conductivity
ECa	Apparent electrical conductivity
EC_d	Electrical conductivity of drainage water
EC_e	Electrical conductivity of a saturated soil paste extract
EC_i	Electrical conductivity of the irrigation water
EC_{ih}	The half effect of EC_i used in the calculation of yield
EC_t	Threshold EC value
EC_{sw}	Electrical conductivity of the soil water
EC_{swf}	Electrical conductivity of the soil water at field capacity
EM38	Proximal sensor for electromagnetic induction measurements
E_{pan}	Class A-pan evaporation
ER	Electrical resistance of a saturated soil paste
ET	Evapotranspiration
icdf	Inverse cumulative distribution function
LWP	Leaf water potential
MAP	Mean annual precipitation
masl	Meters above sea level

PR	Profile ratio defined as $EM38_{hor}$ / $EM38_{vert}$
PTF	Pedotransfer function
RSE	Riviersonderend (Sub-catchment of the Breede River)
SAR	Sodium adsorption ratio
SCL	Suction cup lysimeter
SS	Sum of squares
TC	Trunk circumference
TMS	Table Mountain sandstone
UBRC	Upper Breede River Catchment
WC	Western Cape Province
WRC	Water Research Commission of SA

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 GENERAL INTRODUCTION

The prime objective of sustainable agriculture, be it commercial or small scale farming, should always be that the soil and water resources are preserved and maintained for future generations. In order to meet this objective, a sound knowledge of these two resources, as well as good managerial skills, is required. Unfortunately, soil and water are the two most misunderstood of all natural resources. This is well conveyed by Hillel (1991): "*All terrestrial life ultimately depends on soil and water. So commonplace and seemingly abundant are these elements that we tend to treat them contemptuously. The very manner in which we use such terms as 'dirty', 'soiled', 'muddled', and 'watered down' betrays our disdain. But in denigrating and degrading these precious resources, we do ourselves and our descendants great - and perhaps irreparable- harm, as shown by disastrous failures of past civilisations*".

Mapping of soil salinity depicts the salinity state at a specific instant in time. On the other hand, repeated mapping of soil, salinity will generate information about its dynamics and provides a perspective to manage it. This space–time modelling requires a consideration of area, depth, salinity status and time intervals. The complexity of dealing with a 4-dimensional process involves a specific sequence of steps (Heuvelink, 1998; Heuvelink & Pebesma, 1999; Heuvelink & Webster, 2001).

It is therefore of the utmost importance to understand soil salinity behaviour in a one dimensional approach, i.e. soil depth, before one can make predictions on a regional and temporal scale.

1.1 Background and problem description

During 1999 South Africa implemented a new water law that placed new demands on all water users. The basic right of access to water was constitutionalised. This brought about a reorganisation of water management as a result of the larger number of rightful users. It also created a need for research geared towards developing catchment management strategies, providing researchers with an opportunity to reorganise and reuse old data to serve this new goal. The incentive was thus created to move from site-specific measurements to more regional and GIS-based investigations that would provide a better basis for decision making.

There is a need to extrapolate point information, gained from measurements in detailed studies, to whole catchments. This study was therefore aimed at expanding existing knowledge, using geostatistics and GIS-applications, in order to establish the basis of a catchment management system.

The effect of soil management is ultimately tested by the response of crops cultivated on that soil. This is especially the case in agriculture where saline irrigation water is used. Such information can be obtained from remotely sensed images that involve the detection of various canopy parameters, in addition to the more direct method of mapping crop yield.

Since 1987, researchers of the Department of Soil Science at the University of Stellenbosch have been assessing the salt tolerance of grapevines in the Berg River Catchment (BRC), upper Breede River Catchment (UBRC) and Stellenbosch regions of the Western Cape Province (WC) (Figure 2.01). Wine grapes are the principal crop under irrigation in the UBRC and it is on the increase in the BRC. This expansion within the BRC, is becoming increasingly evident in its effect on water quality. On the other hand, the Cape Town Metropolis is also expanding rapidly. It has required supplementary water since 2006 and since the Berg and Breede Rivers are the nearest alternative, urban water use from these rivers has placed a large burden on local agriculture. These two catchments are not the only amongst the most important food producing areas in South Africa, but also the largest sources of employment in the WC region. Concern exists that increased irrigation water salinity may affect the sustainability of agricultural production of this region. Even in Stellenbosch, where only supplementary irrigation is applied, poorer water quality or the lack of water may also in future hamper sustained grape production.

1.1.1 Water requirements in the Berg and Breede River catchments

In the Berg River catchment, agriculture and specifically irrigation, is the largest consumer of water. Recently, the whole water supply and management system was brought in line with the new water laws of South Africa (1999), the principles of which reflect fundamental concepts contained in the constitution of South Africa.

A comparison of the estimated water requirement and the total storage capacity of all the large dams listed by the Department of Water Affairs in each of the three regions supporting the Larger Cape Town metropolitan area (Anonymous, 1986), shows that the volume of water stored in dams is insufficient to meet the requirements in those regions. In 2006, the annual water requirement in the Berg River catchment exceeded the existing storage capacity, even though this was only expected to happen in 2008. Stringent water restrictions had to be put in place (Shand *et al.*, 1993; Berbel & Gomez-Limon, 2000).

A portion of the water used for irrigation will, however, always be returned to the river system by drainage, albeit at a higher salt content because of evapotranspiration losses and salt gains during leaching. In the BRC, for example, Moolman and de Clercq (1992) illustrated that drainage losses equivalent to as much as 40 % of the applied water can occur under certain circumstances. However, very little quantitative data are available regarding irrigation return flow in the different river systems of the WC. If a river system is used both to convey water to irrigated fields and to drain the landscape, some of the return flow will inevitably be used by downstream irrigators, thereby increasing the overall efficiency of water use (Cass, 1986; Moolman and Lambrechts, 1996).

More recently, Görgens and de Clercq (2001) indicated that for the BRC, return flow and the quality thereof should be considered separately from the dryland salinity problem.

1.1.2 Impact of irrigated agriculture on soil and surface water quality

Irrigated agriculture has a large impact on the soil and surrounding surface water conditions. Moolman and Lambrechts (1996) indicated that a soil in its original state is in equilibrium with its environment. For example, the chemical composition of a natural soil is a direct result of soil forming factors such as climate, (particularly rainfall and temperature), natural vegetation and parent material. With the introduction of irrigation, especially in semi-arid and arid regions, this equilibrium is disturbed and the weathering of soil minerals is accelerated. This in turn releases soluble salt into the soil solution, which leaches past the root zone and eventually finds its way to a river. As a direct consequence, rivers flowing through regions with irrigation schemes invariably experience an increase in salt concentration. The degree of mineralisation in rivers is therefore a function of the underlying geology, the amount and rate of irrigation return flow and the degree to which dryland salinity has developed. Irrigation return flow is to a very large extent determined by irrigation management and efficiency (Moolman and Lambrechts, 1996).

In the WC, the main concern for the sustainability of the rivers and environment is the increase in the salt content. Two examples serve to justify this concern.

Firstly, in Table 1.01, some statistics on the progressive increase in the salt content of the Berg River from Franschhoek downstream to Misverstand are listed. These values are the summary statistics of chemical data collected between 1985 and 1990 at various positions along the Berg River. It shows the increasing trend in EC and total dissolved solids (TDS) downstream as the water finds its way toward the river mouth. Expansion of irrigated agriculture in the middle and lower reaches of the Berg River, as well as the UBRC, is bound to mobilise salts. Without the necessary precautions, such as artificial drainage and proper on-farm irrigation management, the salt content of the Berg River will also inevitably increase. This in turn can have serious effects on agriculture, industry and the ecology of the river.

Table 1.01 Summary statistics of the total salt content in the Berg River, expressed in terms of the 50 and 99 percentiles for the specific EC and total dissolved solid content at various positions along the Berg River (Moolman and Lambrechts, 1996).

Sampling Site	Distance upstream (km)	Collection period (year)	EC (mS m^{-1}) percentile 50	99	TDS (mg/l)
Driefontein	155	5	4.8	18.9	19
Paarl North	135	10	10.4	21.4	60
Hermon Bridge	90	5	20.7	47.0	111
Drie Heuwels	75	18	25.0	66.0	134
Misverstand	50	6	36.0	87.2	188

Secondly, research conducted in the UBRC over the past three decades, has suggested that the steady increase in salt content of the BRC and its tributaries is directly related to irrigation (e.g. Fourie 1976, Moolman *et al*. 1983, Moolman 1985, Greef, 1990). Other surveys in the UBRC (Moolman and de Clercq, 1992; Bruwer, 1993; Görgens, 1994; de Clercq *et al*., 2001) have shown that drainage losses from irrigated lands can be as much as 40 % of the irrigated amount. This suggests that the farmers themselves are partly responsible for the salinity problem of the UBRC. In contrast, the BRC irrigation developments are mainly along the river system, occupying the lowest areas in the valley and therefore return flow is affected by and affects a small part of the system. It is only now that areas further away from the river (as is allowed by the new water law) are being developed for irrigated agriculture that the magnitude and impact of return flow are expanding (de Clercq *et al.*, 2001). This is why the detailed mapping of salinity and its dynamics is essential.

1.2 The general and specific aims of this study

The general aim of this thesis is to provide methodology through which the time-space dynamics of soil salinity, within the framework of saline irrigated viticulture, can be assessed more rapidly and accurately on a regional scale.

The specific aims of the study were therefore as follows:

- To investigate the sensitivity of grapevines (*vitis vinifera, L*), to the quality of irrigation water it receives.
- To establish soil water sampling (as opposed to laboratory estimation using a saturated paste) as a preferred basis for measuring the effect of saline irrigation on plants.
- To analyze from the repetitive sampling of soil water, ways of predicting soil salinity profiles over time, using polynomials of the lowest possible order and to indicate the minimum amount of information required to make such predictions.
- To optimize soil sampling positions in view of the fact that partial wetting of soil during irrigation is the norm within the study area.
- To explore the positive management aspects of partial wetting in terms of salt storage during the irrigation season.
- To assess and model long-term irrigation and the change in soil salinity on a regional scale and link this to regional sustainability of table grape production.
- To quantify the relationships between soil classification, soil electromagnetic induction measurements and topography as an improved basis for mapping soil salinity on a catchment scale.

1.3 General structure of the thesis

The thesis first reviews (Chapter 2) the state of knowledge on the salinity problem in the Western Cape region that existed at the commencement of the study. The study area is described with regard to features such as geology, geomorphology, climate, available water resources, the soils and their chemistry and land use.

In Chapter 3, an overview is presented of the saline irrigation experiments that formed the basis for the research. Here the sensitivity of vines to water quality was investigated. Because of the impact of water quality on grape production, these studies prompted the investigations that followed, aimed at discovering the level of water management needed both on a farm scale and a regional scale.

An automated system for retrieving soil water samples was developed and its operation and construction are presented in Chapter 4. This made possible the measurement of depth trends in soil salinity in a vineyard after prolonged irrigation with saline water.

An account is given in Chapter 5 of how the automated retrieval system allowed data to be collected as the basis for predicting soil salinity profiles over time, using first order polynomials, and then linking such capability to remote sensing applications.

The seasonal change in soil salinity with depth, measured at a number of points in the landscape is dealt with in Chapter 6. Chapter 7 explores the profile distribution of salts between vine rows. The fact that most irrigation systems are based on partial wetting of the soil surface raised important considerations for regional salinity assessment.

In Chapter 8, the effect of long-term irrigation on the variation of soil salinity in vineyards is considered on a regional scale, with particular emphasis on predicting the response of vineyards to such variation. The regional sustainability, of table grape production on saline soils, is investigated in Chapter 9. These two chapters deal with the space-time response of soils and vines to salinity of irrigation water in the region.

Since data were collected on the distribution of salinity in the study area, the question arose as to whether salinity could be correlated with soil type. In Chapter 10, a method is proposed for integrating electromagnetic sensor (EM38) mapping with soil salinity, elevation and pedological classification as a further basis for catchment wide extrapolating of salinity assessment.

Detailed soil data from four sites with contrasting soil types were used to demonstrate the effect of saline irrigation on salt distribution and the quality and impact of return flow. The experimental structure and spatial scope of the study are indicated in Table 1.02. The geographic location of the listed sites is indicated later in Figure 2.02.

These studies were carried out over more than a decade and for the most part have been either published or presented at conferences. There is inevitably some overlap and repetition between the chapters but they are presented in a sequence, which hopefully provides a useful perspective of how soil, plant and hydrological information can be collected and interpreted geostatistically in order to facilitate catchment management.

Table 1.02 The experimental structure of the study

Activity	**Location (Figure 2.02)**
Monitoring the movement and distribution of water and salt	Goedemoed farm Robertson farm
Measurement of soil and plant responses to irrigation (salinity, pH, EC, grapevine canopy and trunk dimension)	Robertson farm Broodkraal farm
Regional soil salinity and EM38 field sensing, mapping and interpretation	Broodkraal farm Glenrosa farm

2 THE STUDY AREA AND ITS SOIL SALINITY PROBLEM

2.1 The geographical location

The study area is located in the Western Cape Province (WP) of South Africa, more specifically the Berg River Catchment (BRC) and the upper Breede River Catchment (UBRC). These two catchments have as central coordinates, S32.5° E18.5° and S33.5° E19.5°, respectively. The study area also forms part of the greater Winter Rainfall region (Figures 2.01 and 2.02).

It is important to realize the very diverse and contrasting occurrence of natural phenomena in the study area. The origins of the rivers are within the folded mountain ranges of the region, the Hottentots-Holland and the Drakenstein ranges, respectively. These ranges have the second highest recorded rainfall in South Africa, exceeding 2000 mm per annum. From here, both rivers flow through regions that are predominantly winter rainfall, to a region with very low rainfall. So, both rivers flow from regions where only supplementary irrigation is used to a region where full-scale irrigation activities are imperative.

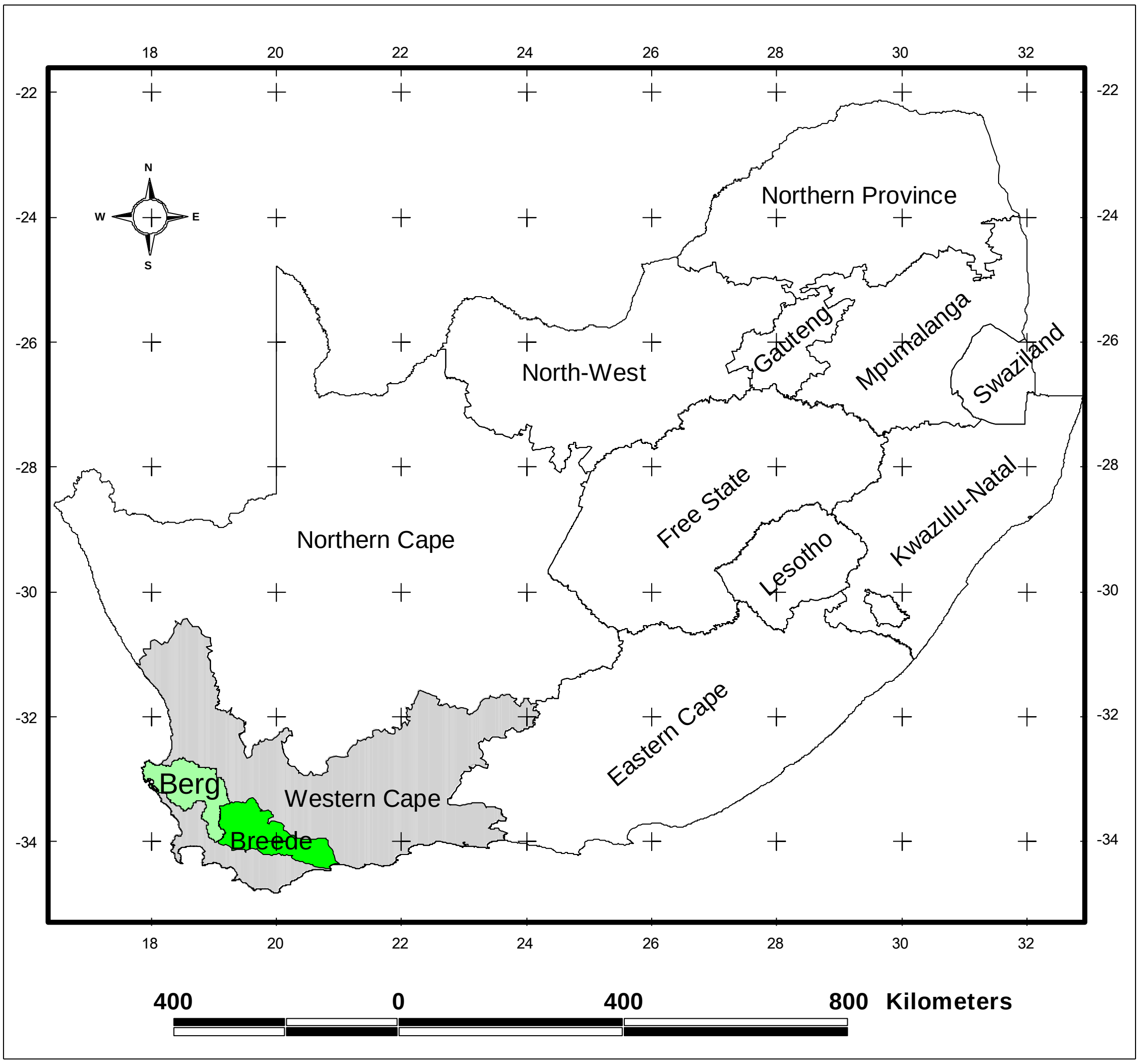

Figure 2.01 Provinces of South Africa and the two catchments (Berg and Breede River) representing the study area of this thesis located in the Western Cape.

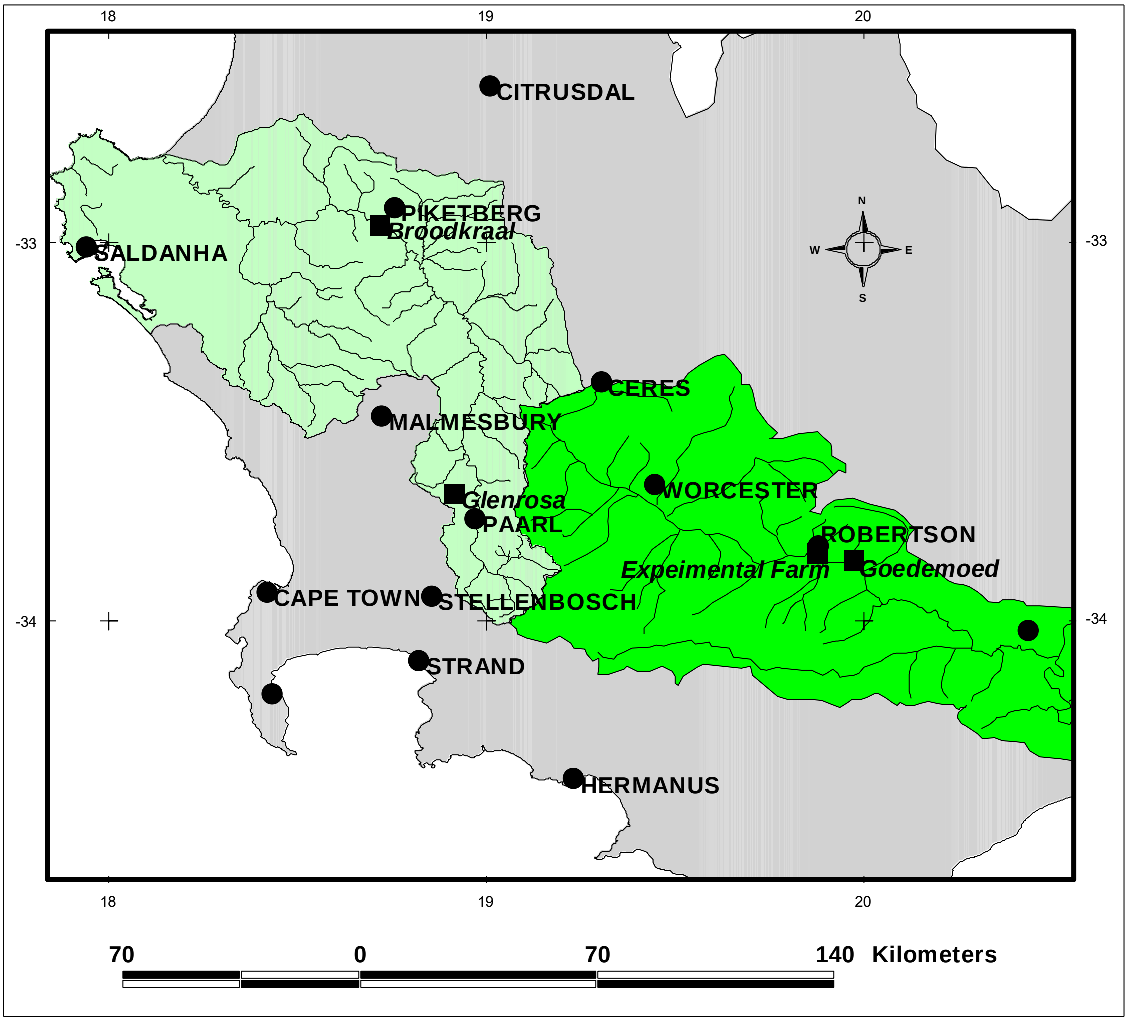

Figure 2.02 The study area with location of the experimental sites indicated by squares.

2.2 A physical perspective of the study area

2.2.1 Geomorphology and geology

The study area can be sub-divided into two broad physiographic regions, each with its own distinct terrain morphology (Wellington, 1955). These are broadly termed the Cape Fold Belt, consisting of mountains with a north west to south east orientation, and the Coastal Foreland, representing the extensive coastal plains cut by rivers that emerge from the mountain ranges. The Cape Fold Belt is characterised by pronounced folded mountain ranges consisting of resistant quartzitic rocks (Trusswell, 1987; Kent, 1980). Generally, slopes are steep to very steep, with exposed rock or with a thin soil cover. Except for some afforestation, these mountain ranges are of negligible use for agricultural activities.

The folded mountain ranges gave preference to the formation of rivers in a north-westerly/south-easterly direction. This resulted from the impact of the Gondwana break-up that was preceded by an apparent collision (resulting in a zone of convergence) in a north-easterly direction (Trusswell, 1987).

Prominent features of the folded mountain zone therefore are the numerous downfold and fault valleys (e.g. Jonkershoek and Franschhoek valleys). These valleys are usually underlain by easily weatherable rocks with high clay forming potential. Most of the valley to the north opens up through Karoo sediments (Karoo is the area bordering the Cape Folded Belt to the north), which are predominantly saline with a high clay/silt forming potential. In these cases locally derived sandy colluvial (gravity transported) and fluvial (water transported) sediments from the mountain slopes cover the clay forming rocks of the valley bottom.

In the lower BRC, the western Coastal Foreland is broken by a number of igneous rock bodies (granite rocks), which also formed the high Paarl- and Paardeberg or the lower Darling and Vredenburg hills. These igneous intrusions are associated with moderate to fairly deep, red to brown, clay loam to clay soils, with moderately steep to steep slopes (usually $\geq$ 8 %).

In the UBRC the river runs through the Worcester-Robertson region to the South Coastal Foreland, but this study will mainly focus on the Worcester-Robertson region, which is cast in similar Table Mountain sandstone mountain ranges as the BRC. This upper section of the valley is mostly quite narrow (10 to 20 km) and the soil mainly developed from Karoo sediments.

The morphological regions of the BRC and UBRC are given in Figure 2.03.

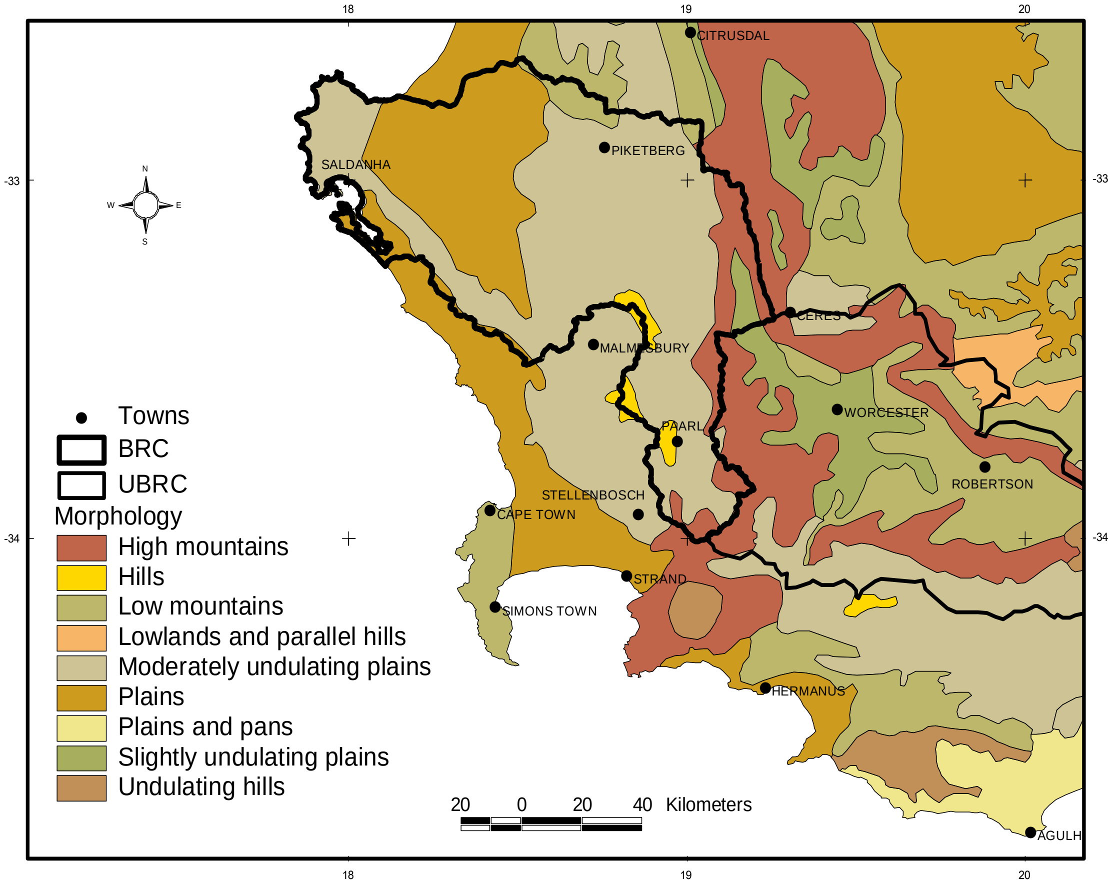

Figure 2.03 The morphology of the central part of the WC.

Both the BRC and UBRC have a terracing nature between the river and the mountains. The terraces are usually quite old in the higher regions and are generally considered part of the old African surface. The land surfaces within the study area are in most cases very old and in balance with the prevailing conditions. The old African land surfaces and the

African geology are considered the most stable and the oldest in the world. Even the natural vegetation types that occur are genetically very well adapted to their environment.

The Cape fold mountain ranges are dated 300 million year and similar in age to the Gondwana episode and dates from the Carboniferous period (Trusswell, 1987). Their positon can be seen in Figure 2.04, indicated as Arenites and Luctaceous Arenites.

Most of the study area is underlain by granite (Figure 2.04) to a depth varying between 0 and 120 m below the land surface. This deep contact, with the more recent granite body, varies between a granite/phyllite, granite/schist contact and a granite/sandstone contact (Trusswell, 1987; Kent, 1980).

The Berg River itself flows from its origin in the Cape Super Group to the older Klipheuwel Formation and Malmesbury shale Formation and the Cape Granites (Table 2.01 and Figure 2.04). The river runs for the last 50 km toward the coast, through a sand and limestone belt that lines the west coast of the Cape. In terms of salinity, from Franschhoek to Paarl the river runs through more recent sedimentary material that originated from the Table Mountain Sandstones, which does not contribute to the salt content of the water. From approximately Wellington, the river runs through a region with more salts that originated from the parent Malmesbury shale material itself (Trusswell, 1987; Kent, 1980). The latter statement is however not entirely true as de Clercq *et al*. (in press) indicated the secondary origin of these salts.

Similarly, the UBRC has a stratigraphical sequence with the youngest being the Table Mountain Sandstones, underlain by mostly Karoo sediments in particular the Bokkeveld shale Formation and below that in places, the Cape granites (Figure 2.04).

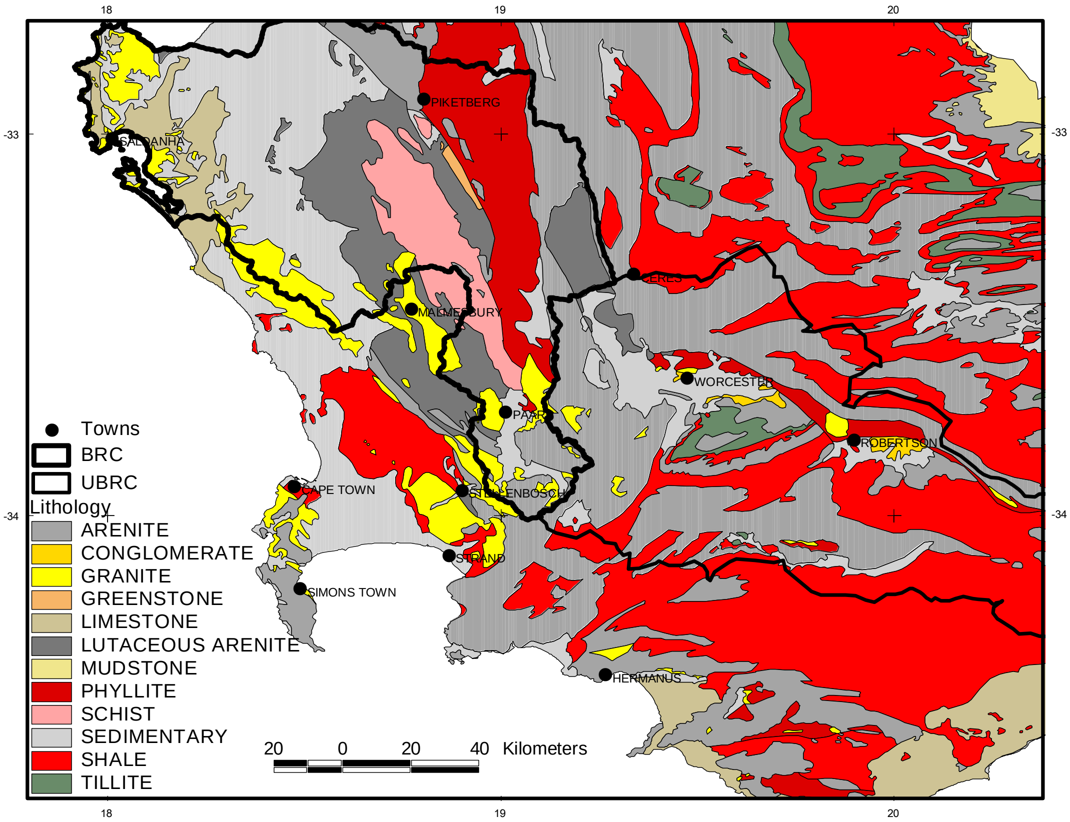

Figure 2.04 A Map of the Berg River catchment to show the geology and in particular the shale formations of the region.

Table 2.01 The geology of the BRC and UBRC with lithological classification and stratigraphical units and related era.

Group and time	Sub unit	Lithology
Recent Late Cenozoic	Recent Sediments Recent Coastal Sediments	Sedimentary Limestone
Karoo Super Group Mesozoic	Dwaika Formation Bokkeveld Formation Enon Formation	Mudstone Tillite Shale Conglomerate
Cape Supergroup Middle Palaeozoic	Pakhuis formation Table Mountain Sandstone	Tillite Arenites
Cape Ganite Suite Early Palaeozoic		Granite
Malmesbury Group Namibian	Malmesbury Shales	Greenstone Luctaceous Arenites Phyllite Schist

2.2.2 Climate

Climate is to a large extent the driving force in the occurrence of salinity in a landscape. Shalhevet (1994) reported that three elements of climate, namely temperature, humidity and rainfall, might influence salt tolerance and salinity response in plants, with temperature being the most crucial. High temperatures increase the stress level to which a crop is exposed, either because of increased transpiration rate or because of the effect of temperature on the biochemical transformations in the leaf. High atmospheric humidity tends to decrease the crop stress level to some extent, thus reducing salinity damage, as has been demonstrated for beans (Hoffman *et al.,* 1978). Shalhevet (1994) concluded that under environmental conditions of high temperature and low humidity, the salt tolerance of plants might change so that the threshold salinity decreases and the slope of the response function increases, making the crop more sensitive to salinity. Prior *et al.* (1992b) in Australia found that symptoms of leaf damage that appeared in December or January were more related to climatic stress than to chloride or sodium levels.

In the BRC and UBRC it is possible to restrict the evaporative demand of the atmosphere in harsh climatic conditions by using shade netting. Under shade netting, the relative humidity rises, the leaf surface temperature is lower and the soil surface temperature is lower. The result is a lower transpiration rate and consequently less salt uptake. The plant can consequently cope with much smaller osmotic potential differences.

An additional factor in causing salt-affected soils is the high potential evapo-transpiration in these low rainfall areas, which increases the concentration of salts in both soils and surface waters. It has been estimated that evaporation losses can range from 50 to 90% in arid regions, resulting in 2- to 20-fold increases in soluble salts (Yaalon, 1963).

The study area has a Mediterranean climate. Fey and de Clercq (2004) indicated that, though the region is predominantly a winter rainfall region, most precipitation takes place in the upper parts of the valleys close to and on the mountains. Towards the coast, the rainfall is generally lower, unpredictable and poorly distributed in time and space. Towards the Piketberg, 30 km from the coast, a much higher rainfall is experienced. From the coast the mean annual precipitation varies from 50 mm to more than 1000 mm in the combined apex of the Franschhoek, Jonkershoek and Hottentots-Holland mountain ranges. More than 80 % of this region has an annual rainfall between 200 mm and 500 mm. Strong winds, especially during summer, are very common and lead to severe wind erosion. Frost and snow are experienced in winter, mainly in regions with elevation higher than 800 m. Both are uncommon in the coastal zones.

Figure 2.05 shows the location of some weather stations in the BRC and Tables 2.02 to 2.04 provide data from these weather stations. From these measurements the effect of elevation and distance from the sea on the climate is quite clear (de Clercq *et al*, 2008).

This gradual change between Franschhoek and Velddrif determines the irrigation management approach from the South East to the North West, ranging from no irrigation, to supplementary irrigation or full scale irrigation. The amount of fresh water available, the electrical conductivity of the irrigation water (EC_i), and the electrical conductivity of the soil water (EC_{sw}) of the soils in general, all follows this sequence.

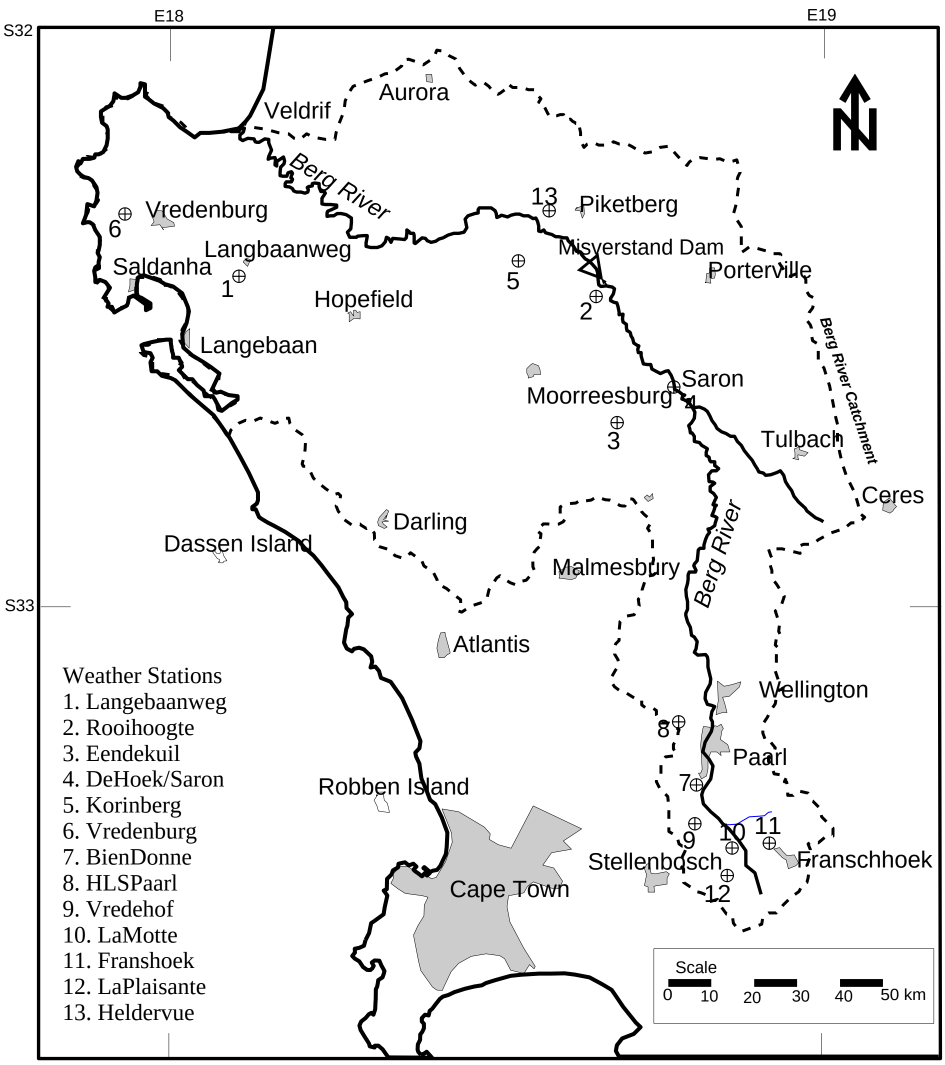

Figure 2.05 Map of the BRC showing the location of weather stations.

Table 2.02 provides information on the distribution of the mean annual precipitation (MAP) in the BRC. It is clear that the monthly means in precipitation and the MAP are linked to elevation and distance from the sea. The same cannot be said for the mean temperatures in the BRC (Table 2.03). Table 2.04, however, where the mean pan-evapotranspiration (E_{pan}) values were subtracted from the MAP, shows a precipitation deficit for the catchment on a monthly basis and a yearly basis. It is clear that most of the farms shown in these tables, with the exception of Heldervue, have a precipitation shortage mainly in the summer months. This implies that for summer crops, water has to be stored during winter for irrigation.

Table 2.02 Average monthly rainfall for selected stations in the Berg River catchment (mm per day) and the mean annual precipitation (MAP in mm per year).

Station	Elevation	Month												MAP
	masl	J	F	M	A	M	J	J	A	S	O	N	D	
Langebaanweg	31	0.2	0.2	0.4	0.7	1.3	1.3	1.5	1.6	0.8	0.4	0.4	0.2	270
Rooihoogte	45	0.2	0.2	0.9	1.4	1.8	2	2.3	2	1.4	0.5	0.4	0.2	399
Eendekuil	114	0.1	0.3	0.5	1.2	0.7	1.9	1.2	1.8	0.8	0.5	0.2	0.1	279
DeHoek/Saron	115	0.3	0.5	1.4	1.7	1.8	3.2	2.9	3.9	2.3	0.7	0.7	0.3	591
Korinberg	128	0.2	0.2	0.4	0.9	1.8	2.1	1.6	1.8	0.8	0.9	0.5	0.2	342
Vredenburg	128	0.3	0.1	0.4	0.7	1.6	1.7	1.8	1.8	0.8	0.5	0.4	0.3	312
BienDonne	138	0.7	0.7	1	2.3	4.1	4.5	4.1	3.9	2.3	1.6	1	0.7	807
HLSPaarl	149	0.4	0.4	0.7	1.1	2.3	2.5	2.6	2.5	1.6	0.8	0.6	0.4	477
Vredehof	154	0.7	0.4	1.8	1.8	3	3.1	3.6	3.4	3	0.9	0.8	0.7	696
LaMotte	206	1.3	0.9	1.5	1.9	4.1	4.3	3.9	3.6	3	1.4	0.9	1.3	843
Franshoek	244	0.5	0.7	0.9	2.3	3.9	4.7	4.7	4.3	2.2	1.9	1.1	0.5	831
LaPlaisante	260	0.4	0.6	0.8	1.5	2.7	3.2	2.7	3	1.7	1.2	0.8	0.4	570
Heldervue	755	0.7	0.7	1.1	2.2	3.9	4.6	4.3	4.3	2.4	1.7	1.2	0.7	834

Table 2.03 Daily average temperature, per month in °C.

Station	Elevation	Month												Yearly
	masl	J	F	M	A	M	J	J	A	S	O	N	D	Average
Langebaanweg	31	21.9	22.6	20	20	15	13	12	13	15	15	19.1	20.2	17.2
Rooihoogte	45	23.8	24.5	22	19	16	13	11	13	15	18	21.4	22.5	18.3
Eendekuil	114	25.8	25.7	23	20	17	13	12	14	15	17	22.2	23.9	19.1
DeHoek/Saron	115	23.8	24.9	23	20	17	14	13	14	16	18	21	23	19.0
Korinberg	128	24.6	25.6	24	22	17	15	13	13	16	18	21	23.3	19.3
Vredenburg	128	20.2	20.6	20	19	16	14	13	14	15	16	18.1	19.4	17.1
BienDonne	138	22.3	22.6	21	18	15	12	12	12	14	17	19.4	20.9	17.1
HLSPaarl	149	22.7	23.7	22	19	16	13	12	13	14	17	20	21.6	17.9
Vredehof	154	22.7	23.5	21	19	16	13	12	14	15	17	20.8	21.5	18.0
LaMotte	206	22.1	22.8	21	19	16	13	12	13	15	17	19.5	21.2	17.6
Franshoek	244	22.2	23.5	22	19	15	13	12	12	13	17	20.2	20.7	17.4
LaPlaisante	260	22.9	23.1	22	18	15	13	12	12	14	17	19.9	21.6	17.5
Heldervue	755	19.1	19.3	18	15	13	11	11	11	12	14	16.7	18.3	14.7

Table 2.04 The average daily rainfall (per month) minus the average daily E_{pan} (per month) of selected weather stations of the Berg River catchment given in mm per day and the yearly total in mm per year.

Station	Elevation	Month												Yearly
	masl	J	F	M	A	M	J	J	A	S	O	N	D	Total
Langebaanweg	31	-11	-9.6	-6.9	-4.6	-1.2	-0.3	0.1	-0.5	-4.2	-8.2	-10	-11	-1992
Rooihoogte	45	-9.8	-9.7	-5	-2	1	2.3	3.1	1.9	-0.6	-5.6	-8.2	-9.8	-1272
Eendekuil	114	-13	-12	-7.4	-3.5	-2.3	1.8	0.7	1.1	-2.5	-6.4	-11	-13	-2016
DeHoek/Saron	115	-9.5	-8.8	-4.2	-1.9	0.5	4.3	3.7	5.1	0.3	-5.2	-7.8	-9.5	-990
Korinberg	128	-11	-11	-8.8	-4.8	0.2	2	1	0.8	-2.7	-5	-8.7	-11	-1785
Vredenburg	128	-10	-9.8	-7	-4	-0.1	0.8	1.1	0.5	-3	-6.2	-8.4	-10	-1707
BienDonne	138	-8.3	-7.7	-5.1	0.1	5.7	7.4	6.3	5	0.6	-3.1	-6.6	-8.3	-420
HLSPaarl	149	-9.3	-8.9	-6	-2.6	1.7	3.1	3.2	2.3	-0.7	-4.8	-7.5	-9.3	-1164
Vredehof	154	-8.2	-8.5	-3.1	-0.7	3.1	4.4	5.2	4.1	1.9	-5.1	-8	-8.2	-693
LaMotte	206	-5.5	-6	-2.9	-0.1	5.5	6.8	5.8	4.3	2.4	-2.2	-4.9	-5.5	-69
Franshoek	244	-7.1	-6.5	-4	0.7	5.1	7.6	7.3	5.8	0.8	-1.2	-4.5	-7.1	-93
LaPlaisante	260	-9.1	-8	-5.5	-1.6	2.5	4.2	3.1	3.2	-0.6	-3.7	-7	-9.1	-948
Heldervue	755	-6.1	-5.5	-2.9	0.8	5.2	7.1	6.4	6.1	1.7	-1.4	-4.1	-6.1	36

2.2.3 Water Resources

2.2.3.1 Hydrology of the Berg River and the upper Breede River drainage regions

The mean annual precipitation (MAP) for the BRC is 456 mm per year, which is considerably less than the world mean for terrestrial surfaces, i.e. 746 mm per year (Alexander, 1985; DWAF, 1986; Baumgartner & Reichel, 1975; Bennie and Hensley, 2001).

The MAP of this region is also less than the MAP of South Africa (501 mm, Bennie and Hensley, 2001), but the runoff coefficient of 16.8 % is well above the national mean of 9 %. A runoff coefficient of 9 % means that 91% of the MAP evaporates directly from the soil back to the atmosphere and never reaches a river (Anonymous, 1986; Lipton *et al.*, 1996). However, it is still very low when compared to the runoff coefficient of, for example, the Netherlands (57 %, DWAF, 1986). The low runoff coefficients are the result of high evaporation rates and not because of low rainfall. This is part of the mechanism in this region that keeps salt on the land and, as in most cases, close to the soil surface. This balance, however, is disturbed once the soils of the Berg River Catchment are irrigated with direct consequences to the quality of the water in the river system.

Flügel (1995) did a sub-catchment study in the BRC indicating the distribution of salt in the landscape and the most affected areas. He found that winter rainfall contributed for 23 % of the annual salt flux. He also indicated that the topography has a large impact on the occurrence of salt in the landscape. On hilltops the salinity was relatively low and salinity increased downhill toward the river. In fact the occurrence of salt in the landscape is very similar to that described in dryland salinity literature from Australia. The Renosterveld vegetation (which is part of the Fynbos biome and the natural veld type in the lower part of the BRC), although comprising of smallish shrubs, has a deep rooting system aand replacing it with winter wheat has changed the water balance with salts gradually moving higher in the profile as a result (Fey and de Clercq, 2004).

The demand for fresh water in the BRC and UBRC caused the government of SA to provide dams to meet this demand. Consequently, dams have been built since 1950, including the Wemmershoek-, Misverstand-, Voëlvlei- and (the youngest) the Franschhoek dam in the BRC. In the UBRC there are the Brandvlei and Kwaggaskloof dams close to Worcester, which supply the needs of irrigators. All of these dams were also adapted to supply water to the major urban areas of the WC (DWAF, 1986).

2.2.3.2 Irrigation water quality

An important factor affecting soil salinity is the quality of irrigation water that farmers receive. If the irrigation water contains high levels of soluble salts, Na, B, and trace elements, serious effects on plants and animals can be the result (Ayers and Westcot, 1985). Salinity problems are common in irrigated lands, with approximately one-third of the irrigated land in the United States being seriously salt-affected (Rhoades, 1993). In other countries, Postel (1989) reported it to be as high as 50 %. Areas affected include humid climate areas such as Holland, Sweden, Hungary, and Russia, and arid and semiarid regions such as the south-western United States, Australia, India, and the Middle East. Each year, about 400,000 ha of irrigated land are no longer productive because of salinity (Yaron, 1981).

The presence of selenium and other toxic elements (Cr, Hg) in subsurface drainage waters is also a problem in irrigated areas. Selenium (resulting from shale parent material) in drainage waters has caused massive death and deformity to fish and waterfowl in the Kesterson Reservoir of California (Schuler, 1990).

Poor quality water supply can be detrimental or hazardous to farmers and other water users alike. Wrong actions by farmers and other water users can in turn be detrimental to the environment. Therefore, sustainability can be defined in terms of the intersection between the two.

Rhoades *et al.* (1990) summarized the situation as follows. Irrigated agriculture cannot be sustained without adequate leaching and drainage to prevent excessive salinisation of the soil. Yet these processes are the very ones that contribute to the salt loading of the rivers and groundwater. Several approaches are available to control and minimize this hazard. Firstly, irrigation can be eliminated. This should be undertaken where the detrimental effects of irrigation outweigh the benefits. Secondly, the amount of water lost in seepage and deep percolation can be reduced, lessening the amount of saline water that passes through the soil and substrata. Thirdly, point sources of drainage return-flow into streams or rivers can be intercepted and diverted to other outlets and uses.

These concepts are quite crucial for water managers who have to supply water of good quality to farming communities and towns in a catchment such as the BRC and who do not have the ability to control drainage-return. Here, the only feasible solution appears to be to avoid irrigated agricultural expansion on unsuitable soils. Research into the exact origin of salts in the landscape and methods to contain these salts should also be continued until the problem is satisfactorily appreciated.

As an example of interpreting hazard, Moolman *et al.* (1999) and de Clercq *et al.* (2001) have shown, with a study done at Robertson in the Breede River valley that certain grapevine cultivars proved to be very sensitive to salinity. Though the grapevines showed low tolerance for saline irrigation water, sustainability was possible with irrigation water quality of up to 100 mS m^{-1}. Irrigation water quality in this case implied high risk for the farmer, but low risk for the environment (UBRC), which was accustomed to higher salinity levels during the summer months prior to the institution of water quality management in the Breede River System. One major problem in these irrigated areas (including the BRC and UBRC) is that salts accumulate unless they are leached. Saline irrigation water, low soil permeability, inadequate drainage, low rainfall, and poor irrigation management all cause salts to accumulate in soils. The salts must be leached for sustained crop production. However, it is leaching of these salts that result in saline drainage waters and that causes pollution of waters, a major concern in saline environments.

2.2.3.3 Irrigation return flow as a water source

Van Schilfgaarde (1974, 1990) mentions that there are ways to minimise effects of irrigation on downstream salinity. More precise irrigation management to limit the leaching fraction to the amount needed to maintain full crop growth can substantially reduce the amount of salt discharge in the drainage water. The recent developments in irrigation technology make the implementing of this concept more feasible. Drip irrigation has definite advantages when used in a saline soil/water environment. The main disadvantage is the much higher skill level it demands of the farmer. Irrigated land in semi-arid regions must have drainage. There must be a net downward flux of water in the soil to prevent the concentration of solutes in the soil solution from rising to a level that cannot be tolerated by the crop. Therefore when natural drainage is not sufficient, drainage systems must be installed (Van Schilfgaarde, 1990). The question that remains is how to dispose of drainage water.

Wolters (1992) argues that it is virtually impossible to prevent drainage losses. A 100 % crop-related irrigation efficiency, in theory implies that no water, and consequently no salts, are conveyed out of the area. Wolters (1992) also argues that a very high field application efficiency that would lead to a build-up of salinity is only acceptable when rainfall, or another source of water, at other times of the year (e.g. winter) leaches salts supplied with the irrigation water.

Kutilek and Nielsen (1994) expressed their concern that point sampling over a number of years has been done in numerous experiments around the world, but with nothing to emerge other than a comparison of soil status with crop production. These measurements did little for improving our understanding of how agricultural practices impact on the quality of water leaving the cultivated field or rangeland. They provided no direct information regarding the subtle changes in soil quality occurring on a farm or within an agricultural region.

The aim of this study is not to give an account of all previous attempts to model return flow but rather to propose an alternative approach of measuring the amounts of solutes lost from a landscape through the use of geostatistical techniques. By modelling the variation of elements in the irrigated soils, the total stock can be calculated and by repeating some measurements, changes over time can be monitored.

Görgens and de Clercq (2006) indicated that most irrigators in the Berg river valley currently make use of micro-irrigation. The order of occurrence in type of irrigation is: micro (49 %), drip (30 %), sprinkler and centre-pivot (18 %) and flood (3 %). Over-irrigation resulting in large potential drainage losses was observed. The findings of this research showed that the performance of the irrigation system depends in practice far more on the management of the system than on the system itself. The efficiency of water use by an irrigation system depends on certain losses in the system, including those due to:

- the irrigation system not having an application uniformity of 100%;
- management decisions;
- leakages in the distribution system;
- a change in EC that can lower infiltration rate and enhance runoff;
- irrigation systems that ignores soil units;
- stony soils or stony patches in irrigated lands.

It can thus be argued that irrigation return flow could also be regarded as a water source in both the BRC and UBRC.

2.2.4 Soils

The soil properties of this region vary away from the mountain ranges. In the BRC and UBRC, one often finds soils that format variance with expectations based on the underlying geology as a result of it being river transported material. For the BRC, one could distinguish between soils derived from transported material, soils on granite, soils on shales and soils on sandstones.

Because of the exceptionally large range of soil forms, soil series, as well as variation in topsoil texture, presence of coarse fragments and profile/horizon depths, pedological information was simplified in Figure 2.06. This must be viewed together with Figure 2.03 as the combination of morphology and soil type, since Figure 2.06 describes groups of soils with similar morphological, physical and chemical properties.

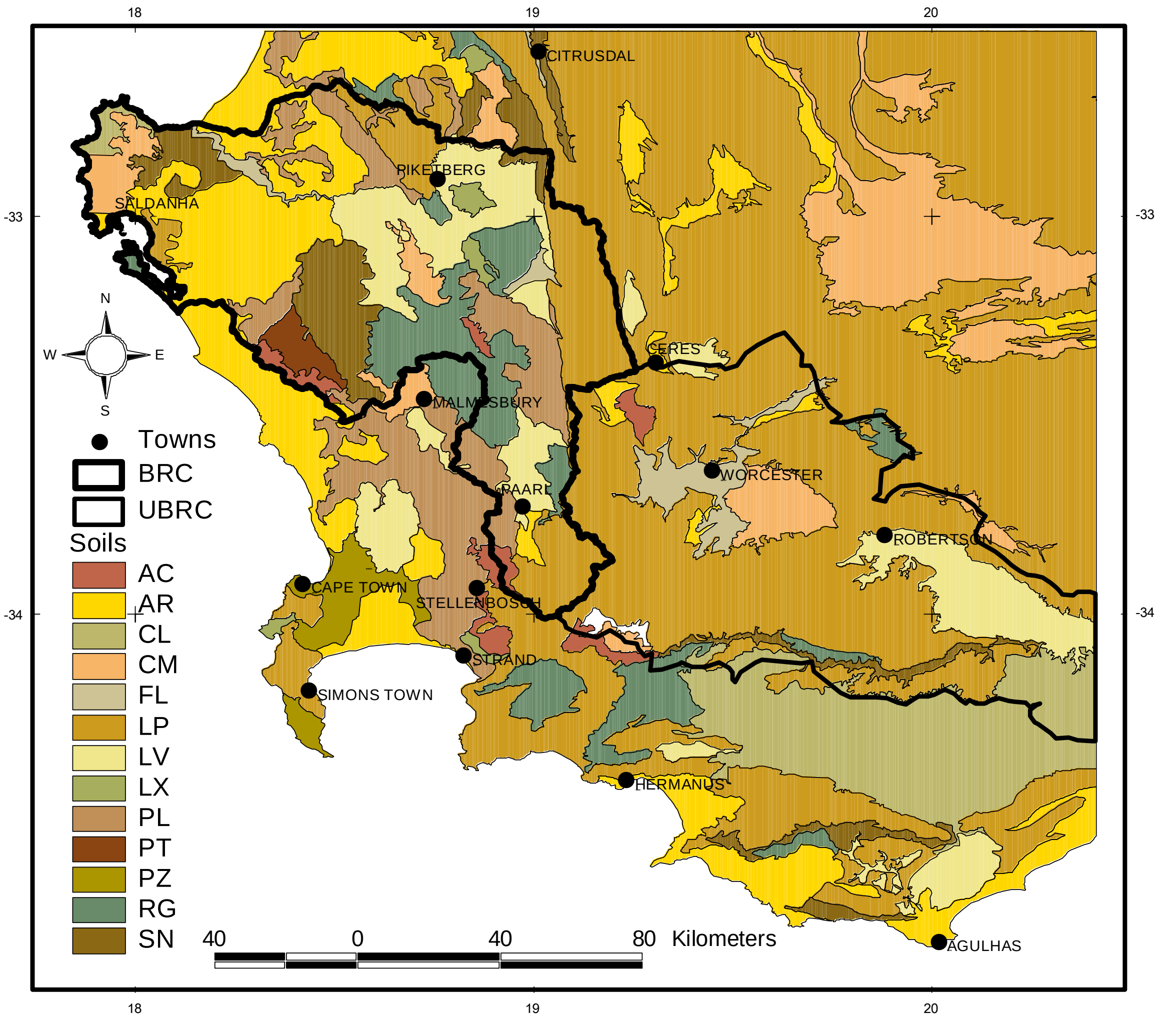

Figure 2.06 Land type map of the study area providing a distribution of soils in the WC based on the FAO (1998) classification (for codes see explanation in Table 2.05).

These can be considered as resource units, and all the soils in a resource unit would require similar management practices (e.g. fertilisation, cultivation, erosion protection methods), and the range of adapted crops and the production potential would be similar under defined climate and terrain conditions.

Table 2.05 A comparison between the FAO (1998) soil classification and the SA soil classification for the WC, indicating also diagnostic characteristics.

FAO code	FAO Soil	SA Soil Classes	Diagnostic horizon or material
AC	Acrisols	Shortlands	Red structured B
AR	Arenosols	Clovelly/Hutton	Red apedal B, yellow-brown apedal B,
CL	Calcisols	Gamoep	Soft or hardpan carbonate
CM	Cambisols	Cartref/Oakleaf/Glenrosa/Trawal/ Oudshoorn/Villafontes/Tukulu	Lithocutanic B or hard rock Plintic, Calcic, Hydromorphic
FL	Fluvisols	Dundee/Inhoek	Regic sand, stratified alluvium
LP	Leptosols	Mispah/Glenrosa	Inceptic, Lithocutanic B or hard rock
LV	Luvisols	Swartland/Klapmuts	(Duplex) Pedo- B or prismacutanic B
LX	Lixisols	Mayo (Very rare)	
PL	Planosols	Estcourt/Klapmuts	(Duplex) Pedocutanic B or prismacutanic B
PT	Plinthosols	Avalon/Longlands/Westleigh	Soft plinthic B or hard plinthic B
PZ	Podzols	Podzols/Fernwood	Podzol B, E horizon
RG	Regosols	Namib/Mispah	Regic sand, lithocutanic B or hard rock
SN	Solonetz	Sterkspruit/Escourt	Natric, Pedocutanic B or prismacutanic B

The soil properties limiting land use include high clay content, swelling clays, shallow soils, hardpans and fast weathering of most of the soils on shale. Most of the BRC and UBRC have soils that are not deep with hard rock at depths shallower than 50 cm. Most of these soils formed on the Malmesbury and Bokkeveld shales. When these soils are prepared for irrigation, they are deep ripped (to 1.2 m) and tilled and in many cases this loosens up a considerable amount of bedrock (Saayman & van Huyssteen, 1980). The bedrock is mixed into the soil and is considered a limiting factor in terms of management. The reason for this is that the maximum water holding capacity of these soils varies enormously and this causes considerable amounts of return flow from zones of lower water holding capacity.

Since this study was carried out in a region with high stone content it is important to discuss the possible effect stone content will have on the salt and water balance of these soils. Fey and de Clercq (2004) investigated the relationship between the stone, clay and water contents of a soil at field capacity. This result is given in Figure 2.07.

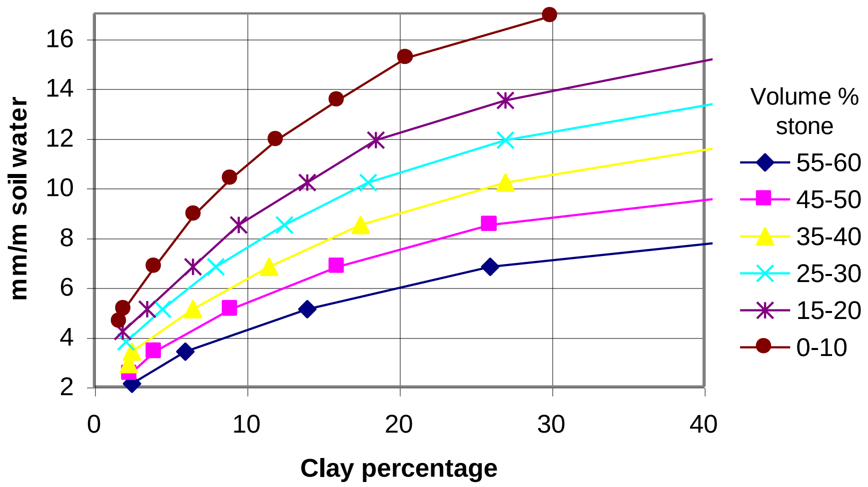

Figure 2.07 Relationship between clay percentage, soil water content and volume percent stone.

It is clear that the soil water content is influenced considerably by the clay and stone content. However, these results fail to show another important effect of stone content, namely that water infiltration into stony soils is characterised by a proliferation of preferential flow pathways.

Moolman *et al.* (1992) have shown that drainage from stony soils commences already about 15 minutes after irrigation has been initiated.

de Clercq *et al.* (2001) showed that clay content plays a major role in determining the effect that salinity, and in particular Na^+, has on a soil. Tanji (1990) noted that structural degradation of soils, depends not only on the levels of salinity and sodicity, but also on clay content and mineralogy, and the presence of binding materials such as organic matter and metal oxides. It is therefore impossible to predict a soil's tolerance of salinity and sodicity without taking these factors into account. It is possible, however, to classify soils according to their stability under saline irrigation, i.e., to distinguish soils that are prone to fast degradation when subjected to saline irrigation, soils that are stable and highly oxidised and do not deteriorate when irrigated with saline water, and soils that are saline in their natural state. These are important principles to bear in mind when modelling the effect of saline irrigation on soils.

Tanji (1990) also reports that soils containing between 15 to 30% clay, and less than 1.5% organic carbon, have a high potential for soil sealing and crusting. Tanji (1990) further notes that this potential increases if the EC_i is low. This is a typical problem in irrigated agriculture where the irrigation water quality varies during the season, resulting in poor infiltration rates when water with low EC_i is applied. It also becomes a problem when the farmer exploits different sources of water with different EC_i values.

For the same evapotranspiration rate, a sandy soil will lose proportionately more water than a clay soil, resulting in a more rapid increase in the soil solution concentration (Shalhevet, 1994). However, if sound irrigation practices are followed, the sandy soil will be irrigated more frequently, thereby reducing the damage caused by increased concentration.

The studies of Prior *et al.* (1992c) demonstrate the need to consider soil properties, specifically texture, when predicting the effects of saline water on grapevine productivity. In their study, irrigation with saline-sodic water caused more damage to sultana grapes in heavier than in lighter soils. Root zone depth and root density was lower in the heavier soils. The textural effect on yield was the result of reduced leaching and increased salinity in the more clayey soils with no effect in the yield response to soil salinity (Prior *et al.*, 1992c)

Soil properties that may alter the salt tolerance of plants and therefore total leaf surface area, are fertility, texture and structure (Shalhevet, 1994). In a generalised statement, Shalhevet (1994) wrote that at high fertility levels, there will be a larger yield reduction per unit increase in salinity than in low fertility soils, meaning that plants are more sensitive to salinity when conditions are conducive to high absolute yields. At extremely low fertility levels, when yields are low, an increase in salinity may have very little additional damaging effect on yield. Using this approach as a management strategy should, however, be avoided. The effects of soil texture and structure are manifested in their influence on the infiltration capacity, water-holding capacity and the ratio of saturated water content to field capacity. A combination of high salinity and low soil oxygen results in greater uptake and transport of chloride and sodium ions to shoots in grapevines, compared with high salinity and well drained, aerated conditions (West and Taylor, 1984). If applied for long enough, these combined factors can have a severe effect on the vine crop (Shainberg and Letev, 1984).

Since the terms salinity and sodicity of soil are used in this research, they are defined as follows (Verster & van Rooyen, 1990):

- Soil salinity: The amount of soluble salts in a soil, expressed in terms of conductivity of the saturation extract, mg kg^{-1}, percentage, or other convenient units.
- Soil sodicity: Soil with low soluble salt content but sufficient adsorbed sodium to have caused significant deflocculation. The exchangeable sodium percentage (ESP) is greater than 15.

2.2.5 Land use

The general land use pattern is driven by the availability of water and the salinity of the soils (Figure 2.08). Irrigated soils are mostly found close to the river systems. Further away from the river, most soils are used for grazing and wheat production. Resulting from the occurrence of soils and salinity in the study area, it is quite common to find that vineyards were established on the higher grounds closer to the Berg River itself as these soils are the older soils, which are well drained and not saline. These soils are well prepared by deep ripping (1.2 m) of the soil. Where necessary, drainage systems are installed (Saayman & Van Huyssteen, 1980).

Agricultural practices that increase the water holding capacity of the non-irrigated soils and the removal of natural vegetation like the renosterbos, contributes to increased saline seep toward the river. This extends further into the summer season since winter wheat cannot utilize the excess winter water. As a result of irrigation mainly around the river systems, saline seeps also receive more water during summer and this contributes to salt from the irrigated landscapes that reaches the river (Fey and de Clercq, 2004; Görgens and de Clercq, 2006).

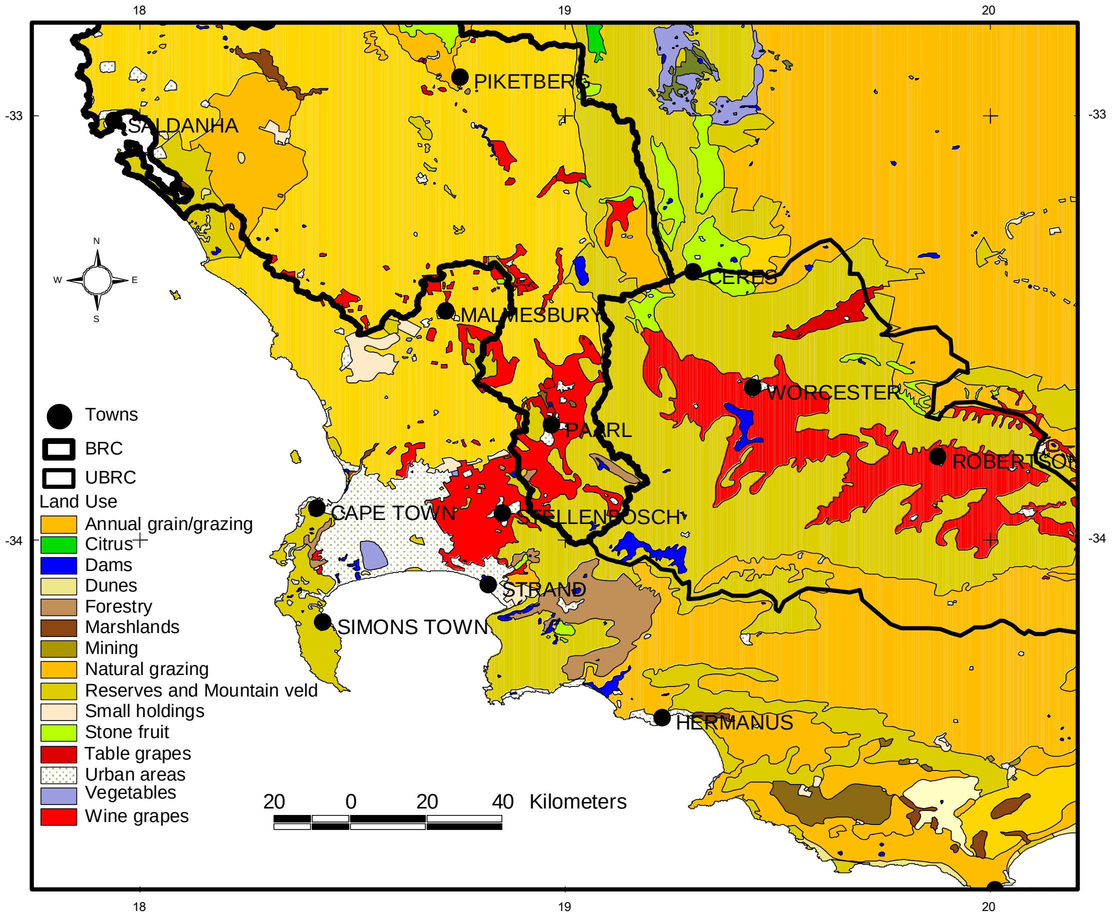

Figure 2.08 Land use within the BRC and UBRC

Farmers mostly make use of more drought and salinity resistent rootstocks. The cultivar used is generally chosen according to “terroir” guidelines that ensures the best wine for the given soil / climate conditions.

2.3 Soil salinisation within the study area

de Clercq *et al*. (2008, in press) found that the salts of the BRC are supplemented by a salt influx through rainfall and dry aerosols from the sea and dominates as source of salts in the catchment in the higher non irrigated areas. This means that in the BRC, salts are being added to these soils continually and that the salts stored in the regolith is not the only source of salt in the catchment. Figure 2.09 provides information of the long term salinity trend of the Berg River. It is clear that the more downstream (Piketberg), the more saline the river is (Wellington is nearer to the source of the Berg River). It illustrates the typical data being logged by the Department of Water Affairs and Forestry (DWAF), mostly from water samples collected on a weekly basis (Figure 2.05).

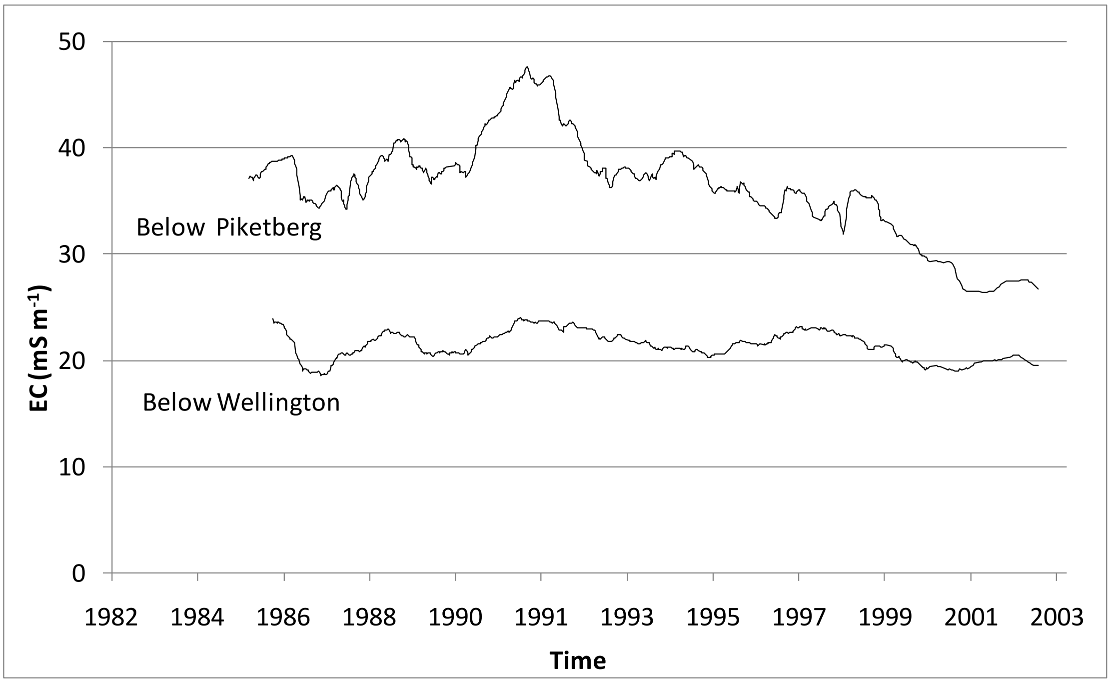

Figure 2.09 The EC in mS m-1 since 1983 of the Berg River water measured below Wellington and Piketberg (see Figure 2.05 for the measuring positions).

On the contrary, salts found in the UBRC, are of a secondary sea origin as these salts originated from the Bokkeveld shales situated to the north of the catchment. The Bokkeveld formation is of a deep-sea origin.

Table 2.06 presents a list of indicators as practical irrigation water guidelines for the successful cultivation of table and wine grapes in the study area. The table highlights three important aspects, namely: (1) a measure of water quality (EC_i and TDS), (2) a measure to assess infiltration problems (relating to EC_i as a function of the sodium adsorption ratio of the soil) and (3) specific ion toxicity levels.

Table 2.06 Practical irrigation water guidelines for the irrigation of table and wine grapes in SA based practical experience and on Ayers & Westcott, 1989.

Variable	**Units**	**Degree of limitation on use**		
		No	**Moderate**	**Large**
		Irrigation water quality		
EC_i	mS m^{-1}	100	100 – 270	> 270
TDS	mg.l^{-1}	<630	630 – 1700	> 1700
		Infiltration: SAR and EC_i relationship		
SAR			**EC_i**	
0 – 3	mS m^{-1}	< 20	20 – 70	>70
3 – 6		< 30	30 –120	> 120
6 – 12		< 50	50 – 190	> 190
12 – 20		< 130	130 – 290	> 290
20 – 40		< 290	290 – 500	> 500
		Specific ion toxicity		
Sodium (Na^+)	me.l^{-1}	< 20	-	-
Chloride (Cl^-)	me.l^{-1}	< 4	4 – 15	> 15
Boron (B^{3+})	me.l^{-1}	< 1	1 – 3	> 3
Bicarbonate	me.l^{-1}	< 1.5	1.5 – 7.5	> 7.5
Nitrate (NO_3^-)	me.l^{-1}	< 4	4 – 10	> 10

The sodium adsorption ratio (SAR) is a relation between soluble sodium and soluble divalent cations, which can be used to predict the exchangeable-sodium percentage of soil in equilibrium with that solution. It is defined as SAR= [Na] / ([Ca] + [Mg])$^{0.5}$, where [ ] is the concentration in mmol dm^{-3}. It is a measure of the quality of a solution (saturation extract, irrigation water, etc.) as regards to the Na^+ content (Verster & van Rooyen, 1990).

Table 2.06 indicates a distinctive relation between SAR of the soil and the EC_i. This implies that the higher the SAR of the soil the higher the EC_i must be to ensure continued good infiltration of the irrigation water.

In terms of specific ion toxicities, in this work attention will only be given to the Cl^- concentration of the water as it is the largest problem for irrigation of vines. A chloride content exceeding 100 mg l^{-1} causes leaf burn (Flowers and Yeo, 1986; de Clercq *et al.*, 2001). Literature reveals a sensitivity of grapevines to salinity with a salinity threshold value of about 100 mS m^{-1} (Flowers and Yeo, 1986; Moolman *et al.*, 1999; Prior *et al.* 1992a,b,c).

To illustrate of the soil salinity of this region, an analysis of saline soils from the Glenrosa farm is presented in Table 2.07. This result clearly shows that the soil conditions in these irrigated soils exceed the known limitations but after a three year preparation phase of these soils, one can rid the soil of most of its salts. This is exactly what we should avoid in catchment management since these salts simply contribute to the salt load of the river. At least regional management of irrigation expansion could be controlled using the information presented in this work.

Table 2.07 A typical soil analysis of a Glenrosa soil of the Broodkraal farm in the lower BRC (see Chapters 11 and 12).

Soil depth(cm)	0-15	15-30	30-60	60-90	90-120	Weighed average 0-90
Stone content (%)	47.5	46.3	42.5	39.0	37.2	42.6
Saturated Water content (%)*	28.7	28.6	28.1	29.7	27.8	28.6
EC ($mS.m^{-1}$)	114.2	156.2	210.9	171.2	142.5	171.2
pH (H_2O)	6.8	6.1	5.3	5.0	5.0	5.6
Ca^{2+} ($mg.l^{-1}$)	84.0	78.8	119.7	85.8	29.1	95.0
Na^{+} ($mg.l^{-1}$)	104.2	170.8	226.6	179.1	189.9	179.8
Mg^{2+} ($mg.l^{-1}$)	22.9	39.5	67.0	44.7	23.6	47.3
K^{+} ($mg.l^{-1}$)	7.5	8.4	9.8	9.5	11.2	9.0
SAR	2.7	4.0	4.9	4.2	6.3	4.1
Cl^{-} ($mg.l^{-1}$)	148.2	205.0	387.9	262.7	299.6	273.7
NO_3^{-} ($mg.l^{-1}$)	141.1	59.6	34.8	102.2	41.8	78.7
SO_4^{2-} ($mg.l^{-1}$)	210.0	481.0	670.5	369.8	219.3	458.7

* Saturated water content experimentally determined as the difference between saturated un disturbed soil samples and oven dried soil samples.

2.3.2 Defining salinity hazard in irrigated vineyards of SA

de Clercq et al., (2001) identified a number of points, which have to be considered when irrigation with saline water is attempted. The definition of salinity hazard for this region is of prime importance to the management of the water resources. A proper formulation of irrigation water quality guidelines should consider the following questions (de Clercq et.al., 2001):

- How much irrigation water is available?
- Is there enough water for leaching?
- Is the quality of EC_i and EC_{sw} being monitored?
- Is it good practice to leach during summer or winter?
- Will leaching have an effect on the water supply?

- Does the farmer use refined scheduling techniques?
- Do the advantages of partial wetting of the soil apply?
- What is the salt tolerance of the crop?
- Does the salt content of the marketable product matter?
- What is the length of season for the crop?
- What is the typical rooting volume of the crop?
- Under saline conditions, should crops be selected with the smallest possible rooting volume?

The salinity hazard in South Africa stems from the large salt laden inland surfaces and the fact that most inland sediments are from oceanic origin (Trusswell, 1986). The South African land surface is extremely stable and old. Most soils in the irrigated agricultural regions are old but in tune with the current climatic conditions. Most soils are also quite shallow and wherever soils are developed for irrigational purposes, a large section of the underlying weathered zone in broken up. This result in a new soil forming while under irrigation but as soon as this soil is abandoned, it usually returns to previous condition with the exception of the existence of more erodible material. Cultivation of land surfaces in South Africa inevitably leads to a larger degree of soil erosion, and the large changes in the water balance of these regions also means a large change in the solute flux of the region. The combination of fine sediment and solute that pollutes South Africa's river systems is therefore a great source of concern (de Clercq *et al*., 2008, in press).

3 IRRIGATION OF VINES WITH SALINE WATER[1]

3.1 Introduction

The irrigation water guidelines in South Africa, regarding vines (*Vitis vinifera,* L), had to be determined. The DWAF had broad management principles regarding the quality of water in the BRC as well as in the UBRC. Both these rivers act as drainage system and water supply system for their catchments. The DWAF therefore managed the water during the irrigation season to a level of about 30 mS m^{-1} and during the remainder of the year to a level of 75 mS m^{-1}. As a result of the fact that vines are the main agricultural crop of this region under irrigation, several studies were conducted that focused on vines.

South Africa is not richly endowed with water. It follows that sustained food production in many parts of South Africa is only possible through irrigation.

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[1]*Published in:*

Moolman, J.H., de Clercq, W.P., Wessels, W.P.J., Meiri, A., Moolman, C.G., 1999. The Use of Saline Water for Irrigation of Grapevines and The Development of Crop Salt Tolerance Indices. WRC Report:303/1/1999.

de Clercq, W.P., Fey, M.V., Moolman, J.H., Wessels, W.P.J., Eigenhuis, B., Hoffman, E., 2001. Experimental irrigation of vineyards with saline water. WRC Report; 522/1/01, (ISBN No. 1868457753).

de Clercq, W.P., Fey, M.V., Moolman, J.H., Wessels, W.P.J., Eigenhuis, B. Hoffman, E., 2001. Establishing the effects of saline irrigation water and managerial options on soil properties and plant performance. WRC Report; 695/1/01, (ISBN No. 1868457753).

In the Western Cape virtually the entire fruit and wine industries are dependent on irrigation. Agriculture, and specifically irrigated agriculture, is the largest consumer of water. In 1980 irrigated agriculture accounted for 52% of the total water use in South Africa (DWAF, 1986). According to various reports published since 1975, the quality of South Africa's water resources, with specific emphasis on the total salt content, is steadily deteriorating (Stander, 1987). Alexander (1980) stated that "*there is no doubt that mineralisation (salinisation) is a serious problem in South Africa - and it can only get worse!*"

Over the past 30 years, an awareness of salinity levels in the Breede River during summer months has grown considerably. It plays an important role in the economy of the Western Cape and contributes significantly to South Africa’s agricultural output. It has a wide and dynamic crop mix, but is primarily a wine-producing area, with 65% of the area under wine grapes. Other crops produced in the valley are peaches and apricots (13%), vegetables, mainly tomatoes (3%) and irrigated pastures (7%). The perception of an increase in salinity over time gave rise to concern about sustainability of using the water for the irrigation of these high value salt sensitive crops Lipton et al, .

It is reasonable to assume that agriculture in future not only will have to bring about substantial water savings but will also have to rely increasingly on water of a poorer quality than at present. However, international research has proved that salinity effects on the yield and quality of agricultural crops are of primary importance (Frenkel and Meiri, 1985; Shalhevet, 1994). Problems associated with salinity (yield decrease, crop quality) have already been encountered in a number of rivers and irrigation schemes in South Africa. A few examples are the

Fish/Sundays-River irrigation schemes in the Eastern Cape (Hall & Du Plessis, 1979; Tylcoat, 1985), the Riet River scheme in the Orange Free State, and the Breede River in the Western Cape.

Worsening of the salinity effect with time can result from important metabolic processes that are weakened season after season. One such process is a decrease in carbohydrate reserves in the perennial organs at the end of the growing season, as shown for grapes by Prior *et al.* (1992b). The most severe salinity effect on grapes was leaf damage that almost killed vines after two, three and four years of irrigation with water of EC_i of 250 - 800 mS m^{-1} (Flowers and Yeo, 1986; Hoffman *et al.* 1989; Prior *et al.*, 1992). In all these studies, the visual damage was considered a specific ion effect, which showed up when Cl^- reached toxic levels in the leaves. Limited leaf damage showed up towards the end of the first season in all treatments with EC_i higher than 300 mS m^{-1}. The leaf damage worsened in proportion to the water salinity and was visible earlier in following seasons. Increased disorders in flowers with the increase in salinity and number of seasons of saline irrigation were also considered toxic effects. Since the soil was leached every winter the increased salinity damage over time suggested a salt carry-over in the perennial organs of the tree. It was previously documented that the build-up to toxic levels of chloride and sodium in plant organs on soils with relatively low salinity and sodicity can take several years (Bernstein *et al.*, 1958; Francois and Maas, 1994; Maas, 1984, 1990). The possibility that winter irrigation lowers the nutrient status of soils was mentioned by Moolman *et al*. (1999). This results in lower nutrient levels at bud break.

Initially, sodium was thought to be retained in the sapwood of the tree. With the conversion of sapwood to heartwood, sodium is released and then translocated to the leaves, causing leaf burn. This may partly explain why grapes appear to be more sensitive to salinity as the plants grow older (Francois and Maas, 1994).

This chapter reports on 10 years of applied research regarding irrigation with saline water. It was not the intension to provide all the result but rather the major findings that had a bearing on the investigation reported in this thesis.

3.2 Materials and Method

The research was conducted at Robertson in an experimental vineyard belonging to the Agricultural Research Council. Robertson (33° 46'S, 19° 46'E) are located in the south-western part of South Africa. Robertson is situated in the BRC. The vineyard was established in 1974 with Colombar vines, grafted on Richter-99 rootstock and trained on a factory roof trellising system (Saayman, 1988). Van Zyl (1984a&b) described the soil as a Hutton fine sandy loam. In terms of the current classification (Soil Classification Working Group, 1991) the soil belongs to the Trawal 2210 family (Cambisol, under the FAO (1998) Soil Taxonomy) and has a duripan at about 1.2 m. Soil preparation included homogenising by deep cultivation to about 1 m.

The 1.2 ha block was divided into 24 plots to which were randomly allocated 4 replications of six irrigation salinity treatments (Figure 3.01). The six treatments had EC_i levels of 30, 75, 150, 250, 350 and 500 mS m^{-1} (alternatively termed treatments 1 to 6), the first being normal canal water and the others canal water to which $CaCl_2$ and NaCl had been added in a 1:1 molar ratio to achieve the desired salinity (Meiri, 1984;

Meiri *et al.*, 1986; Wessels *et al.*, 1995). Irrigation was applied with microjet sprinklers, scheduled according to water use on the lowest salinity plots (canal water), and included a 10 % leaching fraction which is standard practice in the region (de Clercq *et al.*, 2001). The predominantly winter rainfall, which was supplemented with irrigation to promote leaching of salts, ensured that there was minimal interference in the water balance by rainfall during the summer months when most of the irrigation was applied.

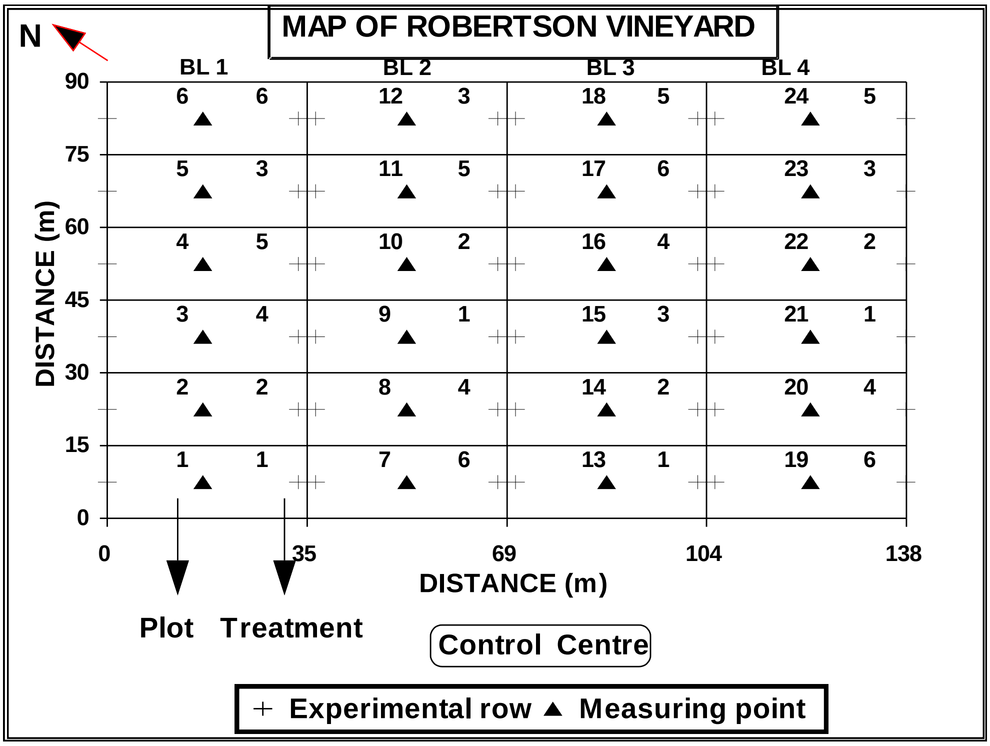

Figure 3.01 Schematic diagram of the experimental vineyard at Robertson showing 24 plots arranged according to a randomised block design consisting of four blocks (replicates) and six treatments (the triangles indicate the centre of each plot where the soil water content and soil solution was monitored). Treatments are indicated as follows: 1 = 30, 2 = 75, 3 = 150, 4 = 250, 5= 350, 6 = 500 mS m^{-1}.

Each plot consisted of five vine rows, 3 m apart, with 23 vines per row at 1 m spacing. Soil measurements were confined to the central ten vines in the middle row of each plot. Suction cup lysimeters (SCL) (for a more detailed description of these SCL's it is referred to Chapter 4) were installed between two vines at depths of 15, 30, 60, 90 and 120 cm and linked to a central vacuum pump, which was synchronised with an irrigation controller allowing remote control of soil water extraction (de Clercq *et al*., 2001). Soil samples were taken twice per year (during September and April) over 8 years, by augering between two experimental vines and to the same depths as the suction cups. One set consisted of 120 samples, i.e., 5 depths, 4 replicates and 6 treatments.

The experiment ran for eight years with prime function to test the salt tolerance of Colombar grapevines and to investigate methods that will allow the use of moderate to high salt content in irrigation waters. It was also a prerequisite that the treatments should at least cover the range of salinities defined by the EC-operational curve used by the Department of Water Affairs for managing water releases from the Brandvlei dam. Secondly, some of the treatments had to exceed the first threshold estimate of the salinity value for *Vitis vinifera* L., i.e. 150 mS m^{-1} (Ayers and Westcott, 1985).

Irrigation was scheduled according to the water use in the freshest water treatment and measurements were done using a neutron probe. An average of 17 irrigation events took place per year over the duration of the project. An additional amount of 10 percent was usually applied as over-irrigation to allow leaching. This was done, as it is standard practice among farmers in this region. Irrigation was systematically applied in the afternoon of each Wednesday and suction sampling was initiated 12 hours after irrigation had terminated, to ensure that the soil water status was effectively at field capacity. Suction samples were withdrawn simultaneously at all depths from all plots. Over the 8 year duration of the experiment at least 12 annual sets (a set consisting of 120 samples, ie., 5 depths, 6 treatments and 4 replicates) of suction cup data were collected, with 7 to 9 of these being collected during the irrigation season and the 3 to 5 during winter (Moolman *et al.*, 1999 and de Clercq *et al.*, 2001).

Various vegetative growth parameters were recorded, which included time of bud burst, shoot growth, shoot intermodal fresh and dry weights, leaf fresh and dry weights, degree of leaf necrosis, leaf size and number, canopy size and leaf density, leaf water potential, vacuole pressure, stomatal resistance, trunk circumferences as well as yield and wine quality. Of these, the intermodal lengths and weights, leaf water potential, yield and wine quality produces the most noteworthy results. The last two were focused on in more detail as these clearly provided the means of expressing the influence of salinity in an economic sense. The growth parameters were logged over the last 7 years and 5 growth stages during each season, i.e., full bloom, pea size, veraison, harvest and post harvest. The methods were fully described in Moolman *et al.* (1999) and de Clercq *et al,* (2001). Leaf water potential was determined using a pressure chamber technique.

3.3 Results and discussion

3.3.1 The soil and water

The seasonal mean soil water content measured before each irrigation event (Table 3.01), did not increase in accordance with the range of salinity treatments applied in any consistent way, as soil and irrigation water salinity increased. This is probably due to the relatively high frequency of irrigation (once per week) and the good internal drainage properties of the soil. However, after extended periods of drying (when no irrigation was applied such as prior to harvest), water content did increase with increasing soil salinity and was indicative of reduced water uptake at the higher levels of salinity.

Table 3.01 Soil water content from September 1995 to April 1996 for the corresponding different treatments at Robertson, calculated as the weighted depth mean .

Treatment	**Water content(%) (n=19)**	
EC_i	**Mean***	**Std. Dev**
30	25.3	14
75	26.6	18
150	25.0	16
250	26.5	13
350	25.9	11
500	26.4	17

n=number of days on which measurements were made.
*= depth weighted mean (15, 30, 60, 90 120 cm depths) soil water content values (all 4 replication).

The water management record is shown in Table 3.02. Irrigation with saline water led to a significant salt accumulation in the root zone during the irrigation season, reaching maximum levels just before harvest in March, but the salt accumulation was not proportional to the salt load of the salinity levels. This is explained in terms of accentuated leaching due to reduced soil water uptake at the higher levels of salinity. To demonstrate this, Table 3.03 shows the treatment mean and standard deviation of the leaching fractions according to the electrical conductivity of the irrigation water and the soil solution at the 0.9 to 1.2 m depth layer. A leaching fraction was calculated by dividing the EC_i with EC_{sw} for each treatment. At this depth, the differential accumulation of salt in across treatments is well demonstrated by Table 3.02.

Table 3.02 Irrigation, rainfall and water balance data of the growing season (September to April), summarised per season for the main Robertson experiment (evaporation based on class A-pan or Penman-Monteith calculation where indicated).

September to April	91/92	92/93	93/94	94/95	95/96	96/97	97/98
Irrigation (mm)							
per vineyard, 12150 m^2	926	613	566	604	661	583	402
per wetted area, 8100 m^2	1389	920	849	907	992	875	604
Rainfall (mm)	126	252	113	201	169	191	125
A-pan data (mm)	1794	1967	1678	1607*	1647*	2020*	1553*
AET=A-pan x crop factor (mm)	782	823	702	672*	689*	841	649

* = Reconstructed A-pan record based on Penman-Monteith equation

The spatial variability within the zone of influence of one microsprinkler showed that one sampling point per microsprinkler (or plant) is insufficient to obtain an accurate water and salt balance from which evapotranspiration and leaching can correctly be inferred. The leaching fractions calculated from the ratio of electrical conductivity of the irrigation water to that of the soil solution (EC_i/EC_{sw}) ranged on average from 0.134 for the control (EC_i = 30 mS m^{-1}) to 0.468 for treatment 6 (EC_i = 500 mS m^{-1}) with indicates a general increase as salinity of treatment waters increased (Table 3.03). The average per treatment leaching fractions suggest substantial deep percolation losses, as much as 47% at the higher levels of irrigation water salinity, compared to irrigation management strategies that are based on non-saline, non-stressed conditions for plant water uptake (Moolman *et al.*, 1999).

Table 3.03 Treatment mean and standard deviation of the leaching fractions according to the electrical conductivity of the irrigation water and the soil solution at the 0.9 to 1.2 m depth layer (Treatment in mS m^{-1}).

	LF=EC_i/EC_{sw}	
Treatment	**Mean**	**STD**
30	0.134	0.031
75	0.227	0.037
150	0.437	0.067
250	0.337	0.074
350	0.413	0.025
500	0.468	0.025

All treatments were irrigated during winter to leach the salt that accumulated in the soil profile during the previous growing season. At the Robertson vineyard, it was found that about 275-300 mm of water during winter was required to reduce the electrical conductivity of the soil solution (EC_{sw}) of the topsoil (0-30 cm) from 300 mS m^{-1} to 100 mS m^{-1}. To reach the same target EC_{sw} of 100 mS m^{-1} at the 0.9 m depth and for the same antecedent condition, about 700 mm of rain and irrigation is necessary (Tables 3.04 & 3.05). It was shown by de Clercq *et al*. (2001) that the EC_{sw} initially changed with similar amounts in all measured depths when winter irrigation was applied. Below the value of 100 mS m^{-1} the rate of change slowed.

Tables 3.04 & 3.05 shows the summary statistics of EC_e indicating the end of summer and end of winter soil samplings done at the Robertson irrigation experiment. From these results it is evident that the EC_e was reduced during winter to about the level of the fresh water treatment.

Table 3.04 The descriptive statistics of the end of irrigation season soil EC_e values taken between 1992 and 1998 (n = 24 per treatment and soil depth).

		End of summer EC_e (mS m^{-1})					
Soil depth cm	**Treatment mS m^{-1}**	**Mean**	**STD Err**	**Median**	**STD Dev**	**Min**	**Max**
15	**25**	67.4	4.3	68.3	9.7	56.2	81.5
30	**25**	75.0	7.2	72.5	16.1	55.5	91.5
60	**25**	76.6	5.2	76.9	11.7	60.7	90.3
90	**25**	81.1	9.9	74.0	22.2	63.1	119.8
120	**25**	85.2	10.7	72.8	23.9	63.7	121.8
15	**75**	91.8	8.9	88.8	19.8	75.8	125.3
30	**75**	94.0	8.3	86.5	18.6	76.0	123.8
60	**75**	112.3	11.3	109.8	25.3	75.5	144.0
90	**75**	123.4	9.7	127.0	21.6	97.4	153.5
120	**75**	123.1	14.8	104.5	33.1	94.0	170.8
15	**150**	142.0	18.9	131.0	42.2	96.0	207.0
30	**150**	155.1	22.5	150.8	50.2	108.0	231.3
60	**150**	175.2	27.9	143.7	62.4	112.9	266.0
90	**150**	181.5	17.1	174.0	38.3	131.2	229.8
120	**150**	165.3	7.6	162.5	17.0	140.3	181.8
15	**250**	193.1	29.6	160.2	66.1	134.0	279.8
30	**250**	208.9	28.1	184.6	62.8	148.5	285.3
60	**250**	277.4	45.0	267.7	100.6	152.0	401.3
90	**250**	275.5	43.1	304.8	96.3	150.2	384.8
120	**250**	256.0	25.2	280.1	56.3	189.3	306.3
15	**350**	268.8	12.4	273.5	27.7	226.8	298.0
30	**350**	291.7	18.9	308.0	42.3	220.8	322.0
60	**350**	300.1	22.2	308.0	49.6	220.0	355.3
90	**350**	301.9	15.3	301.3	34.2	266.0	345.3
120	**350**	288.8	29.6	298.3	66.3	183.8	356.0

Table 3.05 The descriptive statistics of the start of irrigation season soil EC_e values taken between 1992 and 1998 (n = 24 per treatment and soil depth).

		End of winter EC_e ($mS\ m^{-1}$)					
Soil depth cm	**Treatment $mS\ m^{-1}$**	**Mean**	**STD Err**	**Median**	**STD Dev**	**Min**	**Max**
15	**25**	63.9	9.3	53.7	20.7	47.9	98.8
30	**25**	57.1	5.2	56.2	11.7	45.5	76.3
60	**25**	59.2	8.8	50.4	19.7	46.3	93.8
90	**25**	55.9	2.8	56.5	6.3	49.4	65.4
120	**25**	61.7	2.5	62.0	5.5	56.7	69.9
15	**75**	57.2	4.6	62.2	10.4	39.3	64.7
30	**75**	53.4	5.9	57.8	13.2	33.3	67.8
60	**75**	56.0	5.2	59.3	11.5	38.0	69.0
90	**75**	66.7	6.6	71.7	14.7	41.3	77.3
120	**75**	70.9	8.0	76.8	17.8	39.5	83.4
15	**150**	51.0	5.4	57.0	12.1	30.5	60.1
30	**150**	53.0	5.6	56.0	12.5	38.8	69.5
60	**150**	54.0	3.4	56.5	7.6	42.3	62.6
90	**150**	62.1	2.3	62.9	5.1	56.6	69.0
120	**150**	59.3	6.3	62.8	14.0	37.3	74.5
15	**250**	63.9	7.1	62.3	15.8	41.0	82.8
30	**250**	66.1	6.7	69.6	14.9	48.8	86.3
60	**250**	89.1	14.2	105.8	31.8	47.3	119.3
90	**250**	125.7	22.9	140.7	51.3	51.8	180.0
120	**250**	140.5	27.5	143.3	61.6	48.3	214.0
15	**350**	59.6	4.0	63.2	8.9	49.0	69.8
30	**350**	73.7	6.4	70.3	14.3	57.9	96.8
60	**350**	90.5	17.5	74.0	39.2	55.4	152.3
90	**350**	110.7	15.4	96.3	34.5	84.0	167.3
120	**350**	121.8	16.6	109.5	37.2	90.8	178.8

It should also be noted that the $CaCl_2$-NaCl solution used for salinity treatments was equimolar with respect to Na and Ca, which means that SAR actually increases with increasing soil salinity (EC_e) in all these trials and consequently SAR also increased with increased EC_i levels (Figure 3.02).

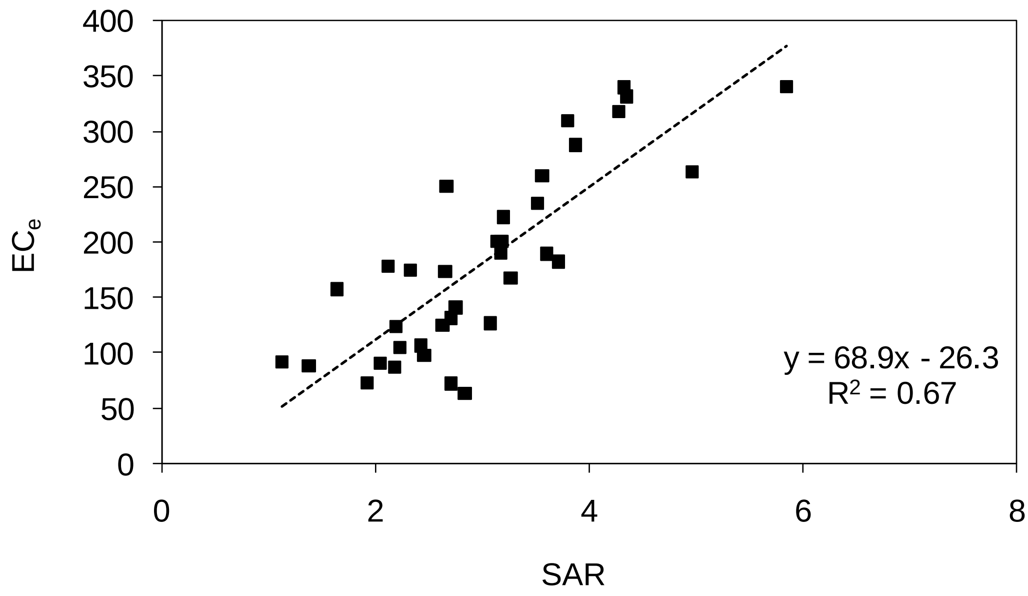

Figure 3.02 EC_e – SAR relationship at Robertson based on all end of season weighted mean EC_e and SAR data over all treatments.

3.3.2 The vine

Despite thorough leaching with low salinity water every winter, the effect of saline water treatments from the beginning of successive seasons caused the first noticeable effect of salinity on expansive growth of shoots and leaves to occur earlier every season. At Robertson this was on day 35 of the 1992/93 season, and day 20 of the 1993/94 season and from then on the higher salinity treatments continually started growing earlier than the rest of the vines on the farm. This suggested that early in the spring, expansive growth was sensitive even to low soil salinity and that saline growth conditions in one season had a large influence on the growth during the following season (Moolman *et al*., 1999).

Leaf specific fresh weights were not sensitive to salinity or leaf age while the internodal fresh weights were smaller in the higher salinity levels. The specific dry weight of leaves increased with age more in the low than in the high salt treatments. From this it was inferred that salinity has a larger effect on the mass than on the sizes of these leaves. Alternatively, it indicated an increase in metabolite deposition in the leaves and decreased metabolite transport to the internodes - a change that can be the result of salinity interference to the metabolite export from the leaves. The reduction in metabolite transport to the shoot under saline conditions also implied a reduced build-up of metabolite storage in the perennial plant organs of the vine (de Clercq *et al.*, 2001).

Leaf water potential (LWP) and stomatal conductance measurements showed that differences in LWP between salinity treatments were best observed early in the day before the stomata start to control transpiration. The results also showed that stomatal closure occurs earlier in the day in the higher salinity levels than in non-saline treatments. This means that the salinity treatment effects on LWP could only be detected with pre-dawn measurements. The minimum recorded LWP at Robertson was about -1100 kPa, which was much higher than the minimum potentials reported from other irrigation studies. In spite of the relatively high leaf water potentials, damage to growth and yield was significant. It was therefore speculated that salinity damage to grapevine leaves may be the result of accumulation of salts in the apoplast, which means that the pressure chamber technique does not measure the total leaf water potential and perhaps also not the hydrostatic component of the xylem water potential of vines. Rather, it measures the difference between the vacuole water potential and the apoplast osmotic potential (Moolman *et al*., 1999; de Clercq *et al*., 2001).

3.3.3 Yield response

de Clercq *et al.* (2001) reported that salinity had a severe effect on yield with an average decrease of 60 % at the EC_i 500 mS m^{-1} salinity level

(Table 3.06). Yield (kg of grapes per vine) was negatively influenced even at the intermediate EC_i levels of 75 and 150 mS m^{-1}. However, a better understanding of the effect of salinity on the yield and reproductive growth of Colombar grapes is complicated by the fact that during the first four years of this study an irrigation water salinity of 250 mS m^{-1} seemingly had less effect on the average kg of grapes per vine yield (Table 3.06). Quantifying the effect of salinity on yield was further hampered by the progressive decrease in the yield on the control treatment. It seems that plant vigour and size are key determinants that influence the response of Colombar grapes to salinity.

Table 3.06 Mean grape yield in kg per vine per treatment of the saline irrigated study at Robertson (Colombar grapes) for the 1992 to 1998 yield years, in relation to EC_e and EC_i.

		TREATMENT (mS m^{-1})						YEARLY AVERAGE
YEAR	**EC_i**	**30**	**75**	**150**	**250**	**350**	**500**	**YIELD**
	EC_e *	**80**	**108**	**161**	**236**	**295**	**361**	**kg/vine**
1992		13.28	10.95	11.65	12.90	10.19	9.72	11.45
1993		10.05	7.86	7.56	8.78	5.26	4.81	7.39
1994		7.83	5.49	5.73	7.50	3.54	2.68	5.46
1995		4.99	4.61	4.20	6.53	2.69	1.91	4.16
1996		6.80	6.06	4.98	5.95	1.16	1.50	4.41
1997		4.74	3.13	3.02	3.20	1.11	0.83	2.67
1998		4.56	3.25	2.30	3.07	0.79	1.03	2.50
AVG		**7.46**	**5.91**	**5.63**	**6.85**	**3.53**	**3.21**	

* The 8 year average EC_e per treatment, measured at harvest time.

Despite these two complicating factors, the results of this experiment indicate that grapevines are more sensitive to salinity than previously thought, and that the threshold soil salinity value of 150 mS m^{-1} as reported by Ayers and Westcot (1985) is too high. These results are more in line with a limiting value of EC_e = 100 mS m^{-1}, as reported by Prior *et al*. (1992 a, b, c).

The results of de Clercq *et al.* (2001) (Table 3.06) showed that yield decreased progressively above an EC_i = 75 mS m^{-1} or an EC_e = 108 mS m^{-1} at a rate (in terms of EC_e) of about 3% per 10 mS m^{-1} (calculated from the average treatment yield values in Table 3.06), which is three times more than the rate of decrease reported by Maas & Hoffman (1977) as quoted by Ayers and Westcot (1985), and which was used as a basis for criteria in document GB/A/88/2 (Figures 3.03). The minimum time integrated soil salinity of 75 mS m^{-1} was attained by irrigating with the Robertson canal water, which had an electrical conductivity of 25-35 mS m^{-1}. If lower soil salinity is to be achieved to avoid any yield loss, and if the existing salinity levels of the Robertson canal remain the same, leaching must be increased. This in turn will increase the irrigation return flow with the concomitant elevated levels of salinity in the Breede River. Any increase in the salinity of the Robertson canal will also lead to increased soil salinity values which in turn will reduce yields. The target EC_i of 65 mS m^{-1} used by the Department of Water Affairs and Forestry to control water releases from the Brandvlei Dam is equivalent to treatment 2, which, in this study, resulted in a volume weighted seasonal mean EC_i that, depending also on rainfall, ranged between 58 mS m^{-1} and 78 mS m^{-1}. Irrigation with this water was associated with yield losses that ranged from 10 to 30% during the course of this study. However, consequent yield losses and salinity damage observed was indicated to be a combined result of osmotic and specific ion effects from Cl^- specifically (de Clercq et al., 2001).

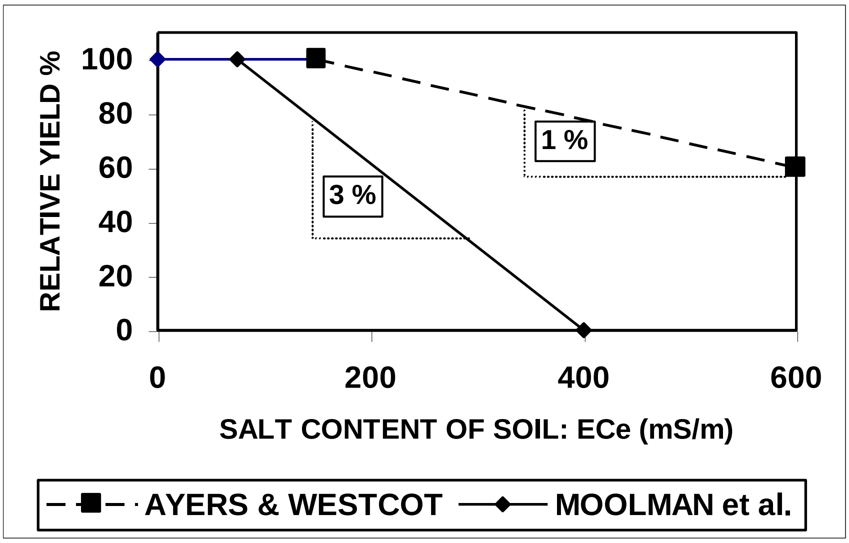

Figure 3.03 Published grape yield – EC_e relationships by Ayers & Westcot and Moolman *et al.* (1999).

Chloride content in the leaves is a good index of salinity damage and it was found that concentrations at harvest of 1.5 to 4 g kg^{-1} were associated with yield reductions of 10 to 20% respectively. Also, a chloride level of 1.5 g kg^{-1} in the leaves, was reached by irrigating with water that had a chloride concentration as low as 40 mg l^{-1}. Therefore, resulting from the Cl^- levels in the Breede River downstream, the conclusion was that the existing EC_i target levels set by the Department of Water Affairs for managing salinity in the lower reaches of the Breede River Irrigation scheme were too high to exclude reduction of yield.

At Robertson, production of wine grapes is fully dependent on irrigation and it was found that salinity effects are cumulative with time. Some negative effects were only manifested after two to three years of salinity exposure.

It was also indicated that yield correlated equally well with sodicity (expressed as SAR, usually calculated as a depth weighted mean over the 120 cm profile) as it did with salinity (expressed as electrical conductivity of the saturated paste extract, EC_e, and usually calculated as a depth weighted mean over the 120 cm profile and for samples taken at different stages in the season).

A high degree of covariance between EC_e, SAR and Cl^- was found. Figure 3.04 compares depth weighted mean EC_e and relative yield. The principle of relative yield was used to bring all the different yield of the different years to a common scale. This was done by using the first yield of this experiment as the reference. Similarly SAR was compared to the relative yield in Figure 3.05. In Figures 3.04 and 3.05 the last year's data was ignored as this did not differ significantly from that of the 1997 results.

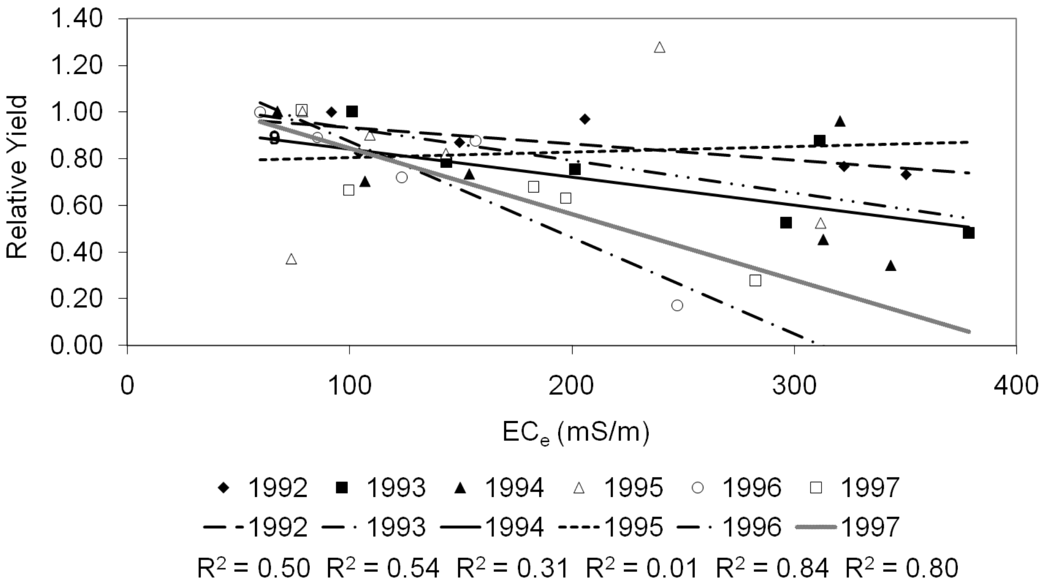

Figure 3.04 Yield – EC_e (depth weighted mean EC_e) relationships at Robertson from 1992 to 1998 based on relative yield (relative to the fresh water treatment, treatment 1).

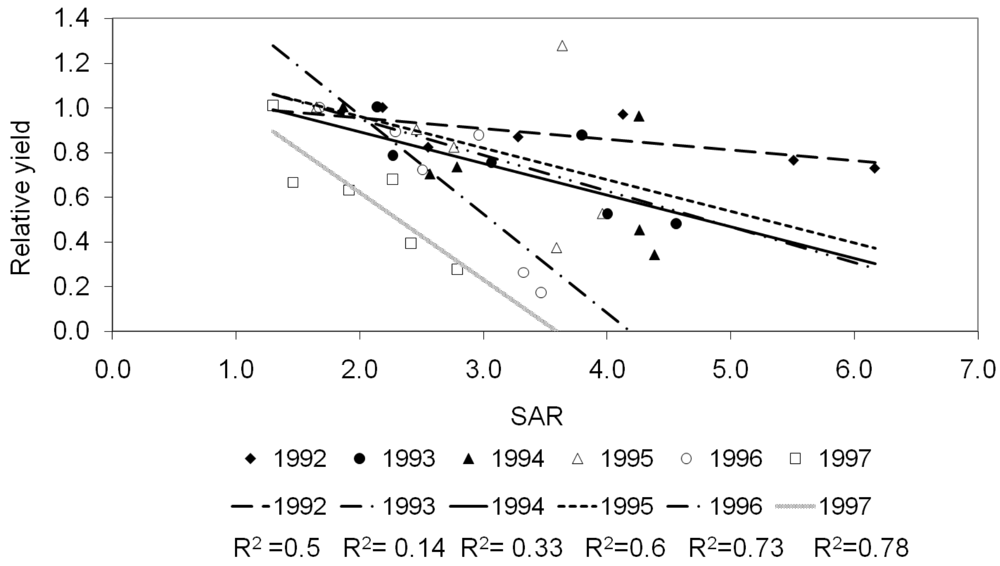

Figure 3.05 Yield and depth weighted mean SAR relationships at Robertson from 1992 to 1998 based on relative yield (relative to the fresh water treatment, treatment 1).

A pattern emerged from these results, which could only be picked up as a result of the duration of this experiment. The essence of the pattern is that, irrespective of whether the inhibitory effect of the saline irrigation treatments on yield is an osmotic one, a toxic one (Na^+ and/or Cl^-), or both, the threshold level remains the same over a number of seasons of irrigation, but the sensitivity of the crop to levels beyond the threshold increases with the number of seasons of exposure. This is reminiscent of an allergic type of response which suggests that, instead of there being one particular cultivar-specific response function, the response pattern changes with time and the effect of the saline/sodic/chloridic water is cumulative on the vines (i.e. not only through a build-up in the soil). After all, vines are perennial plants. This might explain why the overall yield of the main trial at Robertson showed a progressive decline, since even the control treatment made use of slightly saline canal water on a site that already was moderately saline. This result has important management implications, because it suggests that even moderately acceptable water may, in the longer-term, have a cumulative, debilitating effect leading to premature failure of the vineyard.

3.3.4 The wine

Wine quality and in particular the concentration of NaCl in the wine, has an influence on the market price of these wines as high NaCl content affects the marketability of these wines negatively, which impacts on the economy of the region. Consequently the wine quality at Robertson was also subjected to a sensory evaluation (a panel of 20 wine experts tasting the wine) and found to have a salty taste when made from the most saline treatment but all wines (from all the treatments) lacked the typical character of the cultivar. The best wine was produced from the 75 mS m^{-1} treatment. However, the result in Figure 3.06 showed that the chemical analysis of must and wine in terms of Na^+, produced the similar results.

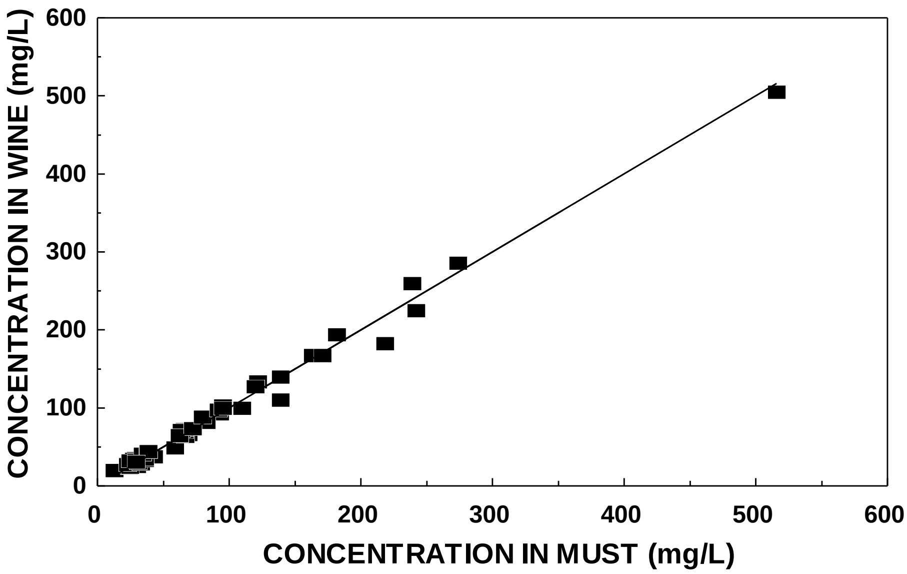

Figure 3.06 Relationship between the sodium content of must and wine of Colombar grapes irrigated with saline water (Na_{wine} = 0.976 Na_{must}+2.961; R^2 = 0.988, n = 47).

When chemically analysed in 1997, the must (unfiltered grape juice in an early stage of fermentation) showed a marked upturn in sodium content in response to the two most saline treatments (Table 3.07).

Table 3.07 Salinity effect on the treatment mean (the mean based in 4 replications) expressed by the mineral composition of the must of Colombar grapes at harvest.

Element in must	**Irrigation water quality (mS m^{-1})**					
	30	**75**	**150**	**250**	**350**	**500**
Cl^- (mg l^{-1})	25	30	64	108	228	560
Na^+ (mg l^{-1})	30	26	44	77	155	303
Ca^{2+} (mg l^{-1})	90	99	118	105	132	140

3.4 Conclusions

It was shown that after irrigating vines for 8 consecutive years with 6 grades of saline water, that vines are influenced by saline irrigation water, even by irrigation water with an EC_i lower than 30 mS m^{-1}.

From this research a soil EC_e threshold of 100 mS m^{-1}, instead of the proposed 150 mS m^{-1}, was found to represent better the sensitivity of vines to soil salinity. The yield response sensitivities were defined for use by the DWAF and various aspects of plant and soil behaviour regarding salinity were documented.

The influence of saline irrigation water on the economy could also be established. Salinity had a major effect on the quality of wine and the quantity of grapes that could be produced, which meant that elevated levels of salinity could seriously hamper the economy of this region.

Saline water had a cumulative effect on the plants as the salts were found to be stored in the perennial parts of the plant and therefore had an effect on yield of the following years.

Perhaps the most important finding of this research was that the threshold level of saline irrigation regarding sustainability remained the same over a number of seasons of irrigation, but that the sensitivity of the crop to levels beyond the threshold increased with the number of seasons of exposure.

Wine quality was also found to be sensitive to saline irrigation water. Irrigation water with an EC_i = 75 mS m^{-1} caused lower yields than water with a lower EC_i, but slightly better wines. Above an EC_i = 75 mS m^{-1} yield and wine quality dropped.

It was found that salinity could be adequately tested in the must and does not need to be tested in the wine.

Irrigation with saline water, inevitable led to over irrigation of the more saline plots as plants in treatments above the EC_i = 75 mS m^{-1} level, used less water.

4 AN AUTOMATED SOIL WATER SAMPLE RETRIEVAL SYSTEM[2]

4.1 Introduction

The use of suction cup lysimeters (SCL's) in a remote salt affected area, made it imperative to redesign them. SCL's were used extensively for repetitive measurements in salinity research (Debyle *et al.* 1988; Grossmann and Udluft, 1991; Wagner, 1962; Moolman *et al*. 1999; de Clercq *et al*. 2001; de Clercq *et al*. 2006). With projects that ran over a number of years, repeated soil sampling is impossible, as it is a destructive way to evaluate soil salinity. Some instances necessitate accurate time based response monitoring and by using SCL's, measurements could be repeated in the exact same soil matrix, over and over. It is therefore of the utmost importance to explain their working as some of the following chapters focus on these results.

The idea and the principles of sampling soil water with SCL's is not new and their usefulness in evaluating soil chemistry has aptly been described (Debyle *et al.* 1988; Grossmann and Udluft, 1991; Wagner, 1962). All authors also indicated the inertness of the ceramic material but also warned for the possible change in chemical composition of the soil water resulting from sampling over a pressure gradient (Debyle *et al.* 1988; Grossmann and Udluft, 1991; Wagner, 1962). Most of these applications

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[2] This section formed the basis of a patent (Automated suction-cup-lysimeters), registered by the University of Stellenbosch, in the name of WP de Clercq, 2003. The patent is a direct product of this study.

of SCL's indicated that the samplers were operated individually and this is precisely the drawback of the method (Stanley *et al.*, 2003). In such circumstances they are time consuming to operate since the specific time of sampling is mostly critical. In most agricultural soil water systems, the soil water content and EC are dynamic over a day and by sampling at different times during the day, the comparability between samples can be lost. Therefore, the objective was to design a system that:

- could be remotely operated;
- had the ability of sampling a number of sites simultaneously or separately;
- minimizes time spent in the field;
- minimizes contamination of samples;
- could be used in non-destructive sampling of the soil solution at any given time.

4.2 Materials and method

4.2.1 The SCL's

The successful use of the SCL's in the field is not always straight forward. The easiest way to use them is between 0 and 20 kPa. Some soils have swelling clays may cause a poor soil contact with the ceramic cup. Generally, type of clay, the amount of clay and low water content is limiting the use of these instruments. On the contrary, the best way to use these instruments is when the soil is almost saturated and has therefore a known water content. It is absolutely imperative that soil water content and soil water samples be taken simultaneously (Grossmann and Udluft, 1991).

The SCL's were made from 50 mm diameter ceramic cups with an air entry value of 100 kPa and PVC tubes in lengths of 150, 300, 600, 900 and 1200 mm (Figure 4.01). A rubber stopper with an inlet for vacuum was placed at the top of the PVC tube. The automated system contains a 25 ml bottle with a special cap that is placed inside the cup sampler. The cap consists of a rubber grommet through which a thin capillary polypropylene tube is fed. This capillary tube extends 10 mm outside and 50 mm to the inside of the bottle. The bottle is placed upside down in the base of the cup sampler with the 10 mm capillary tube extension touching the bottom of the ceramic cup. Any water that collects at the base of the sampler will therefore be in contact with the small bottle. Because the capillary tube on the inside of the bottle is at least 50 mm long, it serves as a moisture trap.

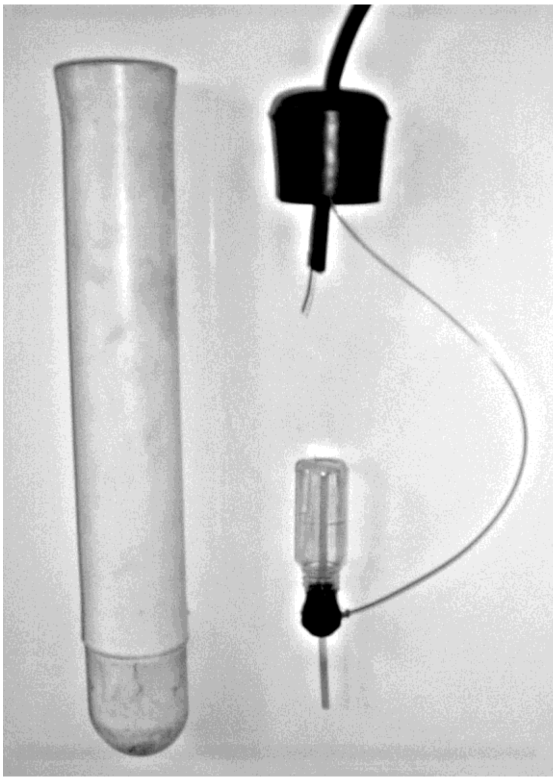

Figure 4.01 SCL with sample bottle that acts as a water trap.

The entire assembly was installed in the soil by auguring a hole to the required depth. The ceramic cup at the bottom end should be in contact with the soil, while the rubber stopper and air inlet should protrude at least 50 mm above the soil surface. When suction is applied to the sampler, using an external device such as a vacuum pump, the applied suction causes the soil water to move from the soil, through the porous ceramic cup into the sampler where it collects at the base of the ceramic cup (Figure 4.01).

When the suction is released the suction gradient reverses. In conventional cups the collected sample must be removed quickly from the soil water sampler otherwise it will permeate back into the soil. However, in the present set-up, the bottle at the base of the SCL acts as a liquid trap. The moment the vacuum is released, the soil water sample is sucked up into the bottle since the pressure is now lower inside the bottle than inside the cup.

Each sampler was connected through a thin flexible tube (diameter, 5 mm) to a central vacuum pump, which was operated via an irrigation controller and telephone link. Suction could be applied in any number of pulses to fill the sample bottles. The sample bottles containing the soil solution could then be collected at any length of time after the suction was applied. The soil water samples are safe in the SCL and the temperature is fairly constant implying the sample is free of contamination or degradation. Upon retrieval of the sample bottles, they are capped and replaced with new ones and the system is set for another run.

4.2.2 Installation of a SCL

An oversized Veihmeyer type auger was developed for installation of the equipment. It consists of three parts (Figure 4.02):

- The tube or Veihmeyer itself, with a finely machined and hardened tip. The tip is made with a resistance rim on the inside, and the outside is machined to be slightly larger than in diameter than a SCL.
- The hammer. It has a handle, a weight of approximately 1 kg and a guiding pin that fits through a special guide
- The hammer guide. The guide takes all the hammering, and prevents damage to the opening of the auger. If the hammer should damage the auger, it will make emptying the auger very difficult.

The hammer and guide allowed the operator to install the system in such a way as to have a very snug fit between the sides of the access tube and the hole.

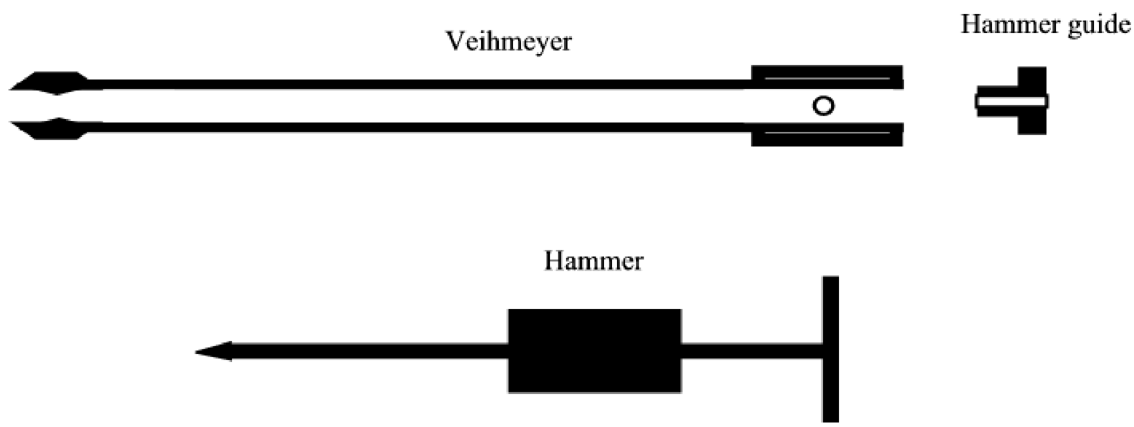

Figure 4.02 The installation equipment for the SCL's, including the Veihmeyer type auger, hammer and hammer guide.

4.2.3 Method of operation

The time to sample a 120 sample system with adequate solution for analytical purposes was about six hours, with a 30 minute equilibration time in between every two hours of applied suction. The system could maintain a negative pressure of more than 70 kPa and could reach its working pressure within 30 minutes. The vacuum pump was an ordinary laboratory Edwards type pump with a displacement of 2700 L air per hour (at atmospheric pressure). The system could be programmed to collect samples at a fixed time after irrigation. A field installation is shown in Figure 4.03.

Figure 4.03 The positioning of 5 suction cup lysimeters (5 depth increments) between two vines with a cartridge of empty bottles on the left.

4.2.4 Measuring the relative matrix potential.

As a control measure, an extra SCL was connected to the system but not installed in the soil. It is simply placed in a bottle half filled with water. This SCL would not have any obstruction in sampling water and the bottle would always be the fullest, indicating the physical upper limit of this sampling event. The relative volumes of soil water sampled, indicated the matrix potential at all sampling positions. Thus both the volume and quality of all samples were important to be registered.

4.3 Summary

The new SCL was designed and successfully implemented during years of field research. Our SCL had the advantage that it could be operated remotely. This allowed sampling at precisely planned times and provided added value in years of monitoring and managing soil salinity. Ease of use is the main characteristic of this system. More details regarding the results were given in Chapter 3.

The soil water samples could also supply information on the soil water content by just recording the mass. This system is fairly inexpensive and if one should choose between different management systems, this research approach can supply more information than conventional SCL's.

The system could always be left in a ready mode and could therefore easily be activated whenever necessary. Since the system allows remote operation, a lot of time was saved in acquiring data.

5 PREDICTION OF THE DEPTH TREND IN SOIL SALINITY OF A VINEYARD AFTER SUSTAINED IRRIGATION WITH SALINE WATER[3].

ABSTRACT

Remote sensing combined with an ability to look deeper than the soil surface is currently high in demand. This study was conducted through scaling down on the amount of soil data from a saline irrigation water experiment to see if one can still capture the essential soil salinity depth-trends within the data, to a level that can enhance the ability of remote methods. A saline irrigation experiment with 6 water qualities was conducted for 8 years on 1.2 ha of vineyard land near Robertson in the Western Cape Province of South Africa. Soil water was sampled at regular intervals at 5 depths between 0.15 and 1.2 m with suction cup lysimeters at a fixed time following each irrigation. Electrical conductivity of the soil water (EC_{sw}) was determined after sampling. Data collected over the full 8 year period were investigated for depth trends in EC_{sw}, seeking trend lines with lowest polynomial order that were still significantly predict the salinity profile. At all treatment levels a first order polynomial equation, fitted to the salinity profiles, significantly predicted the salinity trends.

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[3] *Published in:*

de Clercq, W.P., Van Meirvenne, M., Fey, M.V., 2008. Prediction of the depth trend in soil salinity of a vineyard after sustained irrigation with saline water. *Agricultural Water Managment*. In press, doi:10.1016/j.agwat.2008.09.002.

The EC_{sw} value at only two depths could therefore be used to calculate total salt accumulation and soil water quality below the root zone. The implication is that considerable value can be obtained from minimal measurements both in estimating salt accumulation in the soil profile and predicting water quality in return flow from saline irrigation.

5.1 Introduction

There are scant reports on soil water salinity dynamics in response to saline irrigation, especially concerning the seasonal variation in electrical conductivity of the soil water (EC_{sw}) as a function of depth. Amongst others, Rhoades *et al.* (1997), Cetin (2003), de Clercq and Van Meirvenne (2005) and Douaik *et al*. (2006) have all emphasised the importance of spatial and temporal changes in soil salinity and the effect on return-flow water-quality when use is made of low quality irrigation water. In such studies, soil salinity is generally reported as an integrated value for the whole profile.

In many countries sustained irrigation with poor quality water is commonly practised and requires close monitoring and control of soil salinity both at the regional and field scales to minimise the adverse effects on production and impacts on downstream users (Odeh *et al.*, 1998; Kelleners and Chaudhry, 1998; Kotb *et al.*, 2000; Görgens and de Clercq, 2004). Rapid assessment of soil salinity is becoming increasingly important for managerial purposes. Salinity depth trends were investigated after sustained irrigation for sugar cane (Nelson and Ham, 2000), winter wheat (Sharma and Rao, 1998) and rice (Mondala *et al.*, 2001). For vineyards, de Clercq *et al.* (2001) reported on the effects of poor quality irrigation and posed the following list of questions that should be considered when considering irrigation quality:

- Does the farmer use refined scheduling techniques?
- Do the advantages of partial wetting of the soil apply?
- What is the salt tolerance of the crop?
- Does the salt content of the marketable product matter?
- What is the length of season for the crop?
- What is the typical rooting volume of the crop?
- Under saline conditions, should crops be selected with the smallest possible rooting volume?
- What is the quality of the receiving waters?

Perssons and Uvo (2002) are amongst others, indicated that, the electrical conductivity measured alone or where for instance time domain reflectometry was used to measure to soil water content and bulk electrical conductivity, a very complicated approach to link soil water EC with other measured parameters. Perssons and Uvo (2002) is perhaps also the most recent example of the complicated situation arising when soil water EC is measured at a range of soil water content values for different soils. These are all at non-saturated conditions. The ability to use these values for any predictions depends on the accuracy of two infield-measured parameters and the calibration of the individual sensors. These measurements can be of great value when plant reaction to soil water EC needs to be tested between irrigations but to compare results between different locations and different instruments becomes quite a daunting task. de Clercq *et al*. (2001) showed that the cumulative effect of bad irrigation water quality on vines could be adequately described using a single set of soil water measurements taken after each irrigation event, when the soil water content was still at field water capacity. These soil water samples, extracted from the soil using micro lysimetry, were then analysed using a single laboratory EC probe. This method then allowed for easier comparison between infield measurements done at different depths and locations and different soil types. Using the extracted soil water at field capacity also has the added advantage that it can be directly related to the quality of the water that moved through the soil. Once evaporation from the soil surface starts and the plant starts to utilise some of the water, the downward movement of water stops and the EC_{sw} starts to change, as salts are concentrated in the remaining soil water.

Modern devices, such as the electromagnetic induction sensor EM38, used for routine monitoring of soil salinity, are limited in their ability to make measurements over the entire soil profile. Shi *et al.* (2006) indicated that they could successfully map coastal sandy soils for reclamation using hyperspectral remote sensing; however, their study applied only to soil surface conditions. On the other hand, Zhu *et al.* (2006) developed a knowledge based system for predicting grain yield taking into account all possible conditions affecting wheat growth, including soil type and soil depth parameters. If these two approaches could be combined, the possibility of predicting subsoil conditions remotely seems attainable. Farifteh and Farshad (2002) emphasized the need to be able to detect and model soil properties from remotely sensed sources. They listed some possibilities of how to be able to tell more about subsoil conditions, in particular soil salinity, from remotely sensed information. They indicated that imaging spectrometry provides large volumes of high resolution spectral data, which can be useful to detect soil properties. They further indicated that a next step would be to link modelled soil processes using existing models (for example SWAP and

CropSyst) to this hyperspectral information base, to model subsoil conditions and the fate of salinity in the landscape.

Metternicht and Zinck (2003) indicated some constraints on the use of remote sensing data in a review article. They stated that monitoring soil salinity cannot be achieved from remote sensing data alone, and requires a solid synergy between remote sensing data, field observations and laboratory determinations as sources of data, and GIS capabilities for processing, transforming and displaying the data. They further concluded that the best results are obtained when integrating remote sensing data with field and laboratory data and that it is the researcher's challenge to identify the most adequate salinity indicators for a particular area, so that appropriate ground and remote sensing techniques can be applied to extract information in an accurate and cost-effective manner. Lesch *et al.* (1995) attempted the link between satellite imagery and EM38 interpreted soil salinity information using multiple linear regression models and found, after successful modelling, that they could reduce the sampling density and still retain the prediction accuracy inherent in their statistical calibration techniques, also facilitating assessment methodology that can be applied in a rapid, practical, and cost-effective manner.

This chapter strives to indicate means of revealing more about irrigated subsoil conditions when using remotely sensed information. For that purpose, it is important to indicate and define subsoil conditions that lend itself to a higher degree of predictability and define a starting point for modelling of this nature. Therefore, a basis needs to be established for making the best use of relatively meagre information about the salinity depth function. To achieve this goal, the approach posed by Davis (1986) was used. This implied using a F-test (Tables 5.01 and 5.02) coupled with trend surface theory (Davis 1986, pp. 405-422) to find trend lines with the highest significance and with the lowest possible polynomial order. The procedure aims to solve curvilinear regressions or trend surfaces in the simplest possible way and the idea was developed before computers became widely available. The choice of a polynomial expression is normally governed by the goal of achieving the highest degree of goodness-of-fit and higher order polynomials are more successful at this, since they encompass the lower order forms (Mondala et al., 2001). However, higher order polynomials require more parameters to be fit and therefore they are more data demanding. Frequently by making use of an adjusted R^2-value, deviation from the trend surface and the degrees of freedom, the decision for using a lower order polynomial also becomes evident. Therefore, for small data sets, lower order polynomials are usually more realistic (Lesch *et al.*, 1995; Forsberg and Nilsson, 2005).

The knowledge base for modelling soil salinity is however well established and similarly the methodology for mapping features of the topsoil from remote sources. The linkup between the two, that could allow us to know more about the soil from the interpretation of remotely sensed information, is currently fuzzy. The objective of this chapter therefore is to examine soil-depth salinity-trends after prolonged irrigation of a vineyard with different salt concentrations, and to find the simplest basis for calculating salt accumulation and return flow water quality from a limited number of measurements that could also be detected remotely.

5.2 Materials and methods

This saline irrigation experiment was carried out for eight years (from 1991 till 1998) in a vineyard near Robertson in the Western Cape Province, South Africa (Figure 2.02, central coordinates 33°49'29.03"S and 19°52'44.77"E). The experimental layout was fully described in Chapter 3 and will therefore not be repeated here.

This is a predominantly winter rainfall region, which ensured that there was negligible interference in the water balance by rainfall during the summer months when most of the irrigation was applied. The average total amount of irrigation applied during summer was 600 mm and the combined winter rainfall and winter irrigation was aimed at 600 mm. During winter, rain was supplemented with irrigation to promote leaching of salts and ensure the success of a cover crop (de Clercq *et al.*, 2001).

Irrigation was systematically applied in the afternoon of each Wednesday and suction sampling was initiated 12 hours after irrigation had terminated, to ensure that the soil water status was effectively at field capacity. Over the 8 year duration of the experiment at least 12 annual sets of suction cup data were successfully collected, with 7 to 9 of these being collected during the irrigation season and the remainder during winter (de Clercq *et al.*, 2001).

5.2.1 Data analysis

Trend surface analysis, as described by Davis (1986), was used to analyse the seasonal soil salinity distribution with depth. In this procedure the order of the polynomial expressions, fitted to the EC_{sw} data (Z) plotted as a function of time (X) and depth (Y) for each treatment, was raised successively to establish the polynomial with the lowest order that was still significant.

To simplify the trend surface routine and to extend this as a statistical decision base tool, an algorithm was developed in Basic programming language, which determines the coefficients (b_0, b_1, b_2) relating X, Y and Z to each other for n observations and calculates the F-test results as shown in Tables 5.01 and 5.02, up to a 3rd order polynomial, based on the following the three so-called *normal equations* (Davis, 1986):

$$\sum Z = b_0 n + b_1 \sum X + b_2 \sum Y \qquad \textbf{Eq}.\ 5.01$$

$$\sum XZ = b_0 \sum X + b_1 \sum X^2 + b_2 \sum XY \qquad \textbf{Eq}.\ 5.02$$

$$\sum YZ = b_0 \sum Y + b_1 \sum XY + b_2 \sum Y^2 \qquad \textbf{Eq}.\ 5.03$$

Having derived these coefficients, the position of Z on a linear surface trend (i.e. EC_{sw} as a function of depth and time) can be predicted. The goodness of fit of this surface trend can be calculated from the total sum of squares (SSt) and the sums of squares resulting from the trend surface (SSr), and the deviation from the trend surface (SSa), where

$$SSa = SSt - SSr \qquad \textbf{Eq}.\ 5.04$$

and the goodness of fit is then calculated as

$$R^2 = \frac{SSr}{SSt} \qquad \textbf{Eq. } 5.05$$

with R^2 being a multiple synonym for the R^2 used in linear regression. Using Eq. 5.04 in 5.05, R^2 can be rewritten as:

$$R^2 = \frac{SSr}{SSt} = 1 - \frac{SSa}{SSt} \qquad \textbf{Eq. } 5.06$$

Because R^2 is enhanced by increasing the order of the polynomial describing the trend surface, it has doubtful value for decision making. Therefore an adjusted R^{2*} was adopted, which is calculated in terms of *SSa* in Eq. 5.06 and not *SSr* in Eq. 5.05, and then corrected for degrees of freedom (*df*),

$$R^{2*} = 1 - \left(\frac{SSa}{n-k-1}\right) . \left(\frac{SSt}{n-1}\right)^{-1} = 1 - (1 - R^2) \cdot \left(\frac{n-1}{n-k-1}\right) \qquad \textbf{Eq. } 5.07$$

where the numerator terms *n*-1 and *n*-*k*-1 are the *df*, in which *n* is the number of observations and *k* is the number of regression coefficients ignoring b_0 (Davies, 1986).

The most important argument for using trend surface analysis in the current context lies in the test for significance (F-test, Tables 5.01 and 5.02). The significance of the specific trend was tested through an analysis of variance or ANOVA (Table 5.01). The degrees of freedom used (*df* minus b_0) were 2 for the 1st order polynomial, 5 for the 2nd order and 9 for the 3rd order. The test for significance was then applied and compared for surface trends of different order in an expanded ANOVA (Table 5.02). For each increase in order the significance of the increase was also tested. The expanded ANOVA in Table 5.02 consisted of three variance analyses, each with its own F value.

Table 5.01 : ANOVA table for a linear surface trend (*n* = number of observations) (Davis, 1986).

Variance	**Sum of squares**	***df***	**Mean SS**	***F* test**
Linear trend	*SSr*	2	*MSr*	*F = MSr/MSa*
Deviation	*SSa*	*n - 2 - 1*	*MSa*	
Total variance	*SSt*	*n* - 1		

Table 5.02 ANOVA table for the significance of increase in order from *p* to *p*+1 where the trend surface of order *p* has *k* regression coefficients (without b_0) and surface of order *p*+1 have *m* regression coefficients (without b_0). The number of observations is *n* (Davis, 1986).

Variance object	**Sum of squares**	***df***	**Mean SS**	***F* test**
Trend surface order *p*+1	SSr_{p+1}	*m*	MSr_{p+1}	$F_{p+1} = MSr_{p+1}/MSa_{p+1}$ (a)
Deviation from order *p*+1	SSa_{p+1}	*n – m* - 1	MSa_{p+1}	
Trend surface of order *p*	SSr_p	*k*	MSr_p	$F_p = MSr_p/MSa_p$ (b)
Deviation from order *p*	SSa_p	*n – k* - 1	MSa_p	
Increase in order	$SSv = SSr_{p+1} - SSr_p$	*m* - *k*	*MSv*	$F_v = MSv/ MSa_{p+1}$ (c)
Total variance	*SSt*	*n* - 1		

(a) Significance test for trend surface with order *p*+1
(b) Significance test for trend surface with order *p*
(c) Significance test for the increase in order

This resulted in two estimates for Z: one from a trend surface of order *p* and one from a trend surface of order *p*+ 1. For each of these estimates, two sums of squares were calculated for the fitted trend surface (SSr_p and SSr_{p+1}) and two for the deviation from the fitted trend (SSa_p and SSa_{p+1}). The latter were derived from SSt, and SSr_p or SSr_{p+1}, respectively. The sum of squares that originates through the increase in order is $SSv = SSr_{p+1} - SSr_p$. Dividing these sums of squares by their respective *df*, produces R^2* (adjusted R^2) values which can then be compared by means of the three F-tests.

The above approach formed the basis for deciding which order of trend surface to use for predicting EC_{sw} as a function of soil depth and time of year. Through this collective approach, an argument can be substantiated that whatever polynomial trend applies for a trend surface, should apply for an individual soil profile.

5.3 Results and discussion

All EC_{sw} data collected in each month over 8 irrigation years were pooled to allow monthly means and standard deviations to be calculated over all depths for each treatment. These were plotted from October onwards for the six salinity treatments and shown in Figure 5.01. It can be observed that the salinity peak between March and May increased in magnitude over the first four levels of irrigation salinity but remained relatively constant thereafter, suggesting that there is a characteristic upper limit of profile salinity governed by the application of a 10 percent leaching fraction in combination with leaching by winter rain. This also suggests that in the high salinity treatments the water uptake was reduced and that as a result the leaching fraction may have been larger than the planned 10 percent. A number of studies showed the effects of salinity on crop yield, by relating the effect soil salinity has on crop ET, and assuming the ET and crop yield to be linearly related (Shani *et al.*, 2007: Ben-Gal, 2008)

The summer data (October to March) for each treatment (192 measurements per treatment) were pooled for the purpose of calculating the statistics shown in Table 5.03. These summer data formed the basis for developing predictive polynomial expressions relating soil salinity to both depth and time.

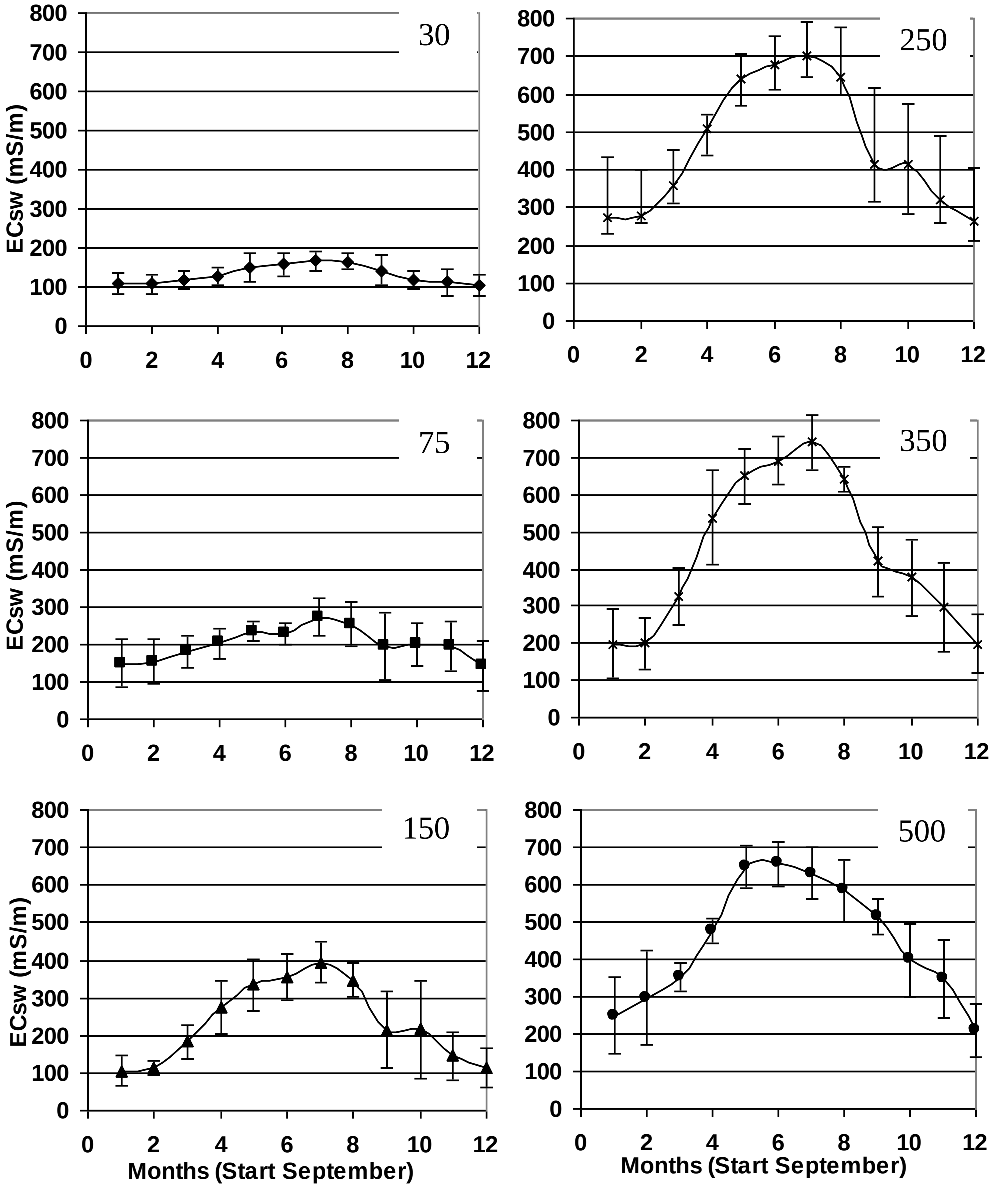

Figure 5.01 Monthly means and standard deviations (vertical bars), calculated for an eight year period, of soil water salinity developed in response to six irrigation salinity treatments (mS m^{-1}).

Table 5.03 Summer month (October to March) statistics for EC_{sw} (mS m^{-1}) as a function of irrigation salinity treatments (n = 192 observations per treatment).

Treatment (mS m^{-1})	**30**	**75**	**150**	**250**	**350**	**500**
Min	0.75	0.80	0.67	1.26	1.12	1.14
Max	2.07	2.61	4.53	7.54	7.58	6.90
Mean	1.28	1.92	2.27	4.55	4.34	4.31
s^2	0.06	0.10	0.21	0.35	0.40	0.29
Skewness	0.52	-0.78	0.30	-0.17	0.06	-0.30
Kurtosis	0.69	-0.45	-1.10	-1.19	-1.47	-0.89

s^2 is an estimator of the variance σ^2.

The procedure of Davis (1986) was applied to identify the polynomial with the lowest order while remaining statistically significant in 95% of the cases. The significance of the increase in trend surface order was tested and the results are shown in Tables 5.04 to 5.06. These tables show the significance, in terms of F values, of first, second and third order polynomials. The F(p, df, df) value is also shown in each case and the latter is consistently smaller than the F value, supporting the argument that a first order trend surface should be sufficient to describe the relationship of EC_{sw} to depth and time.

Table 5.04 ANOVA table for a linear surface trend.

Variance object	**Sum of squares (SS)**	***df***	**Mean SS**	***F* test**
Trend surface order *p*	29088	2	13158	128
Deviation from surface	26316	27	102	
Total variance	2772	29		F(0.05,2, 27) = 2.62

Table 5.05 ANOVA table for the significance of an increase in order *p* to *p*+1 where the trend surface with order *p* has *k* regression coefficients (without b_0) and the trend surface with order *p*+1 has *m* regression coefficients (without b_0). The number of observations is *n*.

Variance object	Sum of squares (*SS*)	*df*	Mean SS	*F* test
Trend surface, order *p*+1	26702	5	5340	53.7[a]
Deviation from surface	2386	24	99	$F(0.05,5,24)$ = 2.62
Trend surface, order *p*	26316	2	13158	128.13[b]
Deviation from surface	2772	27	102	$F(0.05,2,27)$ = 3.36
Increase in order	386	3	128	1.294[c]
				$F(0.05,3,24)$ = 3.01
Total variance	29088	29		

[a] Significance test of **trend surface** with order *p*+1
[b] Significance test of **trend surface** with order *p*
[c] Significance test of the increase in order

Table 5.06 ANOVA table for the significance of an increase in order from *p*+1 to *p*+2 where the trend surface with order *p*+1 has *k* regression coefficients (without b_0) and the trend surface with order *p*+2 has *m* regression coefficients (without b_0). The number of observations is *n*.

Variance object	Sum of squares (*SS*)	*df*	Mean *SS*	*F* test
Trend surface, order *p*+2	27793	9	3088	47.65[a]
Deviation from surface	1295	20	64.7	$F(0.05,9,20)$ = 2.39
Trend surface, order *p*+1	26702	5	5340	53.70[b]
Deviation from surface	2386	24	99.4	$F(0.05,5,24)$ = 2.62
Increase in order	1090	4	272.6	4.20[c]
				$F(0.05,4,20)$ = 2.87
Total variance	29088	29		

[a] Significance test of **trend surface** with order *p*+2
[b] Significance test of **trend surface** with order *p*+1
[c] Significance test of the increase in order

The trend surfaces representing first, second and third order polynomials were mapped for all six treatments in Figure 6.02 (the surfaces are salinity contours, the shading intensity of which is proportional to the salinity degree). Figure 5.02 indicates that the salinisation tendency as summer progresses from October to March was strongest at depth in the low salinity treatments but was more uniformly distributed through the soil profile in response to more saline treatments. Since only five depth intervals were sampled, fitting a polynomial higher than the first order for a single sampling event would probably correspond to over-interpretation. In Figure 5.02, treatments 150 and 350 mS m^{-1} showed differences in the general trends compared with the other treatments.

These differences were associated with lower infiltration rates, as part of these treatments were affected by ancient termite nests, causing different soil water behavioural patterns. Regardless of the latter, the way in which trend surface analysis was applied, combined the parameters of space and time in the test. Therefore the different sampling points in the landscape showed similar behaviour.

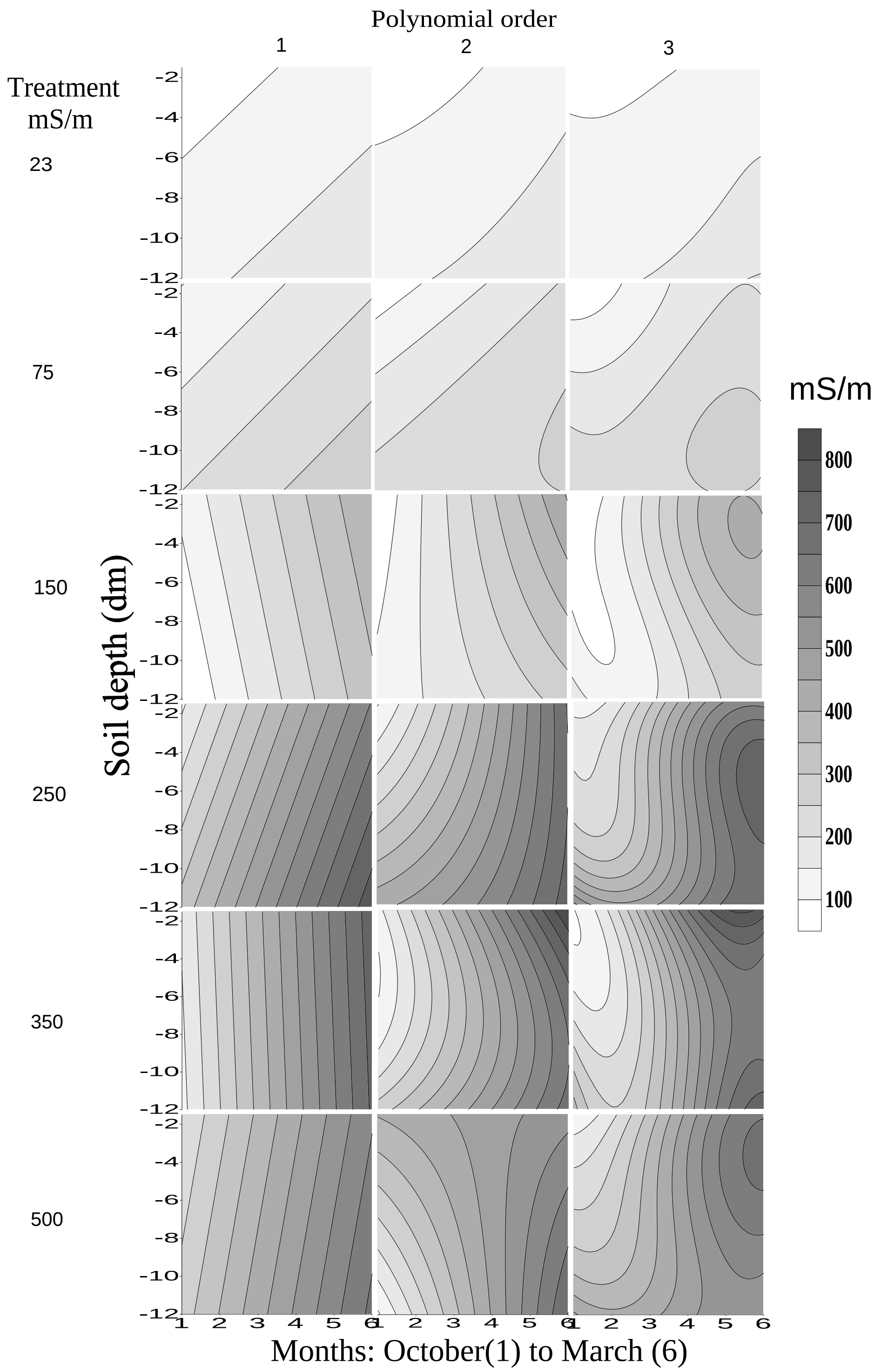

Figure 5.02 Trend surfaces represented by contours of soil water salinity (EC_{sw}) in relation to time in early summer and depth of soil in plots treated with six levels of irrigated salinity over eight years. Graph columns from left to right are based on the 1st, 2nd and 3rd order polynomials as applied to the time to depth EC_{sw} relationships.

Table 5.07 shows the changes in both R^2 and $R^{2}*$ with increasing polynomial order as was applied to the *p*, *p*+1 and *p*+2. It is clear that the difference in R^2 values has shrunk considerably by using the adjusted R^2 to such an extent that there is almost no difference between p and p+1.

Table 5.07 R^2 and the adjusted R^{2*} for the three trend orders.

Order	R^2	R^2*	R^2 - R^2*
***p* first**	0.905	0.898	0.007
***p*+1 second**	0.918	0.901	0.017
***p*+2 third**	0.955	0.935	0.020

Due to the significance displayed in the first order polynomial above (Table 5.04), it should be possible to describe salinisation of the soil profile during an irrigation season on the basis of only two measurement depths (preferably conveniently shallow). This could enable quick estimation whether over- or under-irrigation has occurred and whether salt accumulation has taken place below the root zone. This can be indicated by knowing the gradient (m) of the first order polynomial. To determine which two monitoring depths are most suitable, the data were subjected to an analysis in which depth trend lines for each time interval were calculated from EC_{sw} measurements at two pairs of shallower depths (either 15 and 60 cm or 30 and 60 cm). The gradients of these EC depth trend lines were then compared with the gradients of EC lines derived from EC measurements at all five depths in Table 5.08. Therefore, the regression between the gradients derived from situation 1 (Table 5.08) and gradients derived from the 5 depth trend lines, produced a R^2 of 0.51 and a highly significant p0.005 value of 0.0034. But, regressing the general soil EC_{sw}-profile from situation 2 (Table 5.08), with the 5 depth trend line gradients, produced a better R^2 value of 0.89 and a p0.005 value of 0.0001. This shows that in about 9 out of 10 cases tested, an increase or decrease of EC_{sw} at a soil depth of 120 cm could be predicted with confidence by looking at EC_{sw} data from only two depth increments in the upper soil. The reason that the 0-15 cm depth showed a poorer result could possibly be related to the fact that ameliorants were added shortly before sampling or salt accumulated on the soil surface as an evaporite. The third depth increment, namely the 30-60 cm depth, proved to be the region where the bulk of the roots were situated and therefore where most soil water was taken up by the plant (de Clercq *et al.*, 2001). It is clear that the predictive accuracy increases when the soil surface layer is avoided but the data for depth increment combination, situation 3 in Table 5.08, show that inclusion of the A-horizon in the prediction still produced a useful result. This demonstrates that the use of an instrument such as the EM38 electromagnetic induction sensor could be of great value in predicting salinity depth trends in irrigated agriculture.

Table 5.08 A regression between the gradient values of the 1st order polynomials derived from EC_{sw} at selected depth increments and from slope values derived from EC_{sw} at all 5 depth increments for situations 1 to 3.

Situation	**EC_{sw} at depths (cm)**	**Regression equation (Y= EC_{sw}, X=depth)**	R^2	$p_{0.005}$
1	0-15, 30-60	$Y = 0.435X + 0.469$	0.51	0.0034
2	15-30,30- 60	$Y = 0.482X + 0.546$	0.89	0.0001
3	0-30, 30-60	$Y = 0.402X + 0.526$	0.65	0.0001

A further step was to test the extent to which the EC_{sw} below the root zone could be predicted using information based on measurements at the centre of the root zone. The resulting prediction is shown in Table 5.09, where the EC_{sw} at 120 cm depth was predicted using the EC_{sw} values at the 15-30cm and 30-60cm depth. The result as indicted in Table 5.09 is highly significant in predicting the quality of the water that would drain from this field. Water that drained past the bottom of the root zone is generally considered lost to drainage unless prolonged periods of under-irrigation occur in which case upward water movement and salt build-up could occur.

Table 5.09 A regression analysis between predicted EC_{sw} values for the 120 cm depth (based on the 15-30 and 30-60 cm increments) and the measured 120 cm depth EC_{sw} values.

R^2	**Standard Error**	*df*	$p_{0.005}$	*F*
73.9	97.4	71	0.00004	198.4

The modelled change in salinity depth trend through the year is illustrated in Figure 5.03. To amplify the seasonal response, Figure 5.05 was added to indicate the change in slope of the depth trend lines when the offset in each equation is ignored and **x** = 1. This signifies the relationships between treatments in terms of their profile inclination for the time of year. In both Figures 5.03 & 5.04, a positive slope mean low salt in the upper and high salt in the lower horizon. A negative slope indicates higher salt in the upper section of the profile. The indicated trend lines tie together at point (15;1) which is again an indication of the excellent predictive quality of the first order polynomial have in this data.

The migration of the regression lines (Figures 5.03 and 5.04), resulting from irrigation with saline water, might have been overlooked without the stating of simplified first order polynomial modelling. Knowing how the soil responds to irrigation over time has important implications for when soil salinity surveys are carried out with electromagnetic induction sensors or when large areas have to be sampled for EC mapping and the prediction of return-flow.

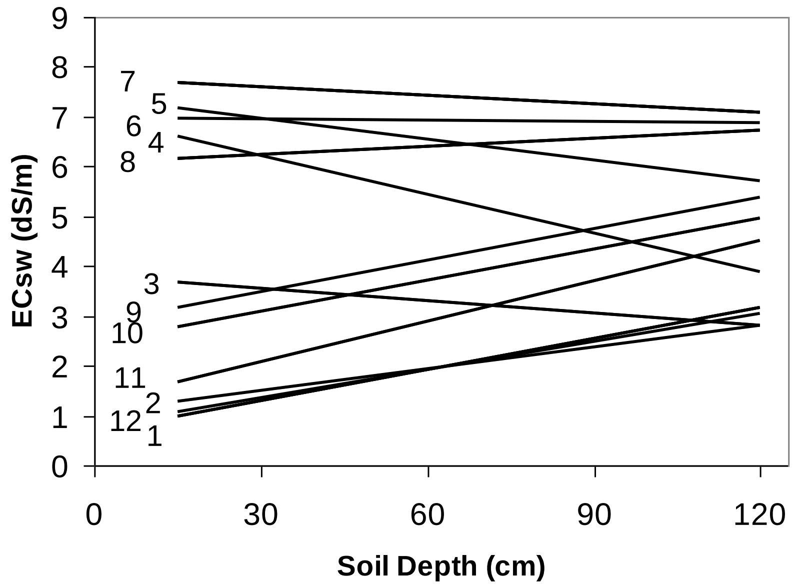

Figure 5.03 Migration of the regression lines for EC as a function of depth resulting from irrigation treatment 5 (350 mS m^{-1}), revealing the dynamics of EC_{sw} over time. Numbers 1 to 12 represent months from October to September of the following year.

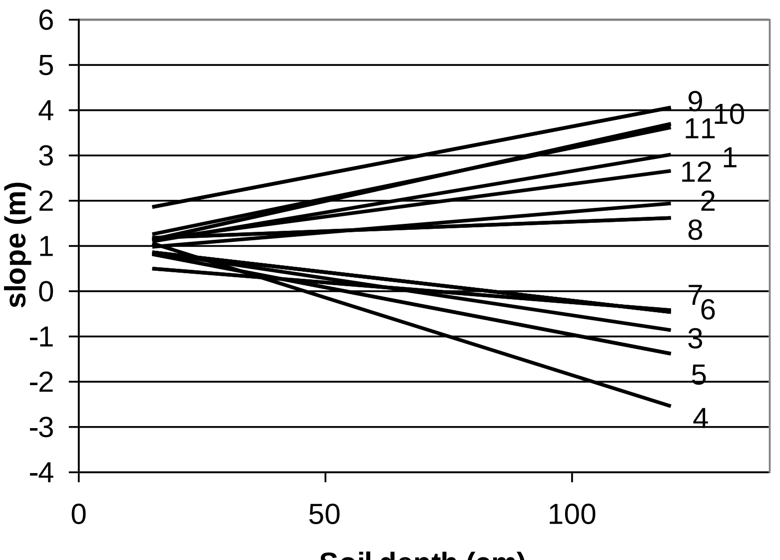

Figure 5.04 A migration of the regression lines for EC as a function of depth resulting from irrigation treatment 5 (350 mS m^{-1}), revealing the dynamics of slopes (m) in EC_{sw} trend lines over time (**x** = 1, offset = 0). Numbers 1 to 12 represent months from October to September of the following year.

Apart from using electromagnetic induction sensors, by knowing the date, irrigation water quality and being able to remotely measure the topsoil EC, estimation of both the subsoil salinity conditions becomes possible.

5.4 Conclusions

Soil scientists often focus on unnecessary detail regarding soils and their behaviour. This study provided an opportunity to better understand the temporal and spatial variation of EC_{sw} by using a simplified approach. The classical trend surface analysis procedure of Davis provided an answer to the problem of finding a suitable depth relationship that could be used as a norm for the soil studied. This simplified the management of salt in the soil and the quantity and quality of return flow.

Prediction of the depth trend in EC_{sw} with a first order polynomial has distinct advantages. Over- or under-irrigation can easily be evaluated for any irrigated land. Prediction of salt accumulation on the soil surface or deep drainage can readily be assessed. The slope of the first order polynomial indicates directly the general trend and whether an accumulation or a depletion of salt can be expected in the soil. When linked to remote sensing, the approach described here could be used in evaluating extensive areas of land in terms of salinity and their suitability for irrigated crops.

Lastly, this research further showed that by knowing the date and irrigation water quality and being able to characterize the topsoil EC remotely, one can estimate subsoil salinity conditions in irrigated lands and further estimate the return-flow component from such irrigated lands.

6 EXPLORING THE VARIABILITY OF EC_e BETWEEN VINE ROWS

6.1 Introduction

Soil water samples could not be taken routinely with SCL's between the vine rows as this would have hampered traffic and soil tillage. Winter wheat is normally sown and used as a cover crop for lowering evapotranspiration from the soil surface during the summer, as the stubble is left, acting as a soil blanket. The cover crop also has a large influence on the distribution of salts in the inter-row region as it minimises evaporation from the soil surface (Figure 6.01). The driving force behind the accumulation of salt near and on the soil surface in the inter-row region is therefore modified. It could be expected that in a region where a cover crop was used, that more water would have been available for leaching in comparison to a site where no cover crop was used. Furthermore, the successful establishment of a following year's cover crop is dependent on the amount of salt in this top soil, implying that less salt ensures more successful germination and better growth. This concept therefore had a large influence on the amount of evaporation from the soil surface. It thus also had a profound influence on the salt gradient found between the row position and the inter-row position (Du Toit, 1995).

Figure 6.01 A vineyard row on the Robertson farm, indicating the vehicle tracks and biomass on the soil surface. Salinity damage on the leaves is also visible.

The general aim of this section was to provide information on the salt content of soils between vine rows, to explore the variability in salt distribution in vineyards where partial wetting of the soils is the norm. This aim should rather be put as a question. Where should one take soil samples in a partially wetted vineyard?

6.2 Materials and methods

To investigate the variability of EC_{sw} between the vine rows, soil samples were taken across rows in three of the irrigation treatments, described in Chapter 3 for the Robertson farm, namely 30, 250 and 500 mS m^{-1}. This sampling was however only done once, i.e. after 4 years since the start of the experiment and in February, the harvesting month. In each case, two lines were sampled across the vine rows and the averages of the two lines were used to map EC_e with depth over distance. Five depths were sampled (15, 30, 60, 90 and 120 cm) in 9 positions across the vine rows at a 0.5 m interval (Du Toit, 1996; Moolman *et al*., 1999).

To map the soil profile data, an omni-directional linear semi-variogram model was used to interpret the EC_e data using ordinary kriging of all the observations (Webster and Oliver, 2007). Figures were generated with the program Surfer™.

6.3 Results and discussion

The interpolated EC_e is given in Figure 6.02 for the control treatment (EC_i = 30 mS m^{-1}) at harvest time (February 1996). A similar presentation is given in Figure 6.03 for EC_i = 250 mS m^{-1} and Figure 6.04 for the 500 mS m^{-1}.

As the treatment EC_i increased over Figures 6.02 to 6.04, the hotspot in the profile changed from deep (Figure 6.02) to the surface (Figure 6.04). This shift is most likely due to the difference in surface cover and the differential amount of water used by the vines between the treatments. It is also apparent that the salt accumulation shown in Figures 6.03 and 7.04 is in the vicinity of the vehicle tracks. These tracks (Figure 6.03, at the 1 and 2 m marks), being small furrows and more compacted than the surrounding soil, possibly led to poorer growing conditions for the cover crop and also created a larger capillary continuity to the lower soil layers which aided evaporation and therefore deposition of salts. It was also observed that the cover crop was less effective in the higher treatments as a result of poorer growth.

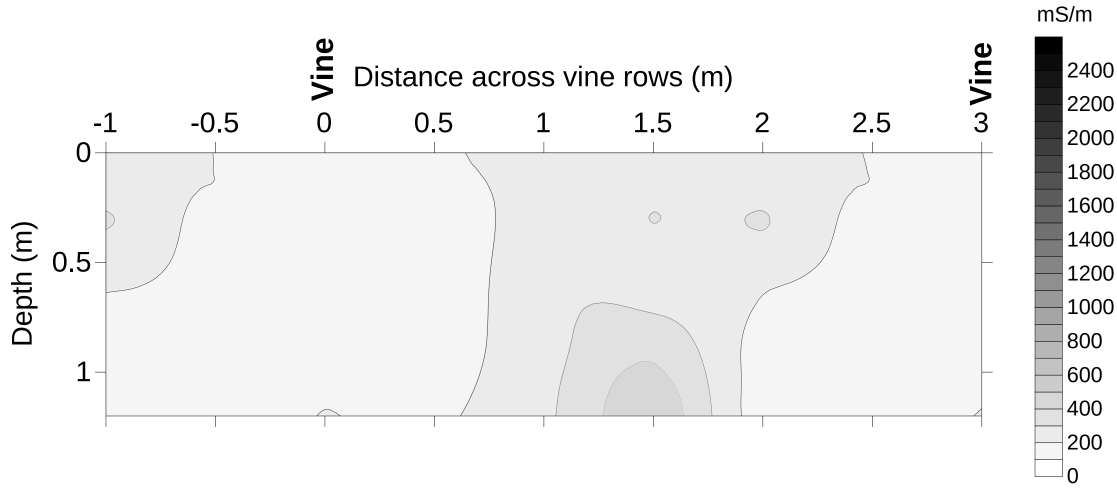

Figure 6.02 Kriged soil EC_e results taken perpendicular to vine rows to a depth of 1.2 m in the fresh water (~30 mS m^{-1}) treatment at the end of the irrigation season. Sampling positions are indicated by all the X-axis tic marks.

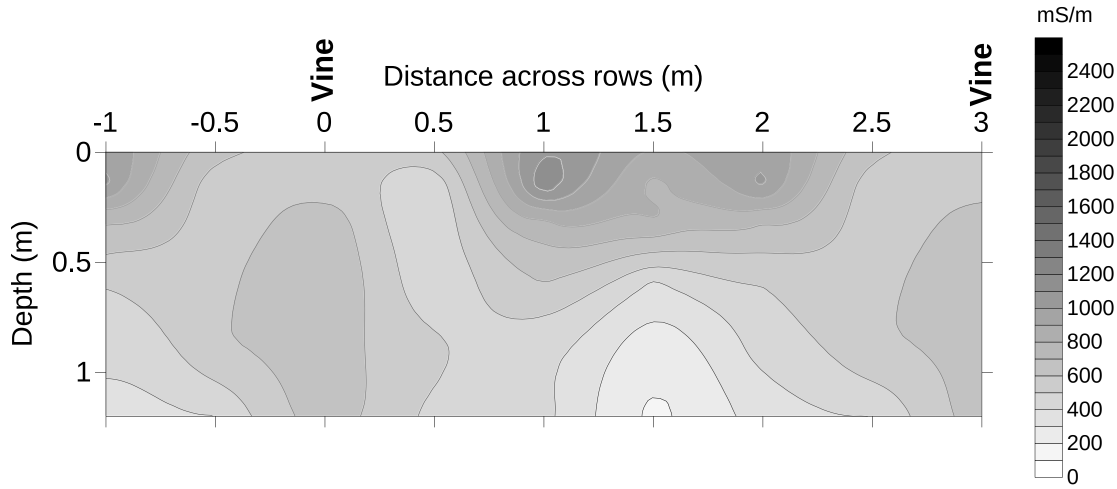

Figure 6.03 Kriged soil EC_e results taken across vine rows to a depth of 1.2 m in the 250 mS m^{-1} treatment at the end of the irrigation season. Sampling positions are indicated by all the X-axis tic marks.

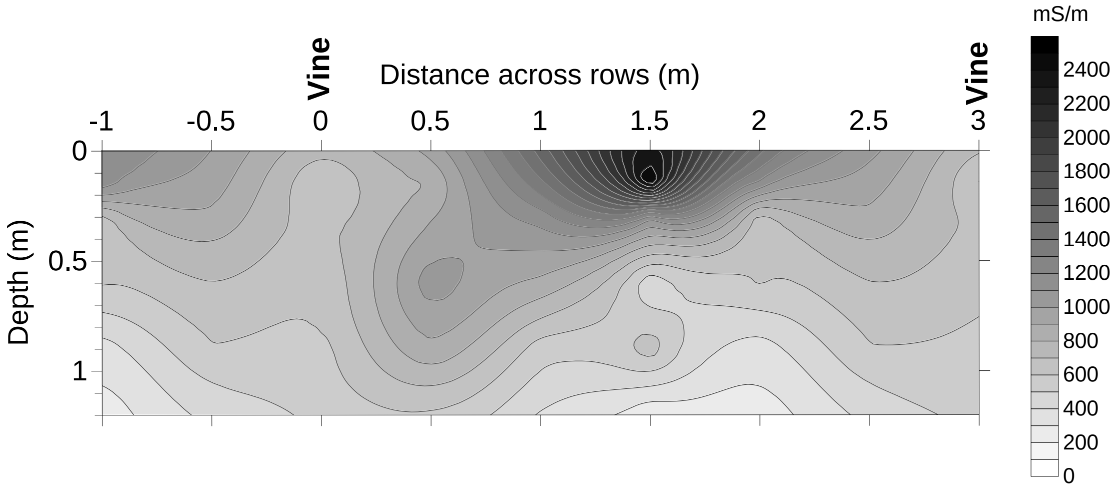

Figure 6.04 Kriged soil EC_e results taken across vine rows to a depth of 1.2 m in the 500 mS m^{-1} treatment at the end of the irrigation season. Sampling positions are indicated by all the X-axis tic marks.

6.4 Conclusions

The results show clearly that the distribution of salts from under the irrigation emitters to a position 1.5 m away in the middle between two vine rows, is highly variable. Though no seasonal data exists for it, the inter-row region can was subjected to a salt build-up over the season and is not always leached by the irrigation. Winter irrigation also meant partial wetting of the soil. Any salts that stayed in the soil over the longer term will be found in the inter-row position.

Factors like the plant density of the cover crop, partial wetting of the soil, the orientation of the vine rows, traffic in the vineyards and the quality of the irrigation water, all play a crucial role in the accumulation of salt in this part of the vineyard soils. This knowledge contains important management aspects for a saline environment.

The results shown here suggest various points to consider when research is being conducted in saline soils as well as management options for saline environments. These are as follows:

- that salt could be stored during summer preventing the contamination of river water,
- during winter, when more fresh water is available, salts could be leached gradually and
- it is also important to know that where partial wetting of the soils is the norm, the position where soil samples are taken, needs to be very carefully considered as the variation across vine rows is always more variable than along vine rows. Samples should be taken both in between (max salinity) as well as in the vine rows (minimal salinity).

7 EFFECT OF LONG TERM IRRIGATION APPLICATION ON THE VARIATION OF SOIL ELECTRICAL CONDUCTIVITY IN VINEYARDS[4]

ABSTRACT

The soil of a section of the farm Broodkraal, in the South Western Cape province of South Africa, was sampled on a 45 by 50.5 m grid to model spatial variation of salinity and predicts the amount of salts lost through irrigation. Sampling was done to a depth of 45 cm. The sampling included vineyards of different age that varied between two and five years since the first irrigation application. Salts mobilized by irrigation have a profound effect on the water quality in the Berg River catchment.

We propose inverse distribution functions as a method to model the temporal change in salt content of the soil. We assume that the parameters of the distribution function for salt content depend on time since land was taken into irrigation. We may therefore take observations of salt content from land that has been irrigated for some known time, and predict the corresponding values in past or future by a simple transformation of the data.

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[4]*These results were published in :*

de Clercq, W.P., Van Meirvenne, M., 2005. Effect of long term irrigation application on the variation of soil electrical conductivity in vineyards. *Geoderma* 128, 221-233.

To test this hypothesis we undertook a second sampling campaign on sections of the farm irrigated for the same length of time as two of our original data sets. We showed that temporal variability of the distribution functions of all data was more substantial than the spatial variability between data sets on land irrigated for the same period of time.

It is clear that the general lowering of EC_e over time caused the variance to reduce. The comparison of variograms showed that the use of only one variogram model to krige the total landscape might result in an over simplification of the young irrigated surfaces while it complicated the older ones. Any mapping of EC_e aimed over larger areas should therefore take cognisance of the irrigation age and the sampling frequency should be increased for younger or non-irrigated surfaces.

Finally, the results were used to estimate the yearly salt return to the Berg River.

7.1 Introduction

The Berg River system supplies about 80 % of the water used by Cape Town. This implies that water is being removed from this catchment leaving less of the natural flow within the BRC. The BRC covers an area of about 12000 km^2 of which about 50 % can be considered as potentially suitable for irrigation although only about 8 % of this land is currently under irrigation. The Berg River is an open system implying that both fresh water and all return flow runs in the same stream. Görgens and de Clercq (2002) determined that a total of 30 % of the irrigation water returns to the river as a combination of surface runoff and shallow (below the root zone) subsurface return flow.

The quality of the return flow water is determined by the salinity status of the soil being irrigated and the path length to the river. The river water is still generally of good quality, having an EC_e of below 50 mS m^{-1}. Moolman *et al.* (1999) and de Clercq *et al.* (2001) found grapevines to be totally sensitive to salinity even at irrigation water quality of below 30 mS m^{-1}. They also proposed an irrigation water quality upper limit of 75 mS m^{-1}, which means that the current irrigation water quality is acceptable.

A variety of water supply expansion schemes are proposed to meet the growing needs of users in the catchment, resulting in the extraction of 20% more water from the Berg River system. These developments may exacerbate moderate salinity levels in the middle-lower Berg River as a result of the utilization of more fresh water from the river during summer, the saline return flow will increase and the capacity of the system to dilute this increase for users downstream will be reduced. This study aims to explain the influence of irrigated agriculture on salinization of river water in the Berg River system. A better understanding of this aspect of river water quality will allow improved management of the system and more accurate prediction of the outcome of expanding irrigation in the catchment. Due to the vastness of the area and the restricted availability of good quality data, catchment-scale modelling is usually done using sparse data with unreliable geographical positioning.

A vineyard was identified where differences in age since first irrigation could be sampled in one large block. The problem is thus defined by a 60 ha piece of land, which consisted of one soil type mainly, that was initially very saline and was irrigated with low salinity water for up to 4 years. The aim of this project was to use data from a single sampling event, taken over an area that included irrigation blocks of different age since development, to estimate the annual salt mass leached (de Clercq *et al.*, 2001). Usually when soil sampling is repeated often enough, repeated detailed mapping of the soil electrical conductivity (saturated paste extract, EC_e), allows insight in soil EC change over time (or the salt flux). Within this study, time is a variable and by using time in the prediction, the amount of salt leached from this landscape could be calculated.

As new land is being earmarked for irrigation development, one must be able to calculate or predict the influence of irrigation return flow on the quality of the river water. This meant modelling and predicting the expected soil response as land-use changes from non-irrigated wheatlands to irrigated vineyards (de Clercq *et al.*, 2001). The problem was how to use results with differences in age from neighbouring plots and how to use the time relationship to quantify or predict the lowering of salinity in the landscape as a result of irrigation. No literature could be found that addressed this problem specifically. The effect time had on the data (between the different blocks) will therefore be illustrated using their cumulative distribution functions (cdf). By using the probability (derived from the cdf) of all age groups and all EC_e values, the expected change in EC_e of any specific point can be predicted using the inverse cumulative distribution functions (icdf) for a specific year. Characterizing the temporal variation in spatially adjacent vineyards that occurred primarily as a result of irrigation then becomes possible. The proposed method allows prediction of return flow salinity from the decline in the landscape salinity without having to model runoff through a conventional intricate 3 dimensional modelling routine. The hypothesis is thus that temporal change can be expressed as a change in cdf explicitly. The accuracy to which the method applies to plots outside of this study area will render the hypothesis true or false.

Methodology of this nature can be beneficial in modelling seasonal return flow over large areas or catchments since the method is based on the variation in the landscape depending on EC_e over time and differs from others found in literature in that space-time research is usually reported involving the same space but with time that varies (Bourgault *et al.*, 1998; Cetin and Kirda, 2003; Lesch *et al.*, 1998; Rhoades *et al.*, 1997; Utset *et al.*, 1999).

7.2 Methods and materials.

7.2.1 The experimental site

The study area is located in the Berg River catchment in the Western Cape province of South Africa, close to the town of Piketberg (Figure 7.01). There is no infrastructure in terms of water supply to the farm other than moderate quality control of the water in the Berg River itself. Most soils are naturally saline and there is concern that large-scale expansion of irrigation activities might adversely affect the water supply in the river, triggering a situation where management of the quality of the river water can soon drain the reserves from the supply dams. Most of this area receives precipitation lower than 300 mm per year, most of which falls in winter. Currently the quality of the water in the Berg River is being manipulated from the three major fresh water dams in the catchment so that a steady supply of good quality water is being made available to farmers and towns downstream.

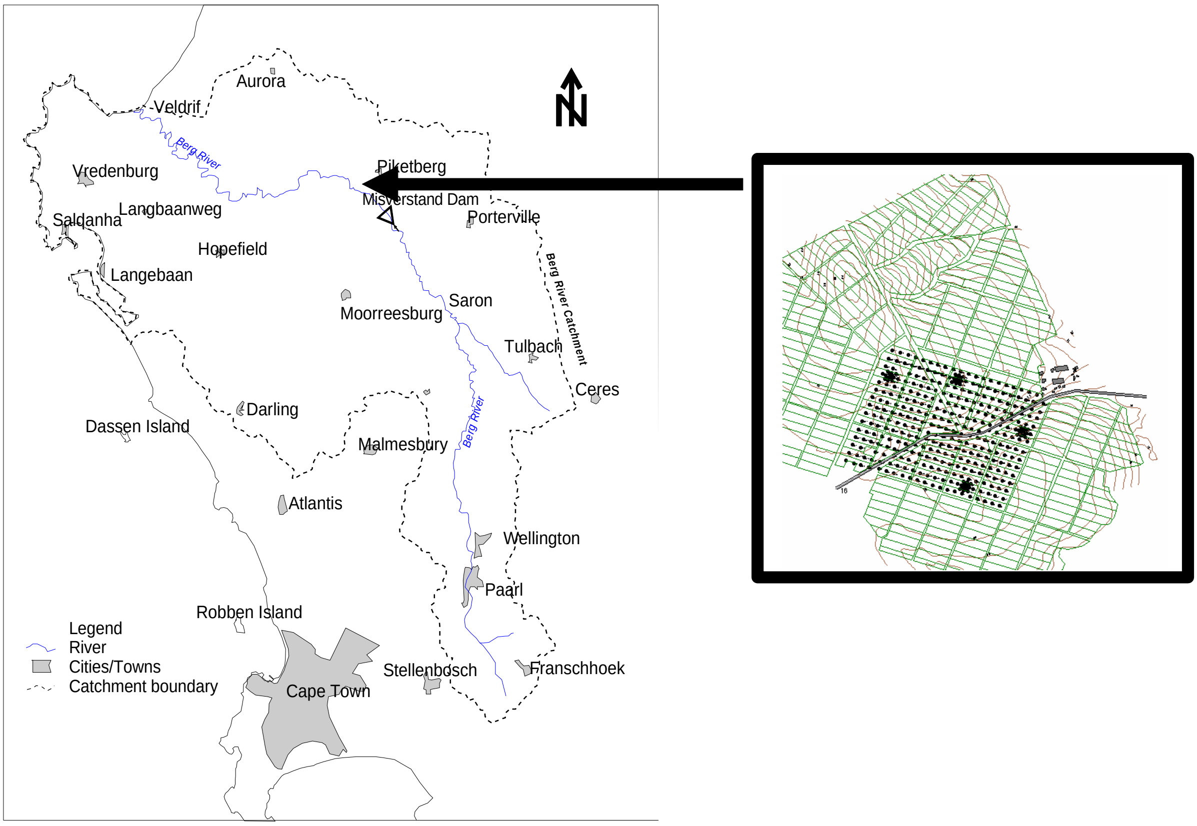

Figure 7.01 Area map and location map of the farm Broodkraal showing the sampling site (approximate scales 1:1000000 and 1:5000 respectively).

The soils vary over the whole catchment but are mostly derived from old marine sediments and river transported material. They can collectively be classified as Luvisols (FAO, 1998). In their natural state these soils are not more than 30 cm deep to the weathering zone and bedrock of Malmesbury shale (Kent 1980). Soil preparation for vines involves deep tillage, breaking up the shale to a depth of about 1 m. Weathering of the shale is usually associated with the release of sodium (Lipton *et al.*, 1996). The major soils of the study area were classified as Oakleaf, Swartland and Glenrosa soil forms (Soil classification workgroup, 1991) (Figure 7.02). Their corresponding names in FAO (1998) would be, Hyperochric Chromic Cambisol, Hyperochric Chromic Luvisol and Hyperochric Leptic Luvisol.

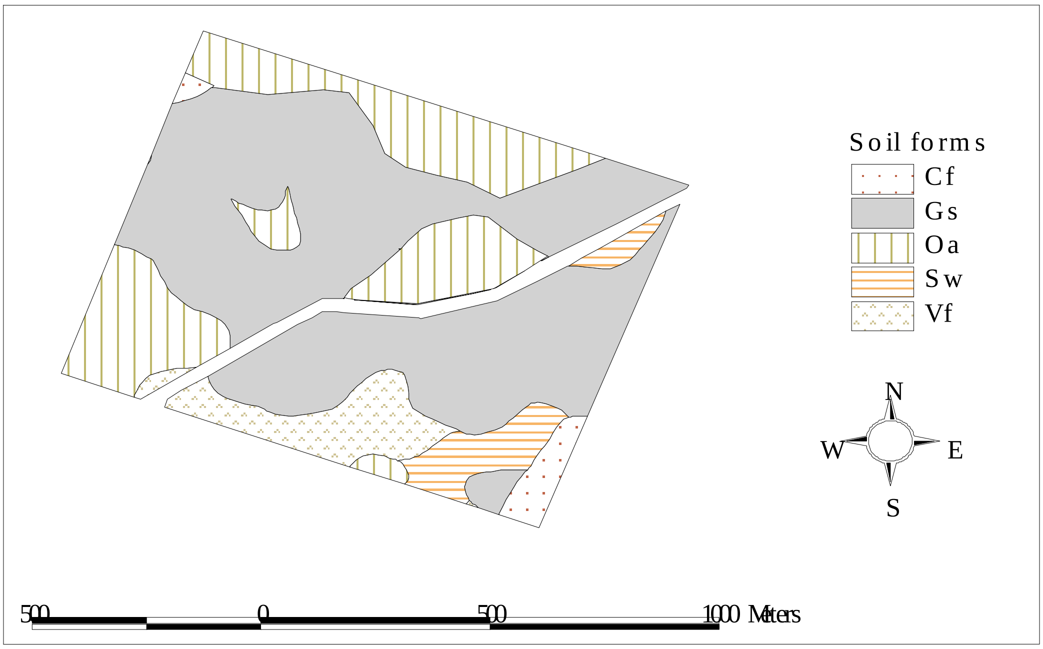

Figure 7.02 Soils map showing the prominent soil types according to the South African classification system (Cf is Clovelly, Gs is Glenrosa, Oa is Oakleaf, Sw is Swartland, Vf is Villafontes; Soil classification workgroup, 1991).

7.2.2 Soil sampling

Soil samples were taken at the Broodkraal farm covering a total of about 60 ha (Figure 7.03). The samples were taken from sites that were irrigated for 2, 3, 4, and 5 years. Soil sampling was carried out in such a way as to allow spatial analysis of the data. It was done in two steps. A primary sample set was taken in 2000, on a 45 m by 50.5 m grid, generating 15 by 21 (315) sample positions. To enable the description of the soil variability over a range of lag distances, 3 sets of 12 samples were taken randomly within 4 of these grid units. Twenty six positions that fell on roads and an old gypsum storage site were omitted, leaving a total number of 325 points included in the analysis. A second sample set was taken in 2001, to the south and west of the primary set, to allow adequate room to test the method that was developed (Figure 7.08). The latter was done on a 90 by 101 m grid. The two blocks were 4 year and 5 year old sites and provided the opportunity to test the methodology by using the icdf of the original 4 year and 5 year old sites to predict the values of the second set.

The soil sampling technique entailed a pooled sample of three micro-positions within a vine row to minimise the effect of micro-irrigation induced variation in salinity on a finer scale. Two depth increments were sampled: 0 cm to15 cm and 15 cm to 45 cm. The reason for this was that 45 cm was generally considered to be the median depth of the root zone and the 0 cm to 15 cm depth increment was seen as contaminated with undissolved fertilizer or gypsum and needed to be separated. All soil samples were air-dried, ground and passed through a 2-mm sieve. These samples were analysed for EC_e (Richards, 1954).

7.2.3 Statistical analysis

In analysing the data, one was confronted with the problem of how to move from point support to block support in soil process modelling. Heuvelink and Pebesma (1999) proposed a route from point support to block support: first interpolate, then run the soil process model (in this case statistical modelling of the EC_e change with time) and lastly aggregate the results. This approach is true in most circumstances where only one site is under consideration that was resampled over a certain time span. This dataset consisted of a single sampling event but with 4 subdivisions that has different ages in terms of its irrigation history. Therefore, it was proposed to first perform the time modelling for the different age blocks on the original data, i.e., on the original support, and then do the interpolation on the time adjusted results. Temporal modelling is in this case done through application of the collective tendency in aging of the vineyards. Four new datasets could therefore be derived for each of the different plots, representing 4 years in the life of each plot individually, derived with a method that did not generate bias. Variography was used to characterise the variance, and kriging was used to map the original and derived datasets for each block. Lastly, through aggregation, predictions regarding the amounts of salt lost from this 15 to 45 cm depth horizon were obtained (Chilès and Delfiner, 1999; Goovaerts, 1997; Isaacs and Srivastava, 1989; Webster and Oliver, 2007).

The proposed process can be summarised as follows:

- Deriving the time sequence for each plot.
- Variography of the data for each year.
- Interpolate the combined yearly data.
- Derive the salt discharge over time.

Histograms and descriptive statistics were computed for the whole dataset and for each of the four sectors in order to assess comparability of the data despite not being equal in size. The use of cumulative distribution functions (cdf's) with a probability on the y-axis provided the opportunity to compare the distribution differences irrespective of sample size.

7.2.4 Temporal modelling

Cdf's were developed for each year from the original support and their resulting inverse cumulative distribution functions (icdf's) were used to generate the temporal data. The STATISTICA software was used for the purpose of modelling cdf and icdf's. Various types of cdf's were tested in search of the most suitable function. The lognormal function provided the best fit for EC_e data, which is in accordance with Lark (2000), Rhoades *et al.* (1997) and Webster (2001). Cdf's and its applications were also described by amongst others Isaacs and Srivastava (1989) and Rhoades *et al.* (1997) as a method to present EC_e data. The method is also used in comparing EC_e data with apparent EC_e data obtained from electro-magnetic induction readings. Icdf's and their predictive capabilities were tested on the second dataset, sampled in 2001.

The lognormal cdf applied was of the form presented in Eq. 7.01 and its inverse function in Eq. 7.03.

$$f_t(\mathbf{x}) = \frac{1}{\mathbf{x}\sigma(2\pi)^{0.5}}.e^{\{-\log(\mathbf{x})-\mu\}^2/2\sigma^2\}} = p \qquad \textbf{Eq. } 7.01$$

with $0 < \boldsymbol{x} < \infty$, $\mu > 0$, s > 0, and where t stands for time, μ is the scale parameter and the mean of ln(**x**), σ is the shape parameter and the standard deviation of ln(**x**), e is the base of the natural logarithm and lastly, p is the probability as a frequency. In short Eq. 7.01 is expressed as:

$$f_t(\mathbf{x}) = \text{ILognorm}(\mathbf{x}, \mu, \sigma) \qquad \textbf{Eq. } 7.02$$

The inverse lognormal function or icdf was used for this back-transform. With this action the probability data are transformed back to original data and is given as:

$$\text{Loginverse}\ (p, \mu, \sigma) = e^{[\mu + \sigma \mathbf{x}\ [\text{Normal inverse (p)}]]} \qquad \textbf{Eq. } 7.03$$

In short, Eq. 7.03 is expressed as:

$$\mathbf{x} = \text{Loginverse}\ (p, \mu, \sigma) = \text{Loginverse}\ (f_t(\mathbf{x}), \mu, \sigma) \qquad \textbf{Eq. } 7.04$$

For all data the $f_t(\mathbf{x})$ from Eq. 7.01 was calculated as a probability derived from the actual data. To transform the data to another year, the icdf for that year was used to transform the probability values. In other words, in $f_t(\mathbf{x})$, t was replaced with $(t + n)$, where n can be between – 3 and 3 as follows:

$$\mathbf{x}_t = \text{Loginv}\ (p_{(t+n)}, \mu, \sigma) = \text{Loginv}\ (f_{(t+n)}(\mathbf{x}), \mu, \sigma) \qquad \textbf{Eq. } 7.05$$

Back transformation of data using Eq. 7.05 has no effect on the spatial pattern of the data even if back transformation is done through an icdf of another year. This is brought about by the fact that the dataset is rearranged in an order of magnitude when the cdf is calculated. With back transformation, a p-value is matched to an $\boldsymbol{x}$-value that has the same geographical position as the original $\boldsymbol{x}$-value, but the size of $\boldsymbol{x}$ was influenced. It is therefore only the magnitude of the original $\boldsymbol{x}$-values that change and not position.

7.2.5 Variograms and kriging

The variogram models for the raw and transformed data were generated using Variowin software (Deutch and Journel, 1992). The theory applied in terms of modelling the variance and the kriging used in this chapter were extensively discussed in Chapter 3 and will therefore not be repeated here. Variograms were calculated for the 1996 raw data and only for the 3 sets of back transformed data based on the 1996 site.

Ordinary point kriging was used (Isaacs and Srivastava, 1989; Goovaerts, 1997; Chilès and Delfiner, 1999; Webster and Oliver, 2007) only to demonstrate the reconstructed change based on the 1996 site for the three years that followed since 1996. By converting the EC_e values to a salt mass per pixel, the total amount of salt lost per site could be estimated by subtracting modelled values from one year from the other in a GIS. To have this information as GIS maps is important as return flow and runoff modelling is done within GIS. It also serves the purpose of sensitising the farmer toward his irrigation management and the ripple effect this has on the environment and local economy.

7.3 Results and discussion

Two depth increments were sampled but only the deeper increment was used for analysis, since it is less influenced by management. Since the 0 to 15 cm data also showed a similar trend than the 15 to 45 cm data, it was decided to focus the modelling on the 15 to 45 cm data. The reason for removing the top layer was that visible undissolved fertilizer could affect the soil surface data.

The post map presented in Figure 7.03 presents both the relative EC_e magnitude of each sampled point and its position. A cluster of points in the area (50,550) was omitted from the data as it was found later that this spot was used to store gypsum. Inclusion of this data led to a strong disturbance of the sample distribution. Figure 7.04 shows a histogram with descriptive statistics for the 15 to 45 cm depth interval and Figure 7.05 shows the age separation statistics of the data split according to the year of planting. The distributions seem quite similar when comparing the coefficients of variation and the standard deviation. From Figure 7.03 and 8.05 it is clear that the average EC_e of this section on the farm (249 mS m^{-1}) is quite low for this region but a large variation exist (74 to 884 mS m^{-1}).

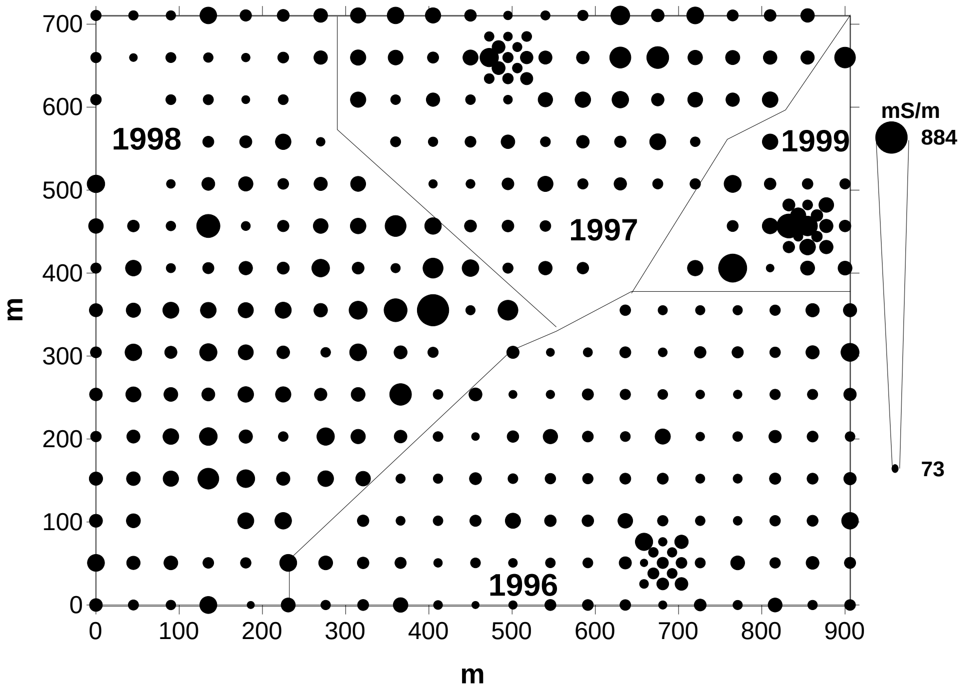

Figure 7.03 Post map showing the sampling positions with indication of the EC_e for the 15-45 cm depth interval and year of planting (the scale is indicating the extremes).

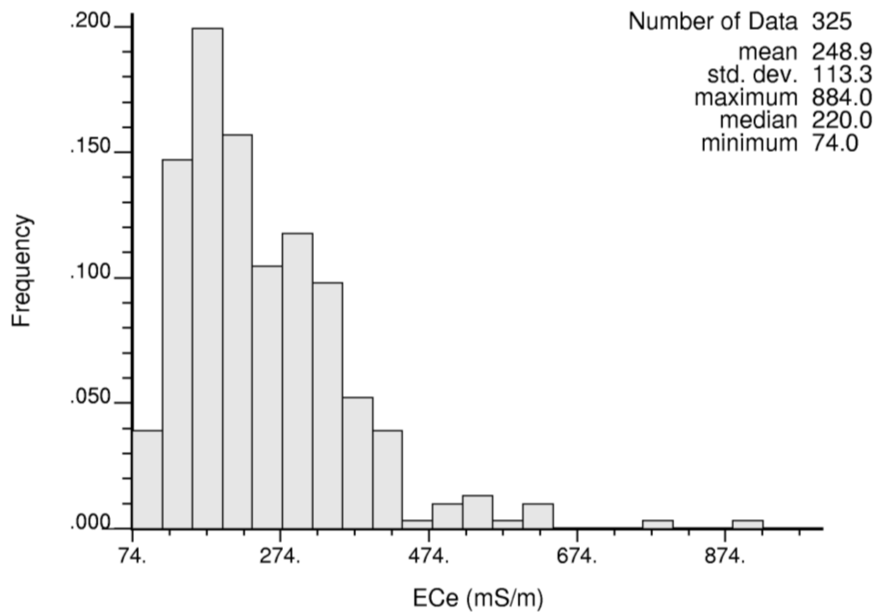

Figure 7.04 Histograms of EC_e for the 15-45 cm depth interval with descriptive statistics.

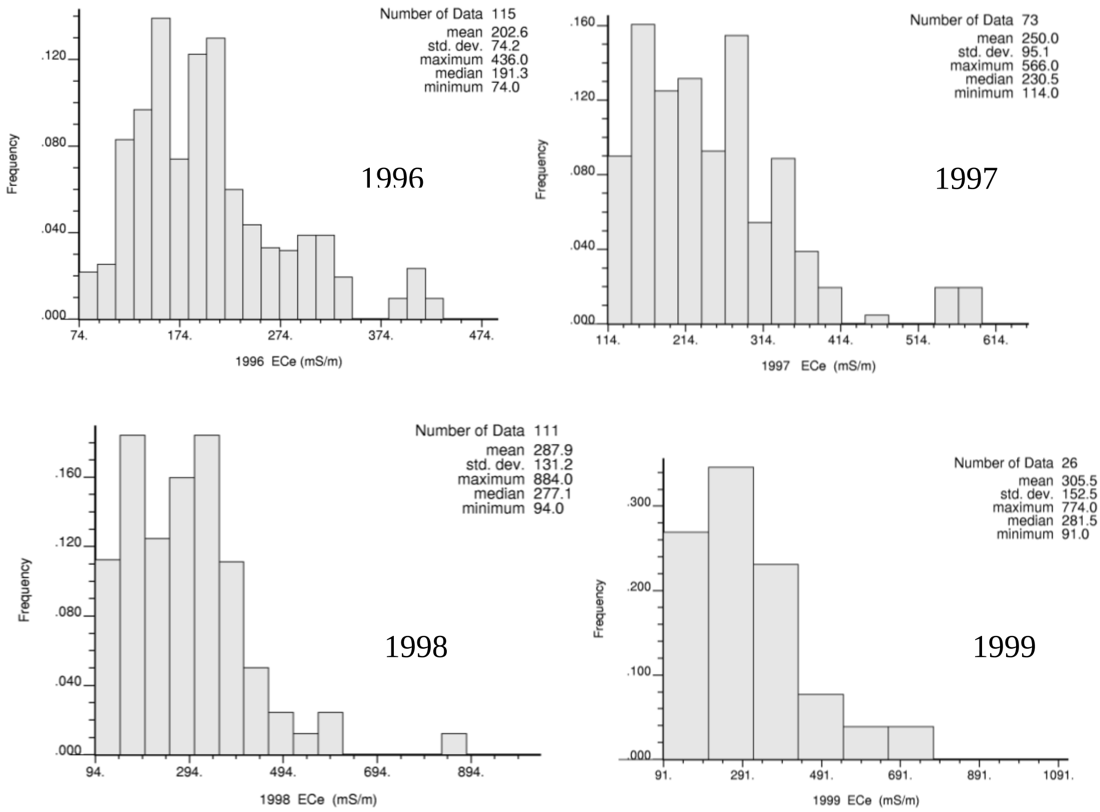

Figure 7.05 Histograms of EC_e for the 15-45 cm depth interval of the 4 year groups.

Table 7.01 summarizes the results of the whole study area, comparing the different age groups with the overall averaged data. The standard deviation and variance coefficient are also given. It is remarkable that the EC_e shows a decline with age and that the standard deviation within that group also shows a decline with age. The EC_e drift with age is almost linear and it is possible to model EC_e for the whole area, ignoring the age difference. However, the principle problem presented in Table 7.01 is the changing standard deviation. Since the variance is not stable over time (Figure 7.06), the need existed to remodel the data for each year by accounting for the change in variability.

Table 7.01 Summary statistics of EC_e (mS m^{-1}) for the whole data set in terms of the two depth increments sampled.

Year of planting	Age (year)	Number of data	Average (mS m^{-1})	Standard deviation (mS m^{-1})	Coefficient of variation
1996	5	115	201.4	46	0.23
1997	4	73	243.3	95	0.39
1998	3	111	288.2	104	0.36
1999	2	26	305.5	155	0.51
Total		325	248.9	113	0.45

Figure 7.06 shows the change in mean standard deviation and mean EC_e of the data when the dataset is divided into the 4 age groupings according to the year of planting. Though the number of samples in each group differs, the standard deviation and mean still presents a strong increase over time. This fact has an important bearing on the sampling and mapping of soil salinity in vineyards and the implication is that younger developments need to be sampled more intensely (on a finer grid) than older irrigated areas because the tendency to vary over shorter distances is much greater in the younger developments than in the older. Since the standard deviation varies over the sampled area as a result of age, any kriging effort must take this into account.

It is clear that the lowest EC_e means, mean variances and the mean standard deviation values are in the oldest vineyards and the highest are in the youngest vineyards. This is a clear indication of the effect of longer exposure to irrigation. Temporal modelling would have to be able to deal with these changes.

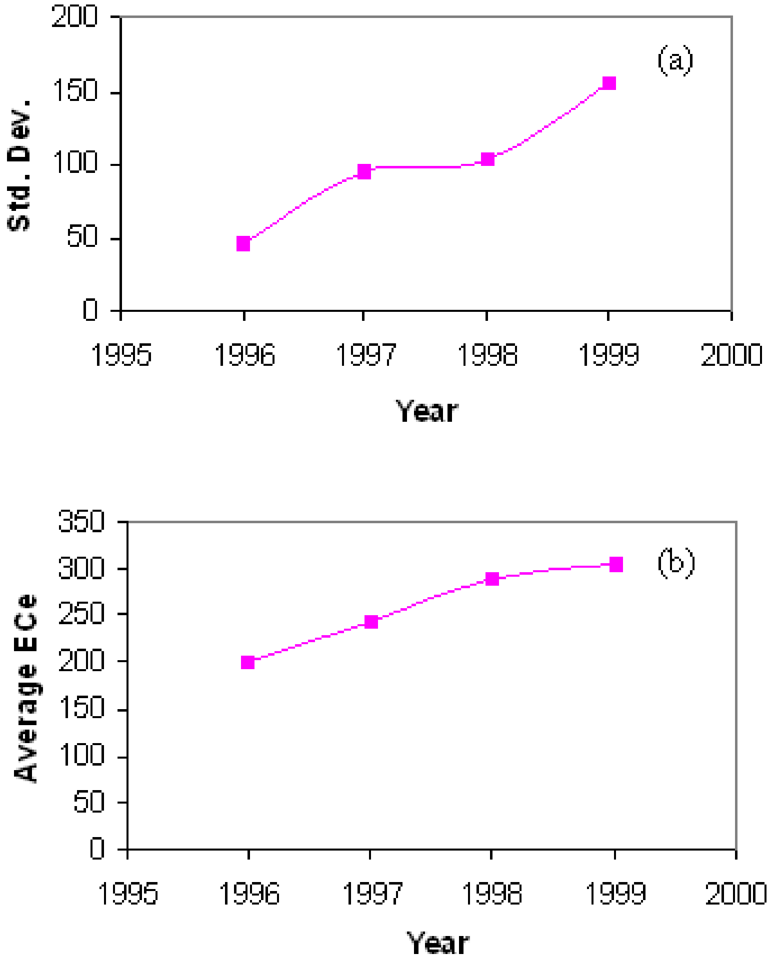

Figure 7.06 The change in the standard deviation (a) and average (b) of EC_e over irrigation age of the vineyards.(Year refers to the time irrigation started and sampling was done in the year 2000).

7.3.1 Modelling time

Since the statistics shown in Figures 7.06 and 7.07 displays a very distinct relationship with time of planting, it was possible to develop a time-series focussing only the 1996 data. In Figure 7.07 there is a total movement of the s-curve to the right from 1996 to 1999. There is also an increase in EC_e values up to 1999.

It was therefore assumed that the cdf for each year group, represented the temporal change in all 4 blocks, each for its specific year. Consequently it was possible to use the cdf to icdf transformations to reflect change in time and to predict the change in EC_e needed to calculate the salt contribution a site made over time to the declining quality of the water in the Berg River. Verification of the results was done by using the second data set (1996a and 1997a). The positions of these two additional areas are shown in Figure 7.08.

The cumulative distribution functions were derived from all 6 results shown in Figure 7.07 and their equations are as follows (Figure 7.09):

$$f_{98}(\mathbf{x}) = \text{ILognorm}(\mathbf{x}, 5.6129, 0.4726) \qquad \textbf{Eq. } 7.06$$

$$f_{98}(\mathbf{x}) = \text{ILognorm}(\mathbf{x}, 5.5917, 0.3947)$$

$$f_{97}(\mathbf{x}) = \text{ILognorm}(\mathbf{x}, 5.4254, 0.3704)$$

$$f_{97}a(\mathbf{x}) = \text{ILognorm}(\mathbf{x}, 5.4512, 0.3779)$$

$$f_{96}(\mathbf{x}) = \text{ILognorm}(\mathbf{x}, 5.2421, 0.3556)$$

$$f_{96}a(\mathbf{x}) = \text{ILognorm}(\mathbf{x}, 5.298, 0.3565)$$

with **x** being the variable EC_e.

The icdf's used for the back transfer of data was determined and given as follows:

$$\mathbf{x}_{99} = \text{Loginverse}(f_{99}(\mathbf{x}), 5.6129, 0.4726) \qquad \textbf{Eq. } 7.07$$

$$\mathbf{x}_{98} = \text{Loginverse}(f_{98}(\mathbf{x}), 5.5917, 0.3947)$$

$$\mathbf{x}_{97} = \text{Loginverse}(f_{97}(\mathbf{x}), 5.4254, 0.3704)$$

$$\mathbf{x}_{96} = \text{Loginverse}(f_{96}(\mathbf{x}), 5.2421, 0.3556)$$

It can be observed from Figure 7.09 that the differences between the 1996 and 1996a, and between the 1997 and 1997a observations, are smaller than between the cdf's of the different years. These relationships are meaningful regardless of the fact that the 1997a and 1996a datasets were sampled on a coarser resolution than the original data.

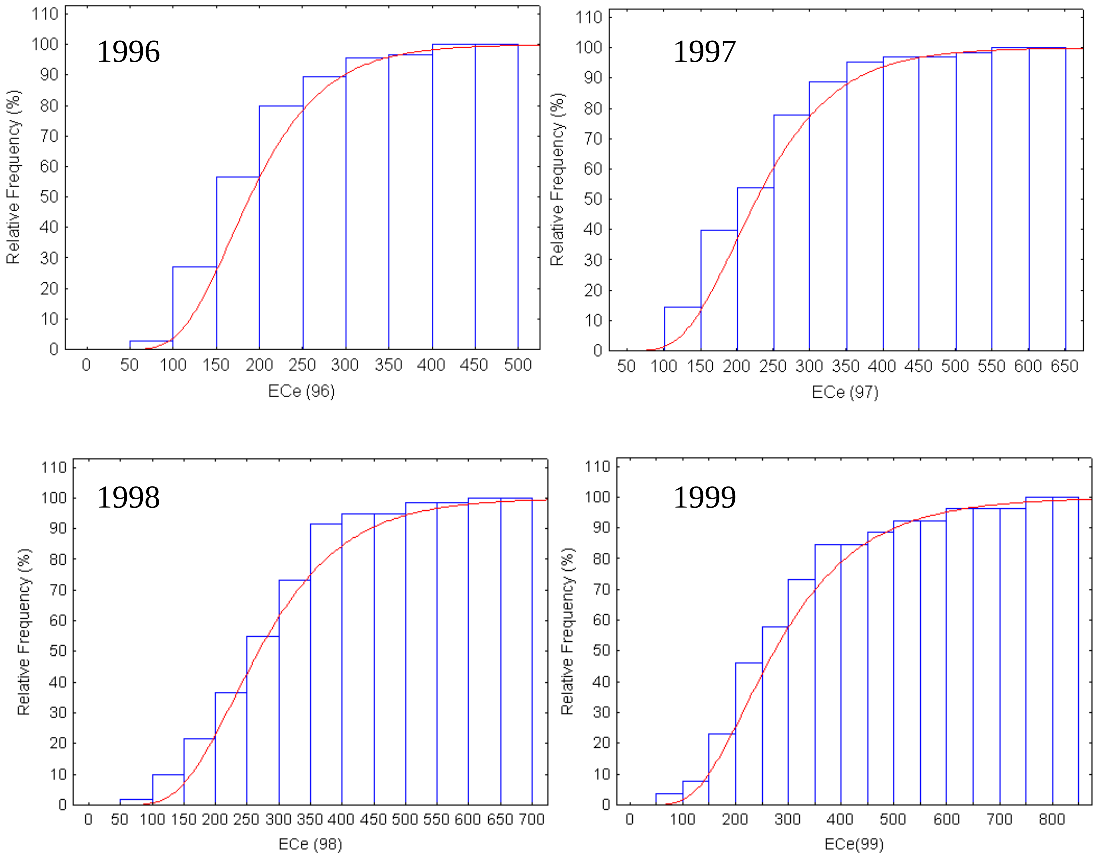

Figure 7.07 Lognormal cumulative distribution of EC_e grouped per year of planting (1996 to 1999).

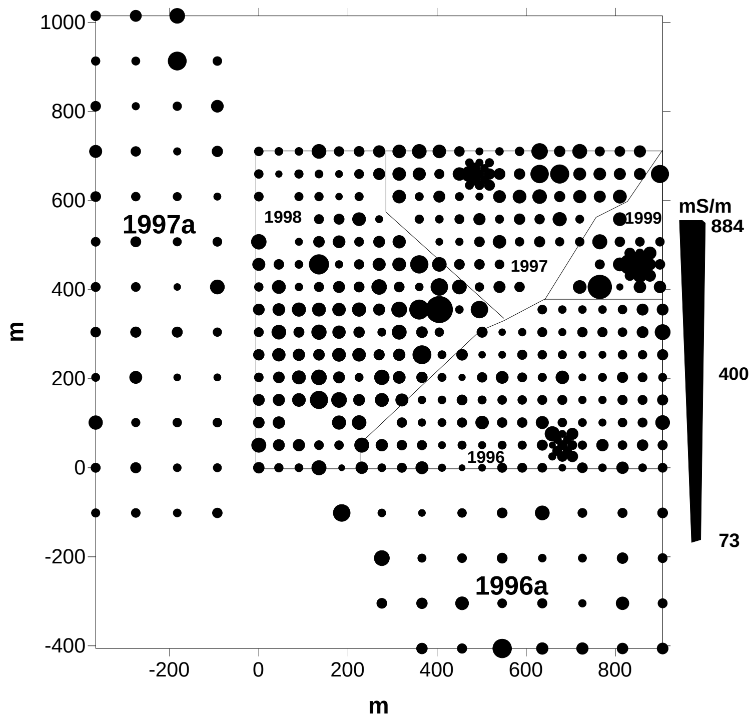

Figure 7.08 Map of the sampling positions and the relative EC_e values, with the 1996a and 1997a sampling positions.

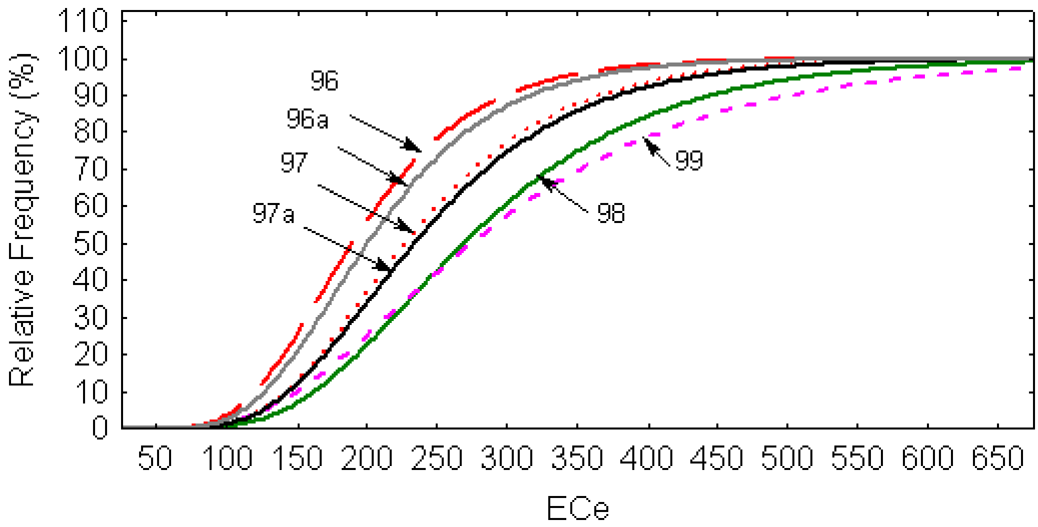

Figure 7.09 The compared lognormal cumulative distribution functions of EC_e for the 4 consecutive years after irrigation started with 96a and 97a being the test data.

The predicted change in EC_e over time for the 1996 data is illustrated in Figure 7.10. The probabilities of the 1996 data were determined using the 1996 cdf and back transformation was done through the 1997, 1998, and 1999 icdf's to generate the time change. The EC_e values in the lower ranges (below 150 mS m^{-1}) showed very little change and the reason for this is that the effective irrigation water quality over the season amounted to about 50 mS m^{-1}. de Clercq *et al.* (2001) showed that such an irrigation water quality usually results in a soil EC_e of about 150 mS m^{-1} toward the end of the irrigation season, hence the time invariant behaviour in this part of the graph. Change in the rest of the graph is amplified toward the highest EC_e values, showing that the highest EC_e values are reduced most by irrigation.

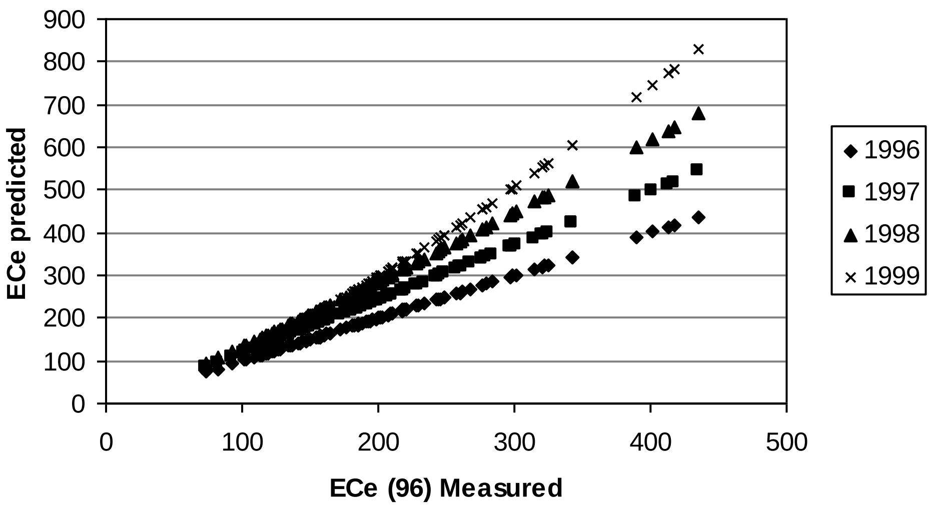

Figure 7.10 Compared measured EC_e and predicted EC_e developed for the 1996 data, i.e. for the oldest block, showing the EC_e reconstruction through inverse cumulative distribution functions.

7.3.2 Modelling the variograms

The change in semi-variances was modelled from the 4 sets of raw data for the years 96, 97, 98 and 99, and is given in Figure 7.11. This shows the change in absolute variance and spatial structure for the 4 years.

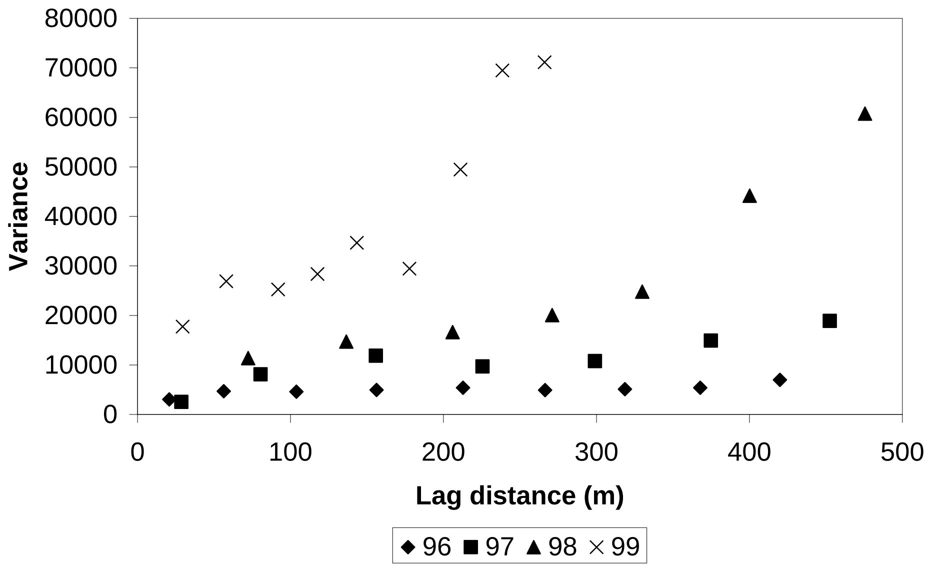

Figure 7.11 The change in predicted semi-variance for the 4 year groups 1996 to 1999 (original data).

As in Figure 7.10, the 1996 original dataset was used to model the 1997, 1998 and the 1999 temporal data. Variograms were then modelled for these 4 datasets. This is shown in Figure 7.12 and the temporal change is clearly visible as a variance effect. By comparing the results of Figures 7.10, 7.11 and 7.12, one can see that the temporal modelling of the 1996 data resembles the trend found in Figure 7.10. On a point base, the general trend seems to be that the high salinity, which was lowered much more with irrigation than the lower salinity sites, and the lowest values stayed almost constant. In a spatial sense, the younger the landscape in terms of its irrigation history, the greater the variance over a unit distance. This effect, captured in both Figure 7.10 and Figure 7.12, highlights the basis for augmenting salt change in an irrigated landscape.

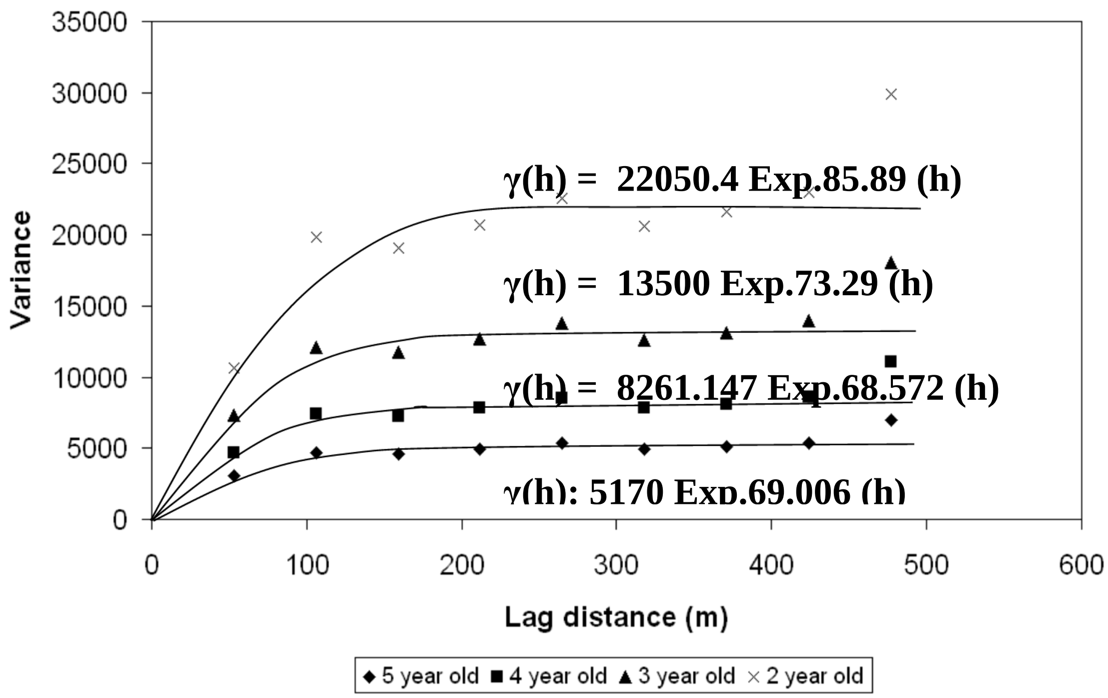

Figure 7.12 Semi-variograms for the 1996 EC_e data and its predicted data for 1997 (4 year old), 1998 (3 year old) and 1999 (2 year old).

7.3.3 Time-space modelling

Ordinary point kriging was applied to the 1996 raw data and its 3 temporal predictions, and the results are presented in Figure 7.13. Kriging was done using a maximum search radius of half the diagonal of each block. This figure indicates the effect time had on this area. By converting the EC_e to kg salt, and subtracting the images from one another in a GIS environment, one can estimate the total amount of salt lost from the profile each year. The results are given in Table 7.02 as mean and median values. Contrary to expectation, the tonnage salt leached during the first year was less than the periods that followed. The reason for this is twofold. Firstly, in the initial stages of irrigation, patches of land with low salt content will take up salt during irrigation, as irrigation was done with mildly saline water. Secondly, it can be attributed to the initial soil conditioning during field preparation before planting.

Table 7.02 Statistics calculated on the difference between yearly modelled EC_e to derive the yearly average and median amount of salt lost from the 15-45cm depth soil horizon of the Broodkraal farm.

		Year	
	3-2	**4-3**	**5-4**
Median:	9	43	39
Maximum:	146	128	103
Mean:	15	46	41
Standard deviation:	23	14	14
Variance:	543	208	186
Coef. of variation:	1.57	0.32	0.33
Coef. of skewness:	1.62	1.18	1.00
Mean square error:	765	2292	1880
Ton salt per 24 ha based on median	30	150	135
Ton salt per 24 ha based on mean	51	158	142

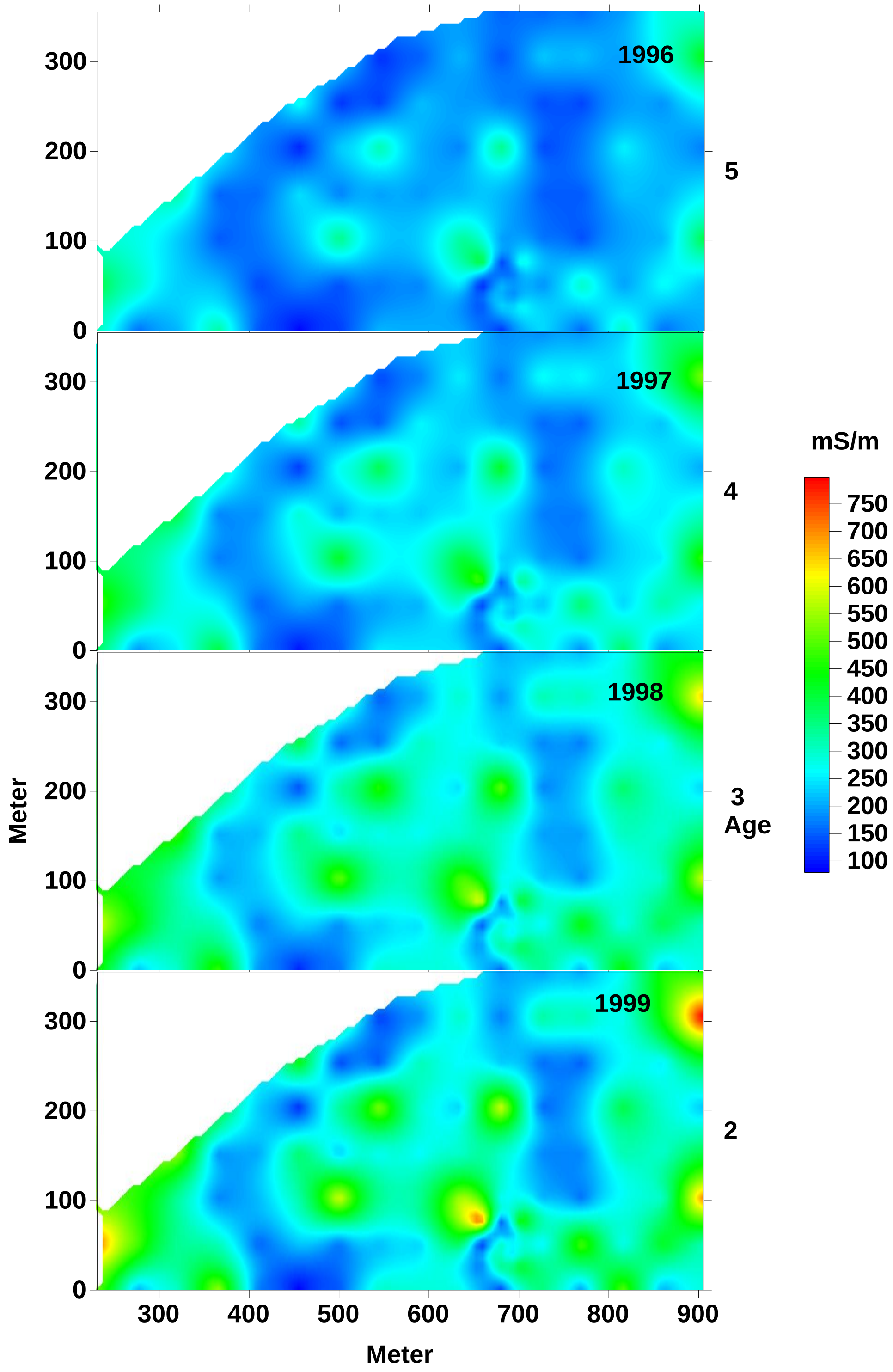

Figure 7.13 The combined ordinary point kriged maps of the original and predicted data from the 1996 (age 5) segment. Age indicate years of irrigation.

7.4 Conclusions

The investigated areas were under table grapes and were subjected to a rigorous irrigation program. The older sites had a lower salt content than the younger sites but the relative variability remained almost constant. So, the data showed proved that there is a general lowering of salinity in the landscape resulting from irrigation practices.

By using the icdf method of predicting change with time, and by sampling the irrigation history from the 2nd year to the 5th year, the period of most dramatic change have been captured. After the 5th year the soil EC_e tends to be subjected to the irrigation water quality of the past season. It is therefore a suggestion to use the irrigation water quality received as a correction factor.

The amount of salt removed from this profile over the study period has a delayed effect in influencing the water quality of the river system. However the amounts predicted is in line with the reaction that was measured in the river system (de Clercq *et al.*, 2001).

Two aspects can be highlighted. Time modelling was approached in a unique manner that proved to be a good predictor, but rigorous proof will however require resampling after a period of time. Secondly, predicting the contribution of this site to the nearby river system in terms of the salt load lost from the soil profile, proved to be a valuable way in bypassing intricate soil process modelling in an era and area where funds, the total land surface and skilled labour places a large burden in solving this problems.

8 REGIONAL SUSTAINABILITY IN TABLE GRAPE PRODUCTION ON SALINE SOILS[5]

ABSTRACT

A study was done in South Africa to investigate the state of the soil salt content and its effect on plant growth on a regional rather than a point basis. The study site went through a development phase since 1996 of establishing new vineyards each year. This provided an excellent opportunity to investigate soil characteristics, plant vigour and their relationship since the start of development. Soil samples were taken and trunk circumferences were measured. The soil properties included in the investigation were soil clay percentage, EC_e, soil pH value and time since initial irrigation. Exploratory data analyses were done and variograms were drawn for all data. Kriging was used to map the variables and multiple regression analysis was used to investigate their relationships on a regional basis.

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[5]*Published in:*

de Clercq, W.P., Van Meirvenne, M., 2005. Regional sustainability in table grape production on saline soils. *South African Journal of Plant and Soil*, 23(2), 113-119.

This chapter was partly presented as:

de Clercq, W.P., De Smet, G., Van Meirvenne, M., 2001. Mapping of soil salinisation in an irrigated vineyard in South Africa. Workshop on Bilateral (Belgium/South Africa) Workshop on Cartographic modelling and land degradation. Gent, Belgium 2001.

A number of useful observations were made. Trunk circumference as an index of growth showed a negative correlation with EC_e and a positive correlation with soil pH. Trunk circumference reflected a positive growth cycle when compared with time since development. Regression analysis showed that trunk circumference as an indicator of vigour could be confidently predicted through knowledge of the vine age, soil pH and EC_e and reflected upon measurement and prediction of sustainability in grape production.

This approach has widespread applications for agriculture in terms of dealing with variation in a landscape and dealing with water supply problems. Methodology that uses a regional approach rather than a point approach in management could enhance the ability to increase profitability and ultimately improve water management.

8.1 Introduction

The Berg River Catchment (BRC) irrigation system, as with many other systems in South Africa, is experiencing increased pressure from a range of water users. The quality of the water in the Berg River system is largely determined by agriculture (as in most other water supply systems). It is also reasonable to assume that agriculture in future will not only have to bring about substantial water savings, but will also have to be increasingly reliant on water of a poorer quality than at present as a result of urban, industrial and agricultural pressure on this water resource. Research has however indicated the role of salts in the irrigation water on the yield and quality of agricultural crops and indicated it to be crucial in terms of management and survival (Frenkel and Meiri, 1985; Shalhevet, 1994; Finke *et al*., 1999; Moolman *et al*., 1999; de Clercq *et al*., 2001).

It is for these reasons that a project was initiated with the aim to contributing toward the creation of a methodology that will enable the prediction of sustainability in agriculture systems and the minimisation of over-development risk and the subsequent over pressure on water resources.

8.2 Materials and methods

The test site was created on the farm Broodkraal near Piketberg (latitude 32 41' South, longitude 18 41' East) in the South Africa. This implied that a history of saline irrigation in saline soils exists from 1995 and that vineyards exist with increasing age of up to nine years.

Soil sampling was carried out following geostatistical methods (Webster and Oliver, 2000). The sample set was taken on a 45 m by 50.5 m grid, generating a grid of 15 by 21 samples. A total of 60 ha were covered generating 264 samples. To be able to describe soil variability within these points, four sets of 17 samples were taken randomly within four of these grid units. One of these sets was later discarded as it was accidentally taken on a location previously used for storage of gypsum. The sampling technique entailed a pooled sample of three micro-positions within a vine row to minimise the effect of the micro irrigation induced pattern. Sampling positions close to roads or any visible influence were omitted. Sampling was carried out at two depths, viz. 0-15 cm and 15-45 cm. Throughout this chapter the weighted depth average values were used in all calculations.

The samples were analysed for electrical resistance (ER), electrical conductivity (EC_e), pH and clay percentage (Görgens and de Clercq, 2005). The method for measuring ER involved the technique of preparing saturated pastes and after a standing period of an hour, the pastes were measured in a standardised cup using a Wheatstone bridge.

Chemical analyses were done, clay percentage and EC_e were determined on 60 % of the samples while ER and pH were determined on all samples. Since there is a general good correlation between ER and EC_e, it was decided to use EC, but expand the EC_e database using the ER values in a co-kriging process (Webster and Oliver 2000). Chemical and physical analytical methods used were reported in de Clercq *et al.* (2001) and Görgens and de Clercq (2005).

Trunk circumferences (TC) of the 16 vines surrounding each soil sample position were measured. The average TC of the 16 plants was used. The age of each vineyard was also noted. Coordinates of all sampling points were registered.

Digital maps of all variables were generated through kriging and used in a GIS environment to correlate the results. Time was introduced as a variable and a model generated making trunk circumference time dependent (de Clercq and Van Meirvenne, 2005). This approach follows the procedures used by Heuvelink and Pebesma (1999) in which modelling first goes through a process of spatial modelling for each variable (kriging) and then modelling of the relationships between digital realisations.

The maximum distance over which a variogram could be calculated, was restricted to half the largest dimension of the study area, i.e. half its diagonal measurement. For ease of reading this distance was calculated in Eq. 8.01. Therefore the maximum lag-distance that could be used in calculation of the experimental variogram was 576 m. Generally, a maximum lag distance of not greater than 500 m was used (Pannatier, 1996):

$$\left\lfloor \sqrt{906^2 + 710.5^2} \right\rfloor / 2 = 576 \text{ m} \qquad \textbf{Eq. } 8.01$$

The theory applied in terms of modelling the variance and the kriging used in this chapter were extensively discussed in Chapter 3 and will therefore not be repeated here.

This procedure of generating digital pictures of salinity distribution and the distribution of vigour allowed comparison to be done on a multitude of points simultaneously instead of deriving answers from an individual point basis (meaning a much poorer dataset). This procedure is therefore better equipped to evaluate regional trends and therefore evaluate sustainability on a regional basis rather than on a single point basis.

8.3 Results and discussion

8.3.1 EC_e and ER

In the histogram of EC_e (Figure 8.01), two definite extreme values were identified that resulted in further investigation. The parameters of centrality, spreading, skewness and kurtosis of the EC_e histogram (Figure 8.01) are as follows: skewness is positive (0.94) and the histogram is leptokurtic (3.91). The mean, maximum and minimum of the EC_e data are 195, 613 and 70 respectively. From Figure 8.02 it is also clear that EC_e, which was not measured at all the sampling points also shows three clusters of higher density sampling and not four. One cluster was omitted as it was inadvertently sampled in a former gypsum storage site. Therefore, to better the quality of the EC_e map, co-kriging was used by including the electrical resistance (ER) dataset as a second variable, as this dataset was much larger and correlated well with EC_e (R^2 of 72 %).

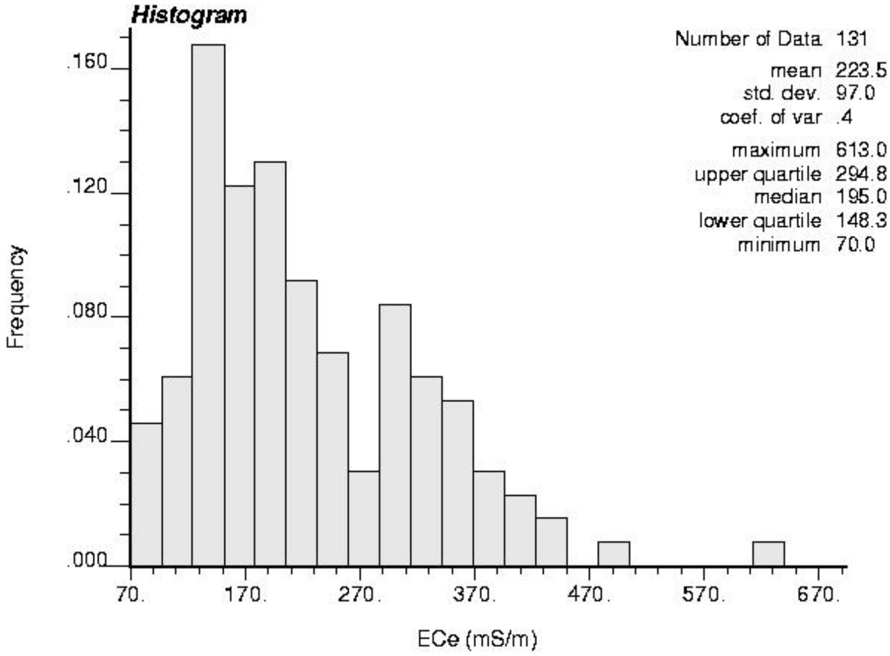


Figure 8.01 Histogram of EC_e of the weighted average (0 to 40 cm soil depth).

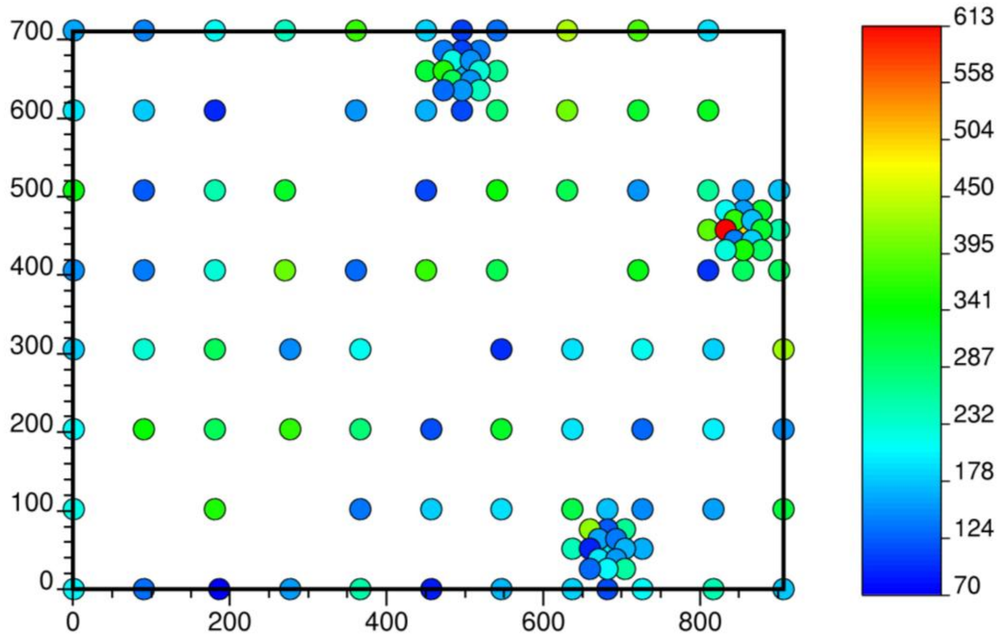
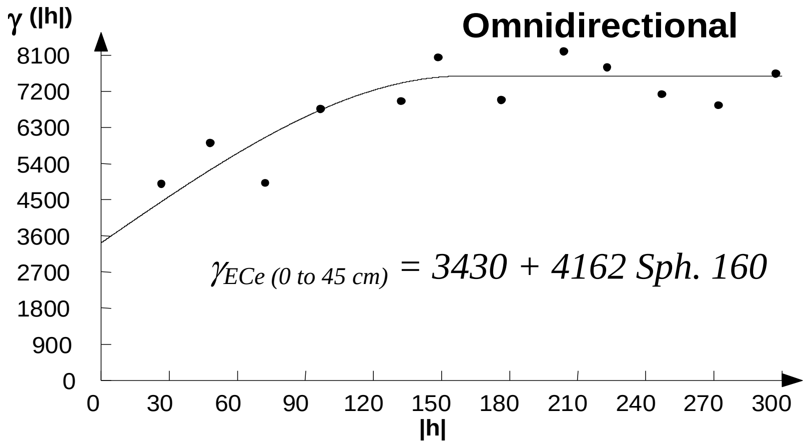


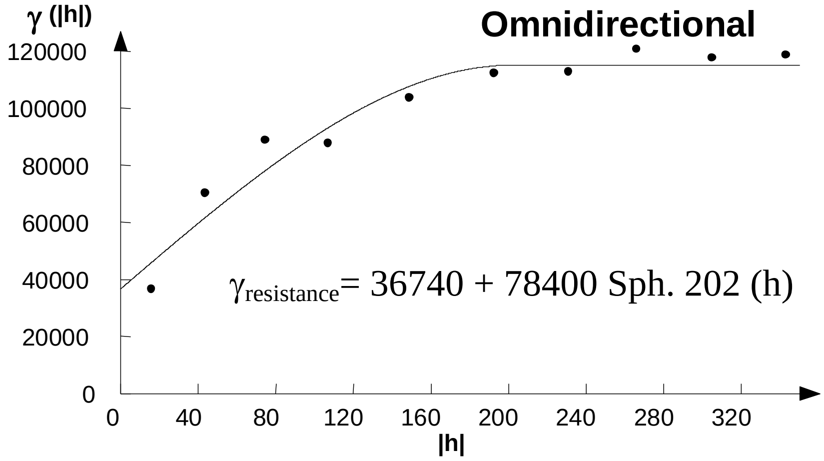
Figure 8.02 A location map of the depth-weighted averaged EC_e values (0 to 40 cm soil depth).

The maximum lag-distance over which the experimental variogram could be calculated for EC_e and ER was 300 m. The fitted variogram model for EC_e is spherical and is given in Figure 8.03(a). The fitted variogram model of the ER is shown in Figure 8.03(b) and the fitted cross variogram of the two variables, in Figure 8.03(c). The experimental variograms were omnidirectional because of the isotropic nature of the data.

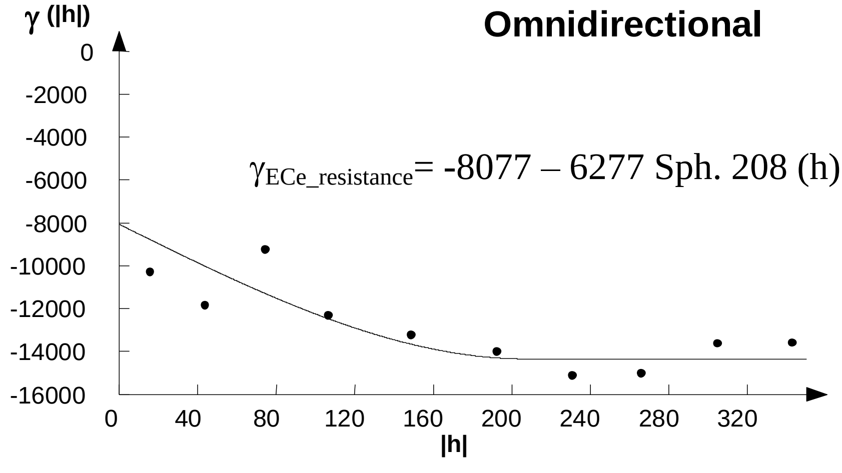
The map of the interpolated EC_e values resulting from the data in Figure 8.02(a) and the application of ordinary kriging is given in Figure 8.04(a). The co-kriged result of the Figure 8.03(c) model is presented in Figure 8.04(b) and it is evident from Figure 8.04 that co-kriging contributed toward the predictability of EC_e in the landscape by improving the mapping detail. It is important to note that co-kriging, when correctly applied, does not alter the prediction of EC_e in the places where EC_e was actually measured but it does improve the prediction of EC_e in these places where EC_e was not measured. The white spots (indicating low EC_e) in Figures 8.04(a & b) are situated on the ridges, the highest points in the landscape, while the black belt (indicating high EC_e) from the south-western corner to the north-eastern corner, is the major drainage pathway, indicating a relationship between site elevation and EC_e.



(a)



(b)



(c)

Figure 8.03 (a) The experimental semivariogram and spherical variogram model of the primary variable EC_e (b) The experimental semivariogram and the spherical variogram model of the second variable, electrical resistance. (c) The cross-semivariogram and spherical variogram model of the primary variable EC_e and the secondary variable electrical resistance.

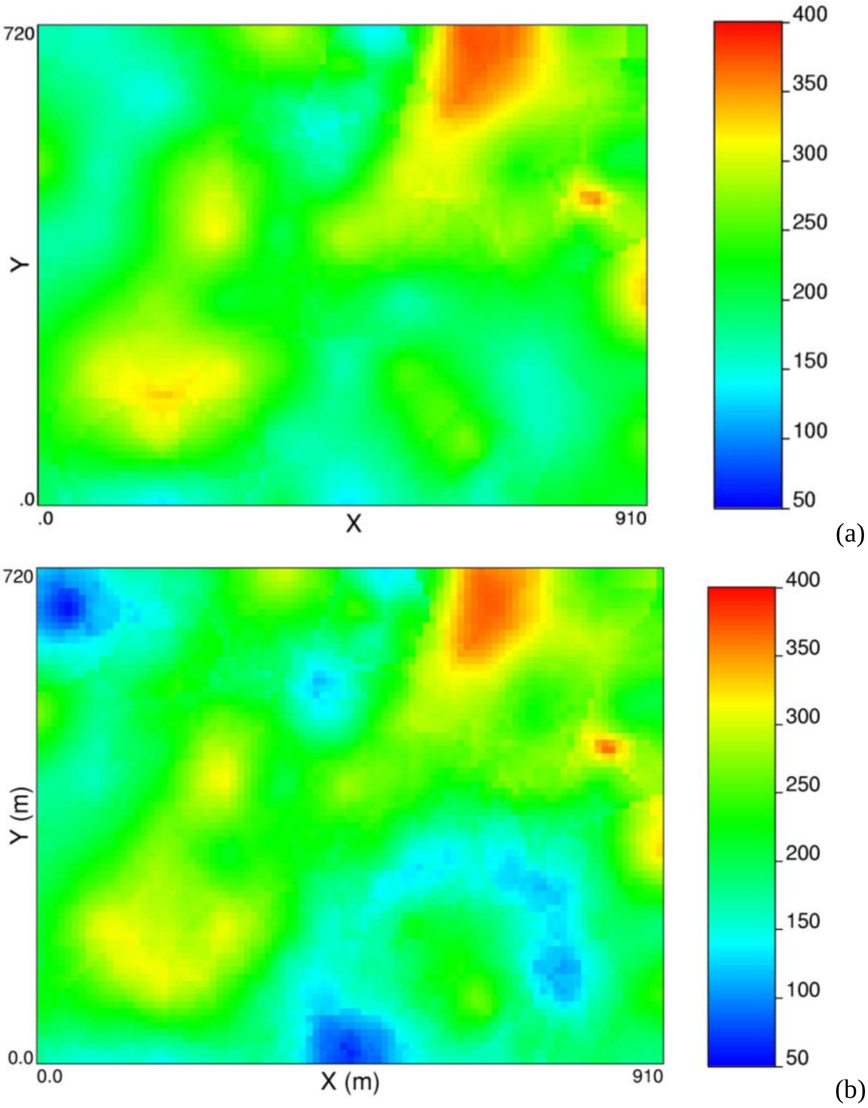


Figure 8.04 (a) Map of EC_e after application of Ordinary Kriging . (b) Map of the variable EC_e resulting from Co-Kriging.

8.3.2 Soil pH value

A histogram of the depth-weighted averages of pH was drawn (Figure 8.05). It shows negative skewness (<0), kurtosis smaller than 3, a mean pH of 6.6, while the maximum and minimum is 8.3 and 4.4 respectively (Figure 8.05). The variation in pH provided the opportunity to successfully map pH and correlate these values with the other measurements. In Figure 8.06, a location map of the occurrence of pH in the study area is given.

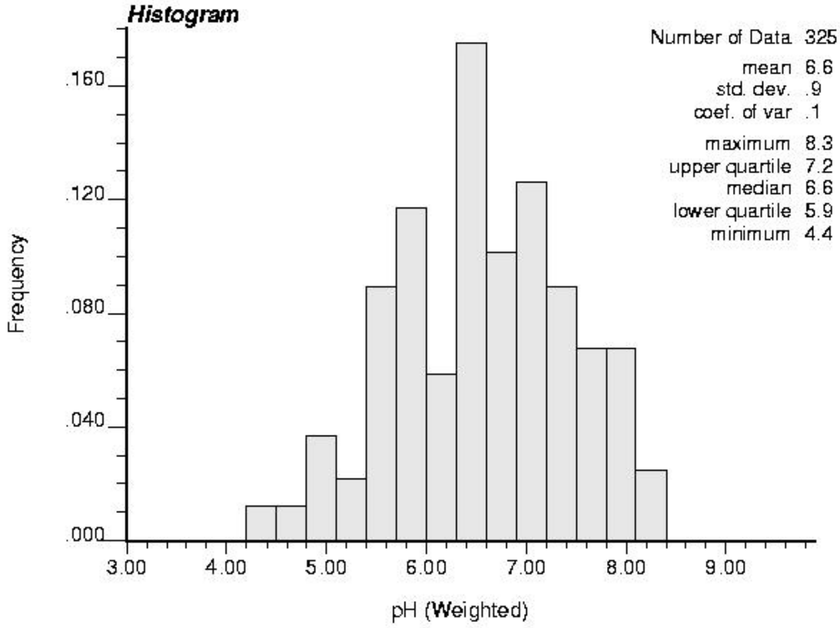


Figure 8.05 Histogram of depth-weighted average pH data (0 to 40 cm soil depth).

Ordinary kriging was applied to pH data. The maximal lag-distance used for pH however, was 300 m. Because of the isotropism an omnidirectional experimental variogram was created. The fitted variogram model is exponential, with a nugget (C_0) of 0.4, sill (C_0+C_1) of 0.752 and range equal to 258 m (Figure 8.07). With kriging, a 4 m by 4 m grid size was used in block kriging. The minimum and maximum number of points involved in the interpolation was 2 and 12 respectively. The radius of the local window was 200 m, circular and isotropic. The pixel map of pH, using ordinary kriging, is presented in Figure 8.08.

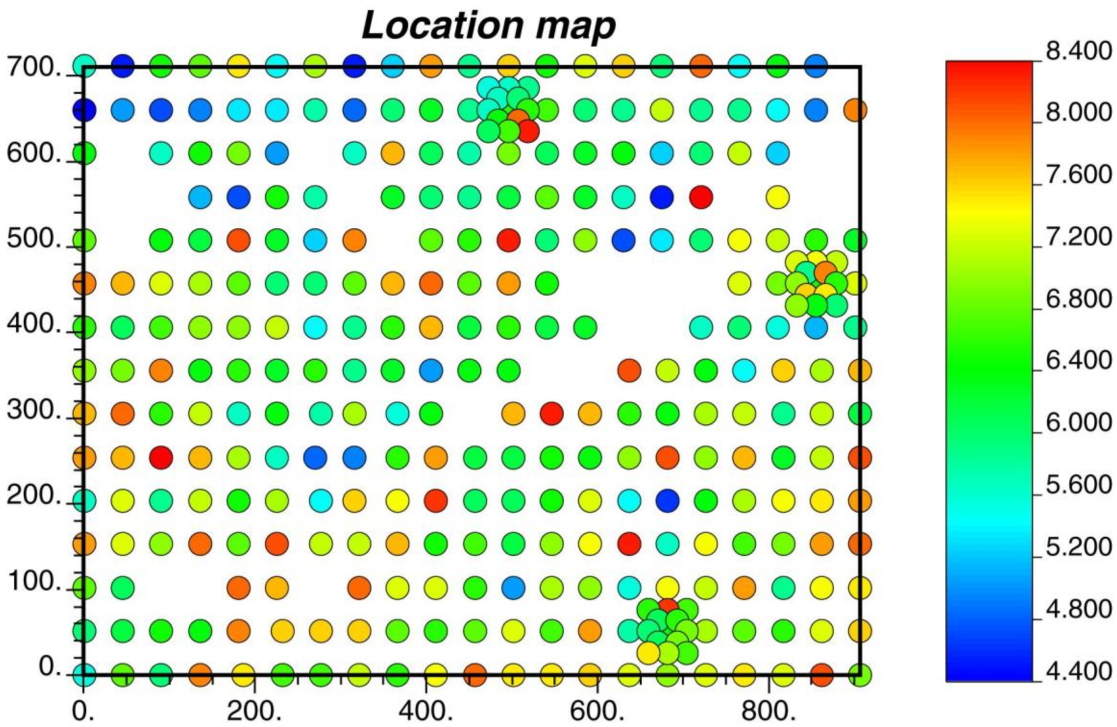


Figure 8.06 Location map of depth-weighted average pH (0 to 40 cm).

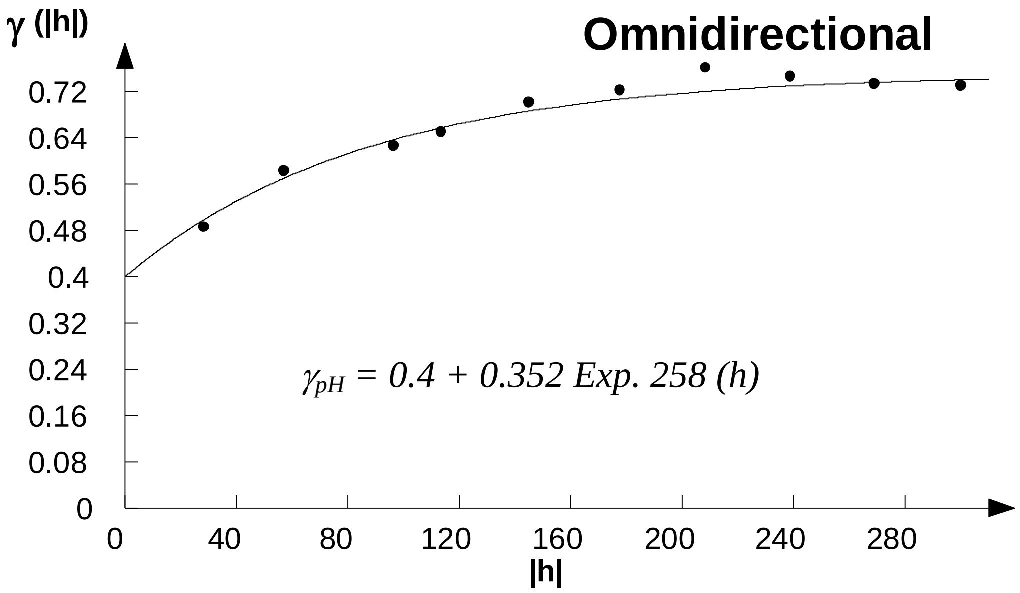


Figure 8.07 An experimental semivariogram and variogram model of the variable pH for soil depth 0 to 40 cm.

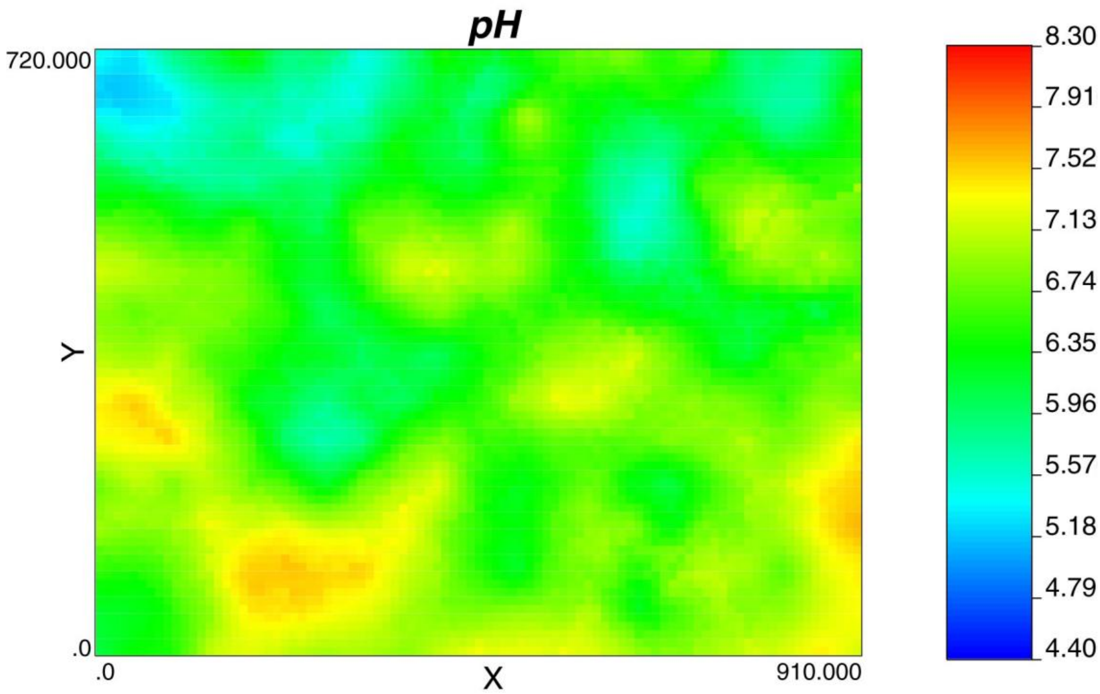


Figure 8.08 Map of pH at Broodkraal generated using ordinary kriging.

8.3.3 The vine

In this section mapping of trunk circumferences (TC) will be discussed. The TC dataset were grouped in age groups, using the year of planting. The averages per yearly group were subtracted from that group. A residual dataset with an average value of zero was consequently generated. The isotropic nature of the data led to an omni-directional variogram and a spherical model with nugget value (C_0) of 1.28, a sill (C_0+C_1) of 3.293 and range of 160 m (Figure 8.09).

Simple kriging was applied to the residual dataset after which the average value for each group was added to the values in the group. The minimum and maximum number of points used with interpolation was 4 and 8 respectively. A circle was chosen as local window with radius of 160 m, which is equal to the range and the result is given in Figure 8.10.

The black lines delineate the different vineyards but also show the areas without any vines such as the roads. Figure 8.13 shows a true year effect.

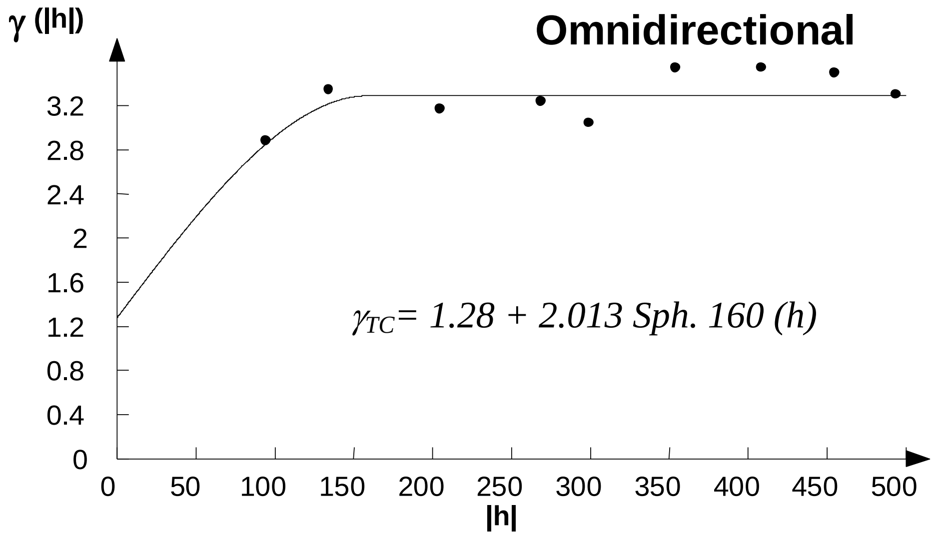


Figure 8.09 An experimental semivariogram of the residual trunk circumference (TC) fitted to a spherical variogram-model.

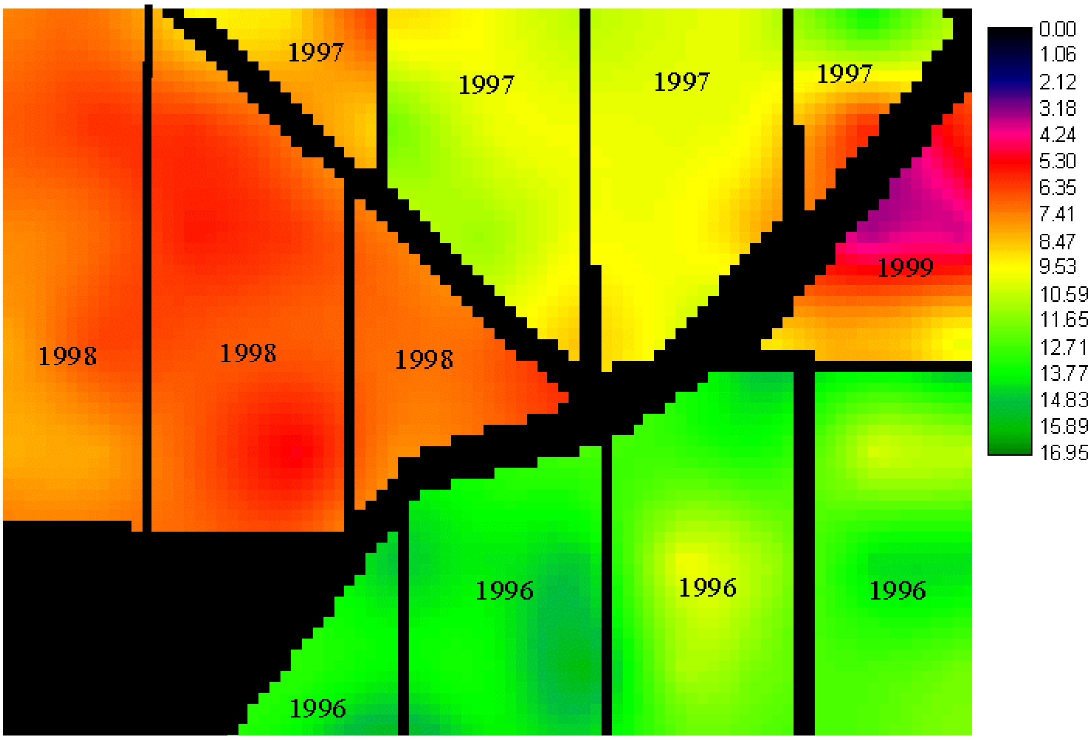


Figure 8.10 A map of trunk circumference data on the Broodkraal farm, derived from kriging with an overlay with the field boundaries and an indication of the planting year of each vineyard.

8.3.4 Soil clay percentage

Clay was found to be relatively unimportant for TC (Table 8.01) and it was consequently decided not to model this variable for this paper. The variable clay was therefore excluded by the multiple-regression analysis, as clay percentage did not improve the prediction of trunk circumferences. The significance of clay percentage (0.165) however, did not comply with the set acceptance criteria for inclusion in the model. The possible reason for the poor relationship with TC could be the stronger correlation between Age, pH and EC_e, causing the benefit of clay to become marginal. This finding may be potentially valuable and it is for that reason that this information was included.

Table 8.01 A multiple regression analysis done with a STEPWISE-method. Exclusion of variables in a multiple regression equation.

Model		Beta	t	Sign	Partial Correlation
1	pH	0.217	2.740	0.008	0.326
	EC_e	-0.197	-2.505	0.015	-0.301
	Clay	0.134	1.663	0.101	0.205
2	EC_e	-0.154	-1.962	0.054	-0.242
	Clay	0.129	1.688	0.096	0.210
3	Clay	0.107	1.405	0.165	0.177

Model 1 = Predictors in the Model: (Constant), Age
Model 2 = Predictors in the Model: (Constant), Age, pH
Model 3 = Predictors in the Model: (Constant), Age, pH, EC_e

8.3.5 Parameters influencing TC

The relationships between all parameters investigated were subjected to a multiple regression analysis. The age effect in the TC data was eliminated to improve the correlation. To accomplish this, the residual dataset as described above was used. The only other significant relationships were with EC_e and the pH. Positive correlations were found between TC and both clay percentage and pH while the correlation with EC_e was negative. These results are shown in Table 8.02, and Figures 8.11 & 8.12.

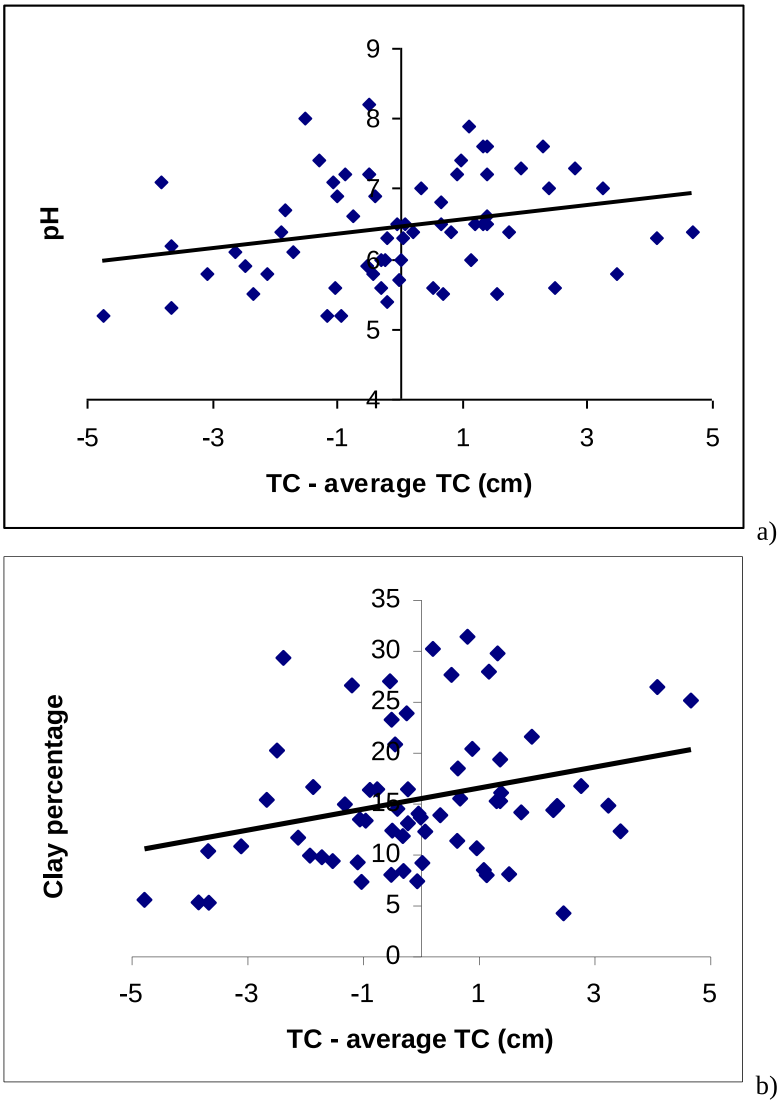


Figure 8.11 The positive correlation between [TC-averageTC] and a) the clay percentage en b) the pH.

Following on the results in Table 8.01, a stepwise-outlier-rejection multiple-regression was used to explore and define the relationships between age, TC, EC_e and pH (Table 8.02).

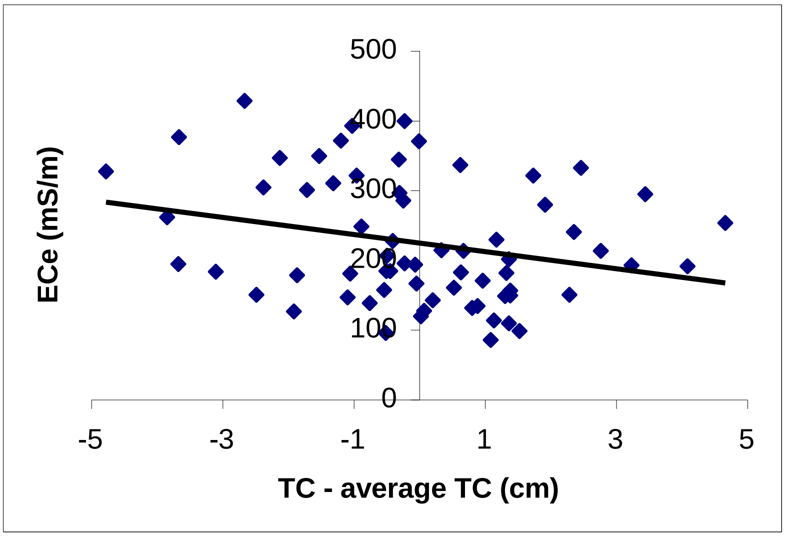


Figure 8.12 The negative correlation between [TC-averageTC] and the EC_e.

Table 8.02 The multiple regression analysis done with stepwise outlier-rejection method with TC the dependant variable.

	Model	Non-standardised coefficients		Standardised coefficients		
		B	Std.Err.	Beta	t	Sign
1	Constant	3.762	0.732		5.138	0.000
	Age	2.275	0.239	0.766	9.524	0.000
2	Constant	-2.085	2.244		-0.928	0.357
	Age	2.106	0.236	0.709	8.932	0.000
	pH	0.979	0.357	0.217	2.740	0.008
3	Constant	0.518	2.564		0.202	0.841
	Age	2.046	0.233	0.689	8.796	0.000
	pH	0.808	0.360	0.197	2.240	0.029
	EC_e	-0.006	0.003	-0.154	-1.962	0.054

The variable Age had the largest influence on the TC as could be expected viz., 58.6 % of TC, was predicted by this variable. However, by inclusion of the other variables in the prediction 65.2 % of the values are predicted within the 95% limits.

Only factors with significance smaller than 0.06 were included in the model:

$$TC = 0.518 + 2.046\ Age + 0.808\ pH - 0.005913\ EC_e \qquad \textbf{Eq. } 8.02$$

Eq. 8.02 was then used in IDRISI (Eastman, 1999), with the results of Figures 8.04(b), 8.08 & 8.10 to calculate the result shown in Figure 8.13. It is important to note that through this process, age became a variable and TC as a measure of vigour, could now be determined and mapped for the whole farm regardless of the true age differences between blocks.

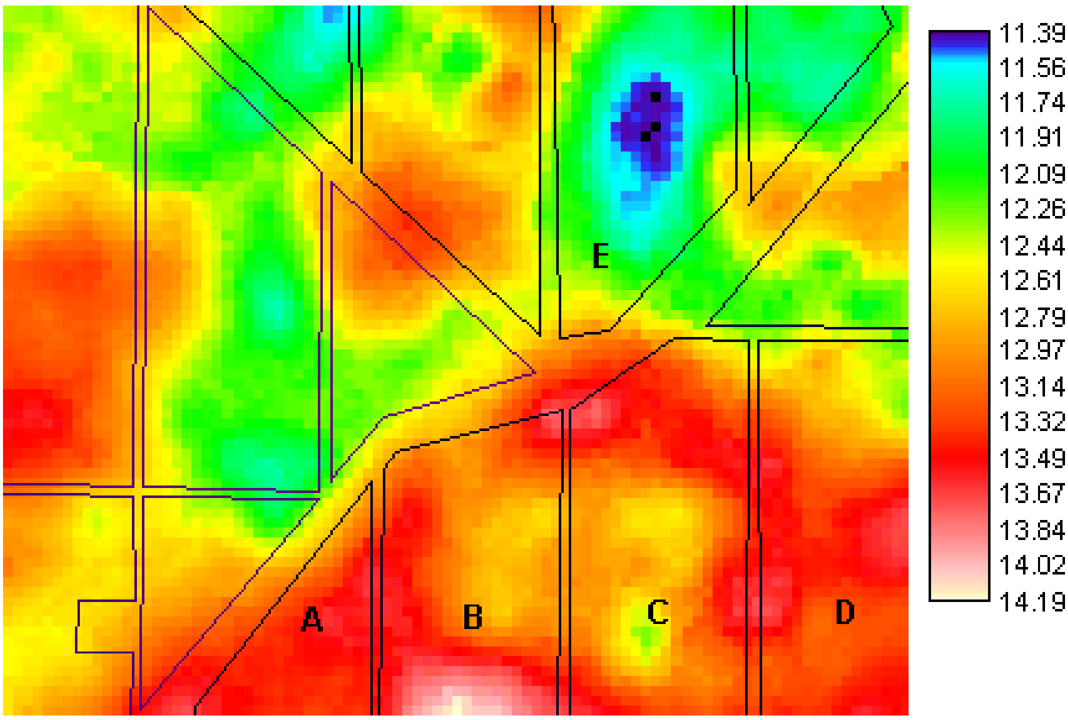


Figure 8.13 Prediction of TC of the vines after 4 years with the different management blocks projected over the TC prediction.

Figure 8.13 shows the prediction of TC after four years of growth. It must however be borne in mind that the prediction in Figure 8.13 was done irrespective of the true age of the different segments on the farm. It is simply an equal age prediction, predicting the TC of all vines after four years of growth.

In Figure 8.13, A and D resemble the sections with the most stable growth and yield, while, B and C are the sections with very large variances. E and the similarly coloured sections to the left of E, show the lowest potential. All of this was in fact confirmed by observation on the farm.

Sustainable growth was however maintained in these saline conditions mainly as a result of over-irrigation. Therefore the negative effect that soil salinity and poor water quality could impose on growth was overshadowed by water quantity.

8.4 Conclusions

By using kriging techniques, EC_e, pH, age and vigour could be predicted at a high resolution for this landscape generating a regional realization or trend. It was shown that modelling of regional trends and comparing these trends statistically produced good results and opened a window on sustainability issues that could barely be possible using data on a point basis. The shown predictable regional behaviour of EC_e in relation to pH, time and plant vigour could have widespread application for the grape/wine industry of the Western Cape.

Resulting from over-irrigation as a means of dealing with salinity in the landscape, no salt build-up occurred and the role clay could play in affecting growth was also reduced. Gypsum was also used to better infiltration and control sodium build-up in these soils and this led to the reduced role clay played as a growth inhibitor.

The soil pH showed a significant influence on the long-term reaction captured in the trunk circumference measurements. The EC_e of the upper part of the soil as being investigated here must be seen in the background of a region with up to 10 mm evapotranspiration per day, very little rainfall and thus totally dependent on irrigation. It can thus be expected that the EC_e will be lowest in over-irrigated segments. In segments that received less irrigation than the evaporative demand, a build-up of salts will occur. In parts that received no irrigation but are close to the irrigated area, the EC_e will soar. In sites where the soil pH is restricting growth, transpiration is reduced and therefore over-irrigation usually occurs, resulting in runoff and increased drainage.

From Figure 8.13 it is clear that areas with expected good or bad growth can be delineated and could be predicted prior to planting. Though the information presented in Figure 8.13 is mostly after the fact, this farmer would surely have benefited from the EC_e and pH maps, as the information for sustained and correct development is contained in them. The fact that this study was based on only the upper part of the soil profile, and that such a good relationship could be defined between plant growth and soil characteristics, implies that the vines reacted more to what was happening in the upper part of the soil than the section below the 45 cm sampling depth.

Perhaps the most important finding in this research was that, while vine age, EC_e and pH, when correlated with trunk circumference separately, generated low R^2-values. However, in combination (Eq. 9.02) their data generated a R^2-value of 66 % and consequently better levels of significance. The fact then that 66 % of the variance (within the 95% confidence limit) is explained by vine age, EC_e and pH in combination (Eq. 9.02), suggests very little else influenced growth negatively in these circumstances.

The most important implications of these results are economic. This research showed that the methods applied here could enhance current knowledge in terms of the behaviour and sustainability of agricultural crops on a regional basis through a process that deals with spatial variation. This could increase profitability from these landscapes and it deals with very important water issues.

9 SOIL SALINITY CHARACTERIZATION USING THE EM38 SOIL PROXIMAL SOIL SENSOR[6]

ABSTRACT

Land used for wheat production since early 1900 in the Berg River catchment of South Africa, was selected for grape production and therefore the soil was characterized and mapped. Soil pits were dug on a 100 x 100 m grid and a large number of parameters were described. EM38 vertical and horizontal scans were done over this 1.6 km^2 area, and at the soil pits. A digital terrain model was developed as part of the detailed soil mapping. The aim was to characterize the EM38's ability to characterize and indicate the transition between soil classes. The parameters that showed a good correlation with the EM38 observations were mapped since the EM38 observations showed complex but predictable relationships with a number of observations made. They also showed an agreement with the soil types mapped in the conventional manner. A typical soil toposequence could be established and linked to the EM38 response.

[6]*Published as part of:*

Fey, M.V. and de Clercq, W.P., 2004. A pilot study investigating the role of dryland salinity in the quality of the water of the Berg River. WRC Report, 1342/1/04 (ISBN No. 1770053059)

de Clercq, W.P., Van Meirvenne, M., Ellis, F., Lambrechts, J.J.N., 2008. Soil salinity characterization using the EM38 soil proximal sensor (submitted to *Soil Use and Management*).

This ability generated a new approach to mapping soils in respect to their suitability for viticulture.

9.1 Introduction

The soils of the Western Cape are known for their large variability even over short distances. This variability is often overlooked by soil mapping and sampling procedures. It therefore often happens that soil change is first noticed in the uneven growth of vines in a single block. This leads to differences in grape and wine quality within the same block. Often the opinion is held that these differences can be mapped before development of the vineyard blocks proceeds. By recent research in the area it was also found that salinity in the region is of an oceanic origin, being brought in by rain and dry aerosols. Salinity is also strongly related to the capacity of a soil to store salt. This in turn determines a unique residence time per soil type for salt in the region. With this in mind when measuring the salinity of soils, salinity could be used to identify soil borders and also soil types. (de Clercq *et al*, submitted).

With the soil changing over short distances, it is not always possible to locate the position where the changes occur. Even when soils are carefully mapped, using a resolution of 100 m by 100 m, the final dividing line between two identified soil types are mostly drawn roughly. These soil maps, as a direct result of their poor resolution, often result in vineyards that were planned over a change in soil. By using a soil sensor like the EM38, soil map information can be refined and georeferenced. The implication for the user is that features on the map can now be transferred to exact locations in the field. McBratney *et al.* (2000, 2003) indicated that conventional soil survey is costly and time consuming compared to soil mapping based on soil sensors. Burrough *et al*. (1997) indicated that most soil maps had the inadequacy of no spatial variation and that the taxonomy had a low level of geographical correctness. Rhoades *et al*. (1997) indicated the importance of spatially referenced information for the assessment of irrigation, drainage and salinity management practises.

The use of electromagnetic induction was first developed as a field survey technique in a geophysical sense and has been used as such since as early as the 1920's. The first suggestion that EM sensors could be used to measure soil salinity was in 1979 by de Jong *et.al.* (1979). The US salinity lab tested the initial model EM31 and found that the instrument readings were too responsive to the conductivity of material below the rootzone (Rhoades and Corwin, 1981). Rhoades later developed the model EM38 sensor that was sensitive to soil depths of less than 1.5 m.

Though the EM38 was initially built to measure salinity, the instrument gained merit as being a good field surveying instrument. The mere fact that the data can be linked and measured to the same and finer resolution than satellite or remote imagery, has contributed to the use of the instrument in prospecting soil variability.

The capacity of the soil to conduct an electromagnetic induction current is synonymous to measuring the electrical conductivity of water. Both are expressed in mS m^{-1}. As in the case with EC of water, the EM38 readings are all inclusive. This means that everything in the soil that affects electromagnetic induction needs to be taken into account, therefore the readings are called apparent EC (EC_a). McNeil (1980) indicated that the EM38 readings are influenced mostly by the clay content in an ionised or colloidal state, the EC_{sw}, stone content as a negative influence and soil water content. Since all of these also vary with soil type, the raw EM38 readings are also broadly sensitive to soil type (Dunn and Lilly, 2001. The measurement resolution of the instrument is virtually limitless, meaning the more measurements the better the detail presented on a map (Fey and de Clercq, 2004).

9.2 Principles of EM38 operation

The EM38 comprises of a transmitter coil and a receiver coil (Figure 9.01), a battery and digital readout. The transmitter current generates eddy-like loops in the ground. These currents also generate a secondary magnetic field and the ratio between the secondary and primary fields are proportional to the electrical conductivity of the ground material (Figure 9.01). The measurement is fast and ground penetration is immediate.

The instrument is always on, and data logging of EC_a readings is continuous. This allows speeding up measurements. The fact that the EC_a readings are continuous is therefore exploited by speeding up measurement through dragging the instrument behind a vehicle on a sled. Measurements from the EM38 are then logged at a constant rate on a recorder.

The instrument can be used in a vertical or a horizontal mode resulting in EC_a-V and EC_a-H measurements or in both simultaneously. The differences in depth response curves (Figure 9.02), indicates that the vertical mode is less effective at shallow depth. This response is then characterised as the profile ratio (PR) (Cockx *et al*., 2007):

$$PR = EC_a\text{-}H / EC_a\text{-}V \qquad \textbf{Eq. } 9.01$$

Logging of the instrument readings were combined with simultaneous GPS measurements. Georeferencing and measuring is normally done with one of two methods. Firstly the GPS is set up to log at a set time interval and the driver then maintains the speed of the vehicle to ensure an even spread of readings. Secondly the measurement positions were carefully planned (almost like a flight plan for aerial photography) and readings were taken automatically when the vehicle passed the predetermined positions. The latter was used to make sure that readings were logged at the soil pits. Readings were also taken by hand.

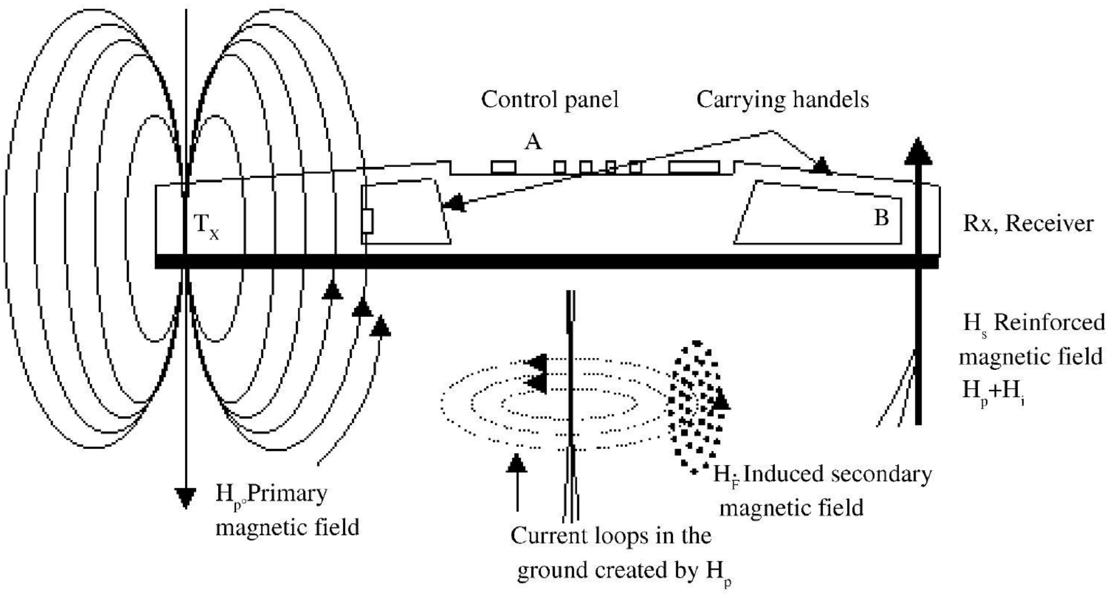


Figure 9.01 Operational principle of the EM38 (Lesch *et al.*, 2005).

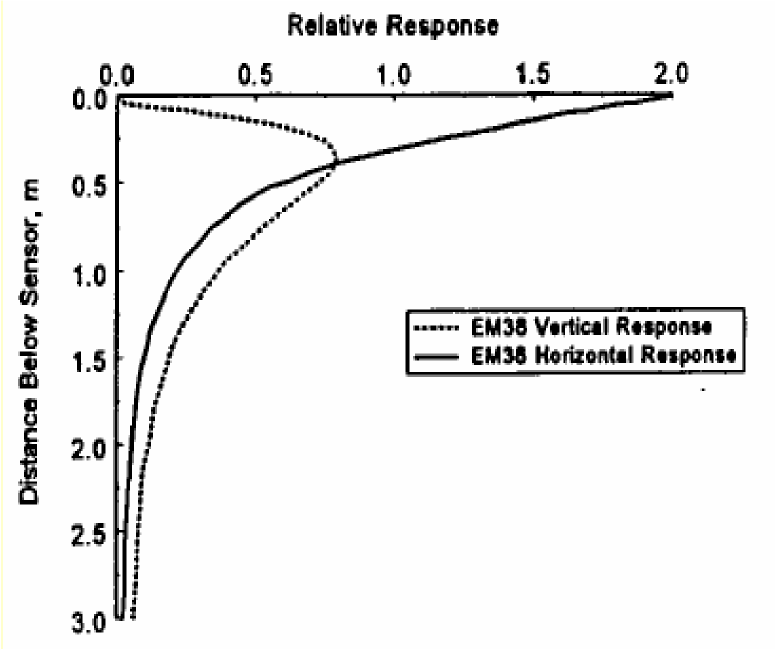


Figure 9.02 Depth response curves for the two orientations of the EM8 (McNeill, 1980).

9.3 Method

The study area was the Glenrosa farm in the Paarl district of South Africa (Figure 2.02). Up to now the land was used for wheat production but recently a new vineyard was planted. The 1.6 km^2 land was surveyed according to the layout seen in Figure 9.03. The spatial resolution of the EM38 measurements was 20 by 100 m. The figure is inclusive of all EM38 measurement positions and all soil sampling/description positions.

Four clusters were chosen at random sites where the measurement interval was increased to a 10 m grid resolution. Soil sampling was conducted at 97 sites over the 100 by 100 m grid that covered the whole area. From the soil samples the clay content was determined, as was Ca, Mg, Na, and K using atomic absorption, EC_e, ER (electrical resistance of a saturated paste), stone content, pH and SAR. From the soil pits various parameters were recorded like soil depth, the distribution of clay in the profile and soil colour and elevation. Elevation was logged using a survey grade GPS and the values were compared to a 1:10000 ortophoto map of this area. Elevation was used to derive gradient since slope is an important element in the toposequence concept in soil classification. This investigation focused mainly on those variables found to correlate well with any of the EM38 derivatives.

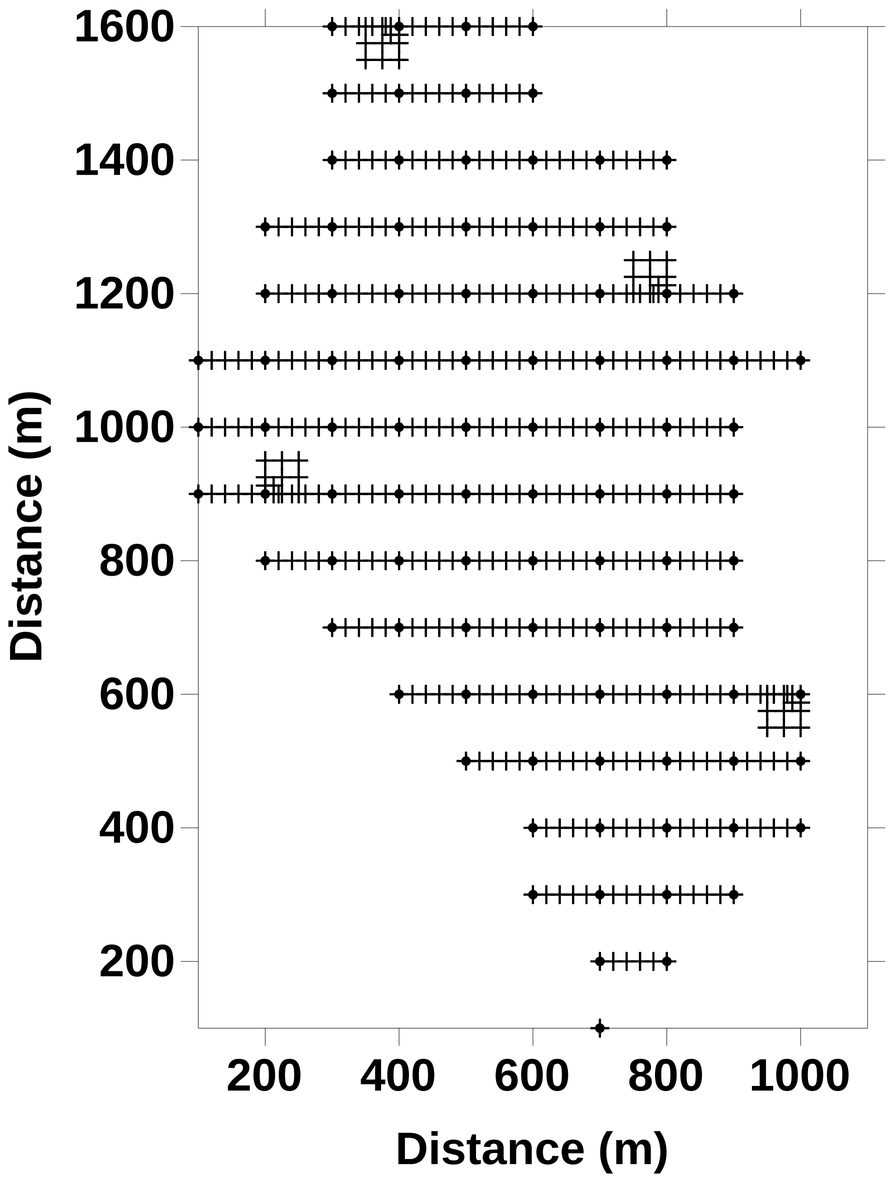


Figure 9.03 EM38 measurement positions (crosses). The dots represent the soil sampling positions.

Since soil type and salt distribution is generally well correlated with topography in the toposequence concept, the aim is to investigate this link for the EM38 observations as well. Therefore the main aim was to explore the sensitivity of the EM38 to a combination of soil variables, variables also used in soil classification, and as such generates an EM38 to soil type relationship, that can be used for general soil mapping.

9.4 Results

Table 9.01 presents the descriptive statistics for the variables observed. What is important in this table is the comparison between direct and indirect measurements of salinity. Both the clay content and the stone content of these soils are high but show similar distribution characteristics (Table 9.01). Clay normally adds to the EC_a readings while stone content lowers the EC_a (McNeil, 1980). All variables showed a positive skewness except clay and stone content, but values were generally small. Table 9.02 lists the correlation coefficients between the variables listed in Table 9.01. This table shows a good correlation between EC_a and EC_e. It also shows a good relationship between the EC_a-H and EC_a-V measurements. Noteworthy as well is the good relationship between EC_a measurements and Na^+, and to a lesser extent with SAR. Stone content showed a poor correlation in general. Amongst all the measurements, SAR, EC_a-V, EC_a-H, Na^+, EC_e and ER showed the stronger interaction.

The elevation, slope and soil depth were mapped and are shown in Figure 9.04. Soil depth and slope angle showed similar spatial patterns. Both maps on slope gradient and soil depth were produced by ordinary kriging with a linear variogram model.

Table 9.01 Descriptive statistics for the variables clay (%), pH, EC_e stone content, ER, Ca^{2+}, Mg^{2+}, Na^+, K^+, EC_a-V, EC_a-H and PR from the Glenrosa farm.

	Clay %	pH	EC_e mS m^{-1}	Stone %	ER ohms	Ca^{2+} mg/l	Mg^{2+} mg/l	Na^+ mg/l	K^+ mg/l	EC_a-V mS m^{-1}	EC_a-H mS m^{-1}	PR ratio
Mean	47.23	5.86	200.1	37.75	1629.76	1.54	1.1	10.58	0.56	107.62	87.72	0.87
Standard Err	1.26	0.06	27.79	1.4	89.12	0.19	0.08	2.08	0.04	6.83	4.85	0.02
Median	47.88	5.62	70.14	38.47	1382.6	1.18	1	5.55	0.48	85.50	79.00	0.83
Standard Dev	8.7	0.84	384	9.72	1238.13	1.3	0.57	14.28	0.26	73.57	52.20	0.21
Sample Var	75.7	0.7	147453	94.53	1532969	1.68	0.33	204.01	0.07	5413	2725	0.04
Kurtosis	-0.48	-0.27	16.18	0.1	-0.59	5.16	0.53	13.61	2.17	4.92	6.02	6.56
Skewness	-0.29	0.79	3.77	-0.18	0.55	2.19	1.17	3.28	1.54	1.97	2.02	1.47
Minimum	28.5	4.22	18.11	13.08	21.77	0.28	0.43	1.64	0.29	4.00	4.00	0.33
Maximum	62.93	8.12	2687	60.16	4782	6.32	2.65	82.44	1.45	446	322	2
Count	48	191	191	48	193	48	47	47	46	116	116	116

Table 9.02 Pearson correlation coefficient between EC_a measurements, PR and various analytical results derived from soil samples (values > |0.6| are given in bold).

	pH	EC_e	Stone	ER	Ca^{2+}	Mg^{2+}	Na^+	K^+	SAR	EC_a-V	EC_a-H	PR
EC_e	0.30											
Stone	-0.07	-0.07										
ER	-0.45	**-0.81**	-0.14									
Ca^{2+}	**0.64**	0.18	-0.09	-0.29								
Mg^{2+}	**0.60**	0.52	-0.22	-0.52	**0.84**							
Na^+	0.20	**0.97**	-0.19	**-0.70**	0.06	0.42						
K^+	0.01	0.20	-0.01	-0.29	-0.05	-0.01	0.15					
SAR	0.14	**0.89**	-0.13	**-0.70**	-0.14	0.20	**0.94**	0.22				
EC_a-V	0.49	**0.76**	-0.06	**-0.63**	0.29	0.55	**0.73**	0.04	0.59			
EC_a-H	0.40	**0.80**	-0.15	-0.58	0.32	**0.61**	**0.79**	0.02	**0.61**	**0.95**		
PR	-0.16	-0.22	-0.13	0.30	0.30	0.16	-0.22	-0.12	-0.34	-0.39	-0.13	
Clay	-0.01	-0.15	0.25	0.06	-0.40	-0.22	0.01	-0.15	0.45	0.01	0.02	-0.17

There is an obvious similarity between the mapped surfaces in Figure 9.04, which were not that obvious from the descriptive statistics (Table 9.01). This means that the factor causing this similarity is possibly related to the catchment forming processes but related to all three mapped variates.

The variograms of the EC_a-V, EC_a-H and PR were best modelled using a spherical model (Figure 9.05). The range of these models is about 350 m. This is practically half the sloping distance within the mapped area.

The similarity, between the three variograms, is also quite clear. Figure 9.06 shows the kriged EM results based on the Figure 9.05 models. Again the similarities between these kriged realisations are easy to see and are an acknowledgement of the good relation between them as were also shown in Table 9.02. The kriged surface of PR in Figure 9.06 (c) shows areas with higher salinity in the subsoil.

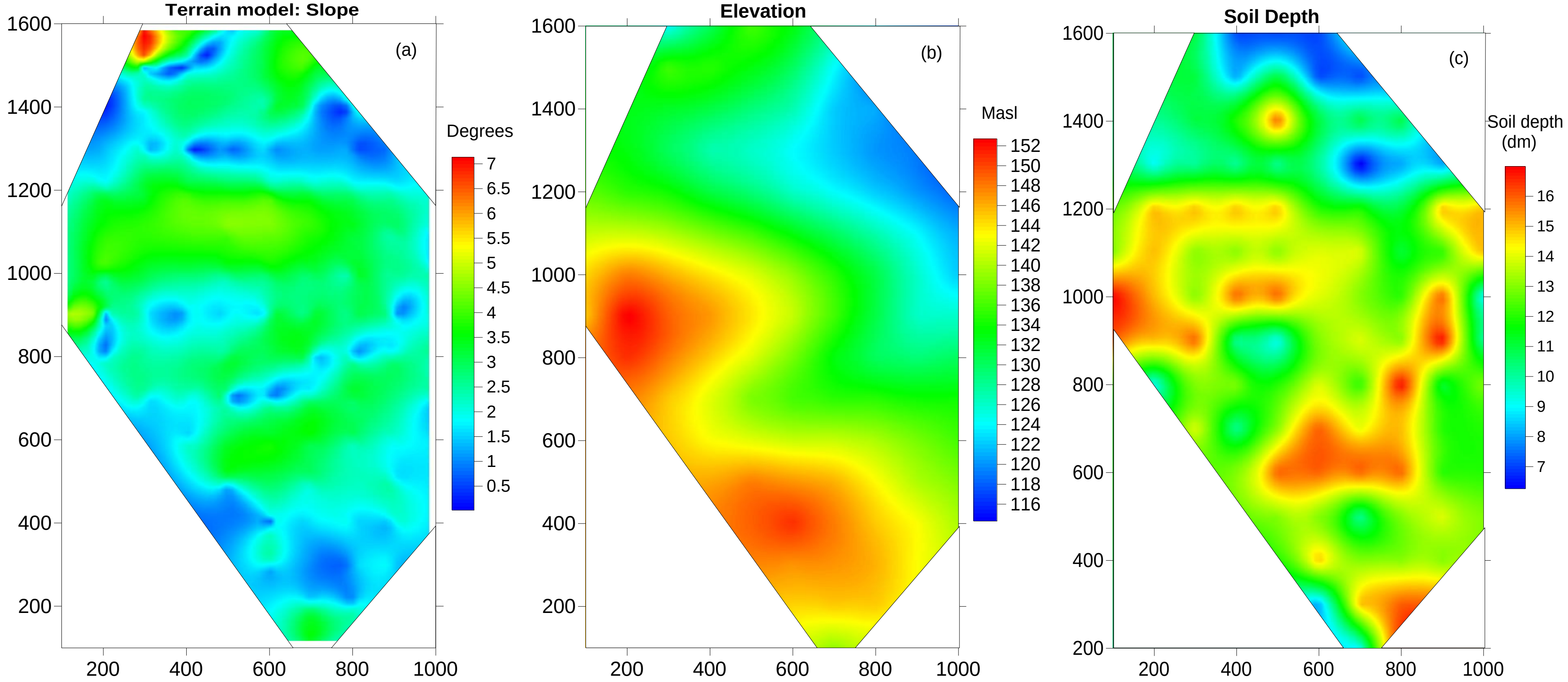


Figure 9.04 Kriged maps of the (a) Slope angle, (b) elevation contours and (c) soil depth (surface to hard rock).

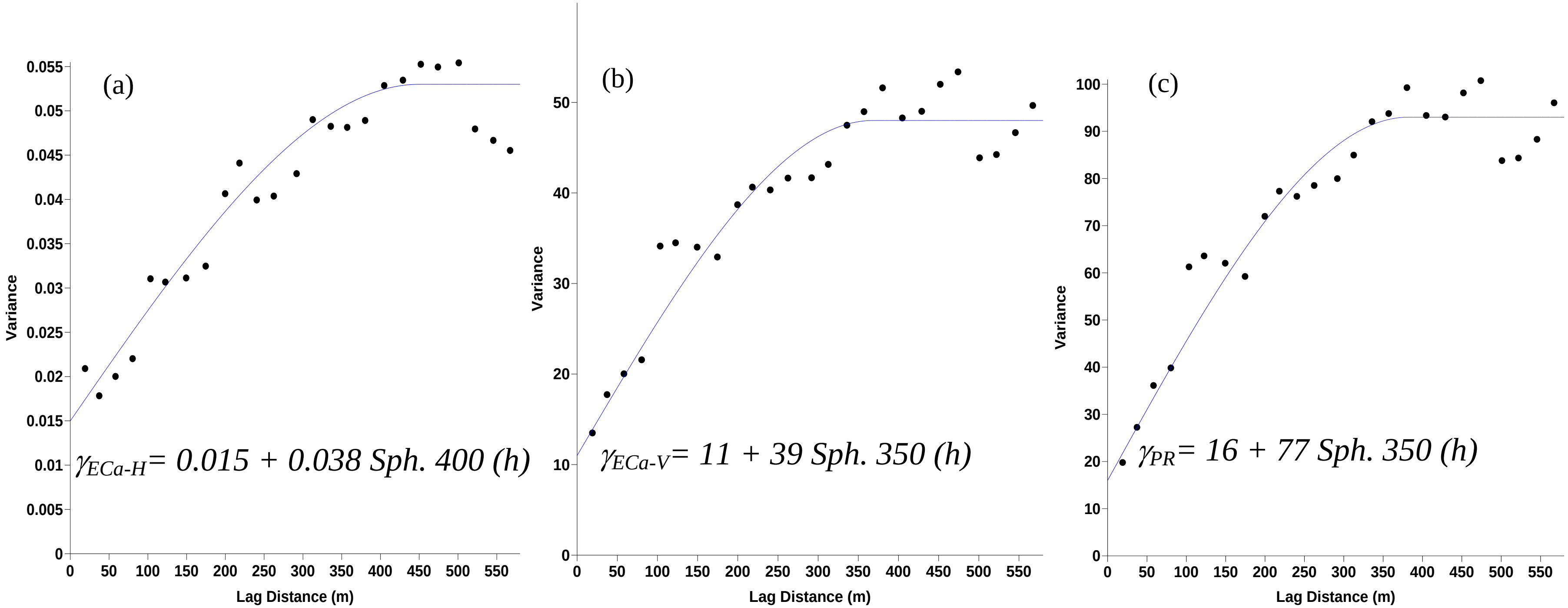


Figure 9.05 Semi-variogram of the EM38 measurements, (a) EC_a-H, (b) EC_a-V and (c) the PR. The equations refer to a spherical model (Sph.) with the coefficients: nugget, sill and range respectively and *h* = lag distance.

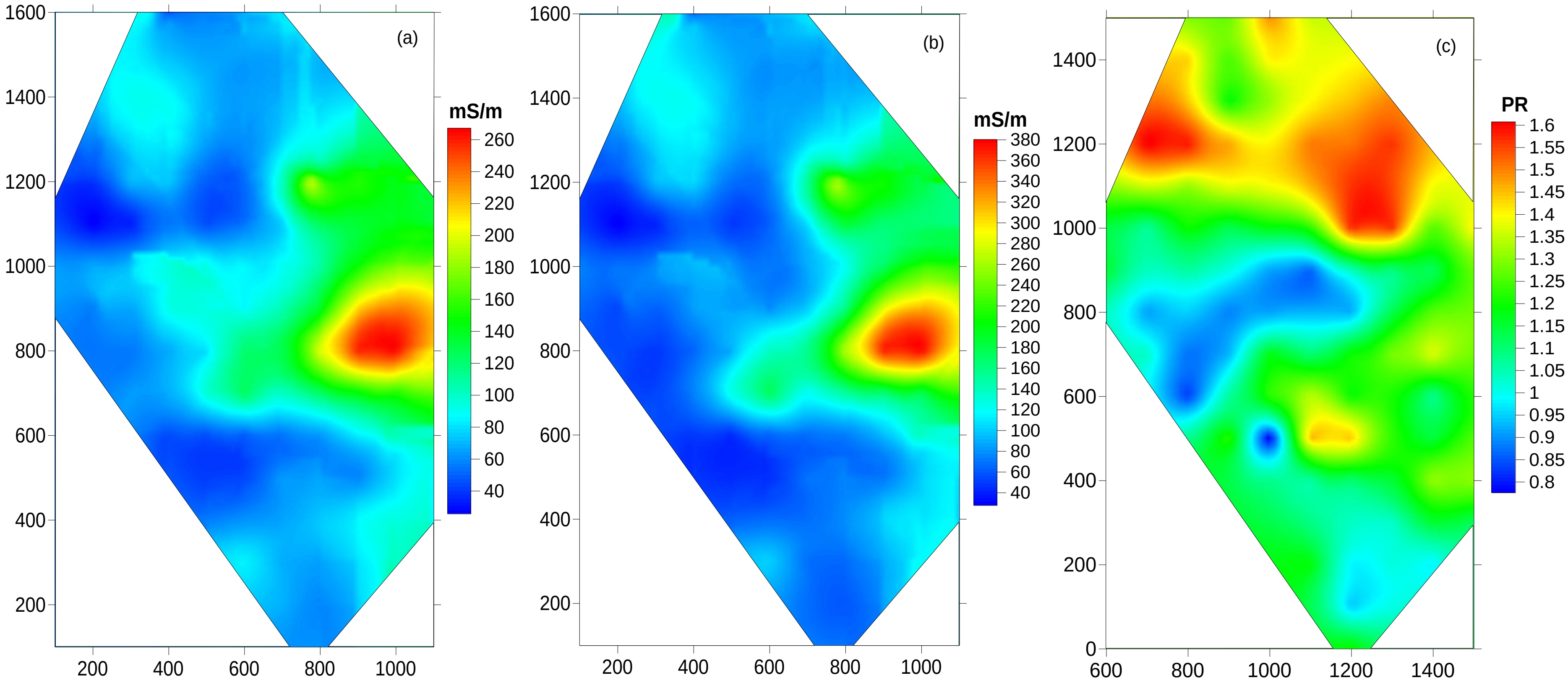


Figure 9.06 Kriged maps of the EM38, (a) EC_a-H, (b) EC_a-V measurements and (c) PR.

Figure 9.07 shows the mapped soil-sample derived EC_e. The resemblance with EC_a of Figure 9.06 is also clear. Though a good correlation exists between EC_e and EC_a, the images are not identical, primarily as a result of the differences in sampling resolution and the subsequent interpolation. The variogram of EC_e shows no nugget effect and had a shorter range, but is also similar in shape to the modelled variogram of the EC_a measurements (Figure 9.06).

Figure 9.08 shows the resemblance between the traditional soil map of this section of land, and a map of EC_a-V. In Figure 9.08(a) only the dominant soil groups were presented. In Figure 9.08(b) only two EC_a-V contour values were chosen, namely that of 50 mS m^{-1} and 100 mS m^{-1}. This compares to an EC_e of 50 and 100 mS m^{-1}, respectively, when compared to the EC_a-V measurement. An EC_e of 100 mS m^{-1} is generally considered as the upper limit in soil salinity when soils for viticultural purposes are demarcated. The area that shows less than 50 mS m^{-1} is considered the region where low natural accumulation of salt occurs and that the natural processes in the region could take care of any salt build-up. The white area on this map is therefore the area indicated with low natural EC and therefore the low risk area in terms of establishing vineyards. The area between 50 and 100 as well as the area above 100 involves increased risk. The thick black line indicated on the soils map was the surveyor’s indication of the soils to avoid in vineyard development to the east of the line. A resemblance can be observed, but it will be clear that the finer resolution of the EM38 observations allowed a much finer localisation of the problem area.

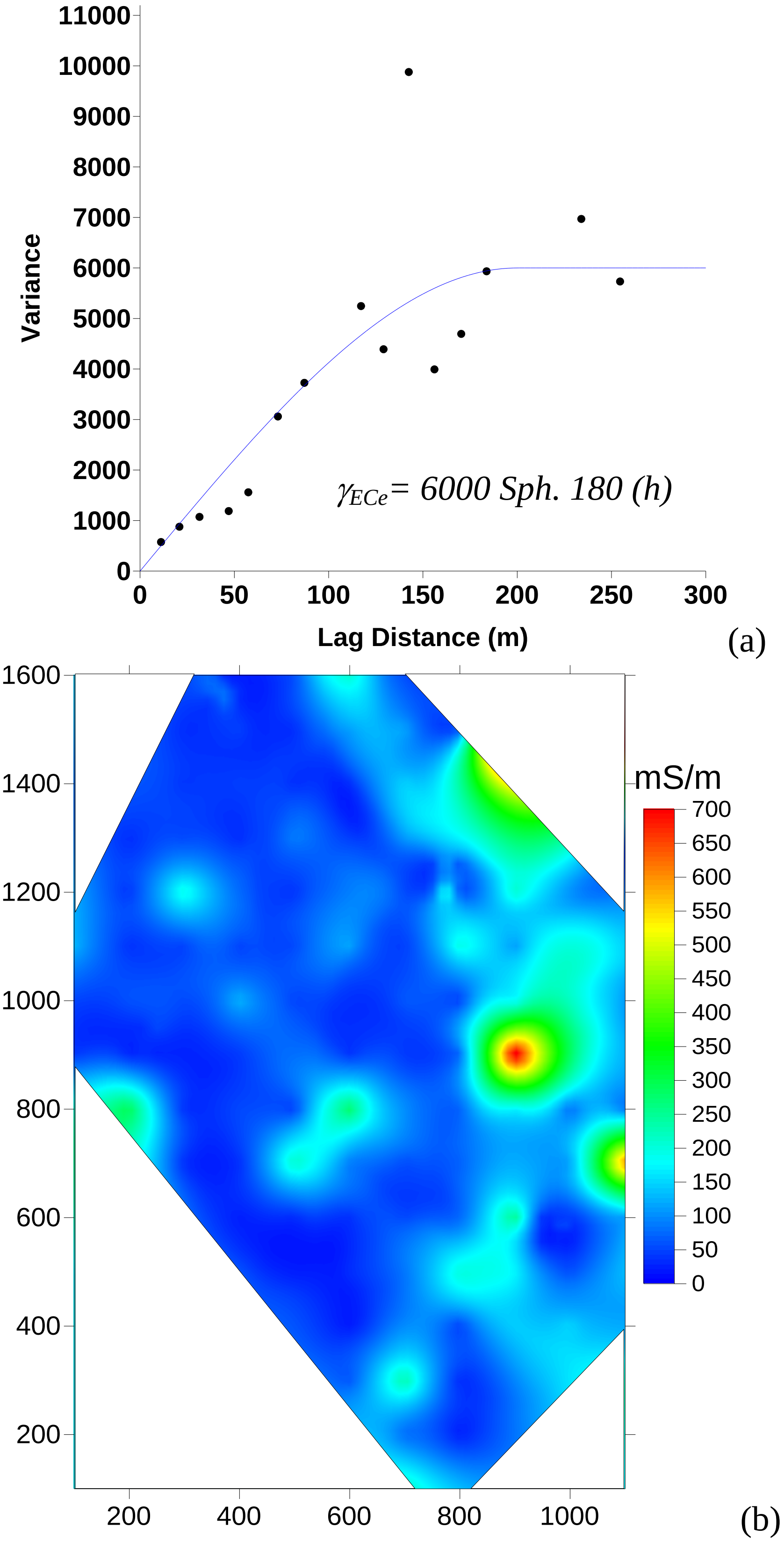


Figure 9.07 (a) Semi-variogram of depth weighted average ECe measurements from soil samples, (b) the resultant Kriged map of ECe (mS m^{-1}).

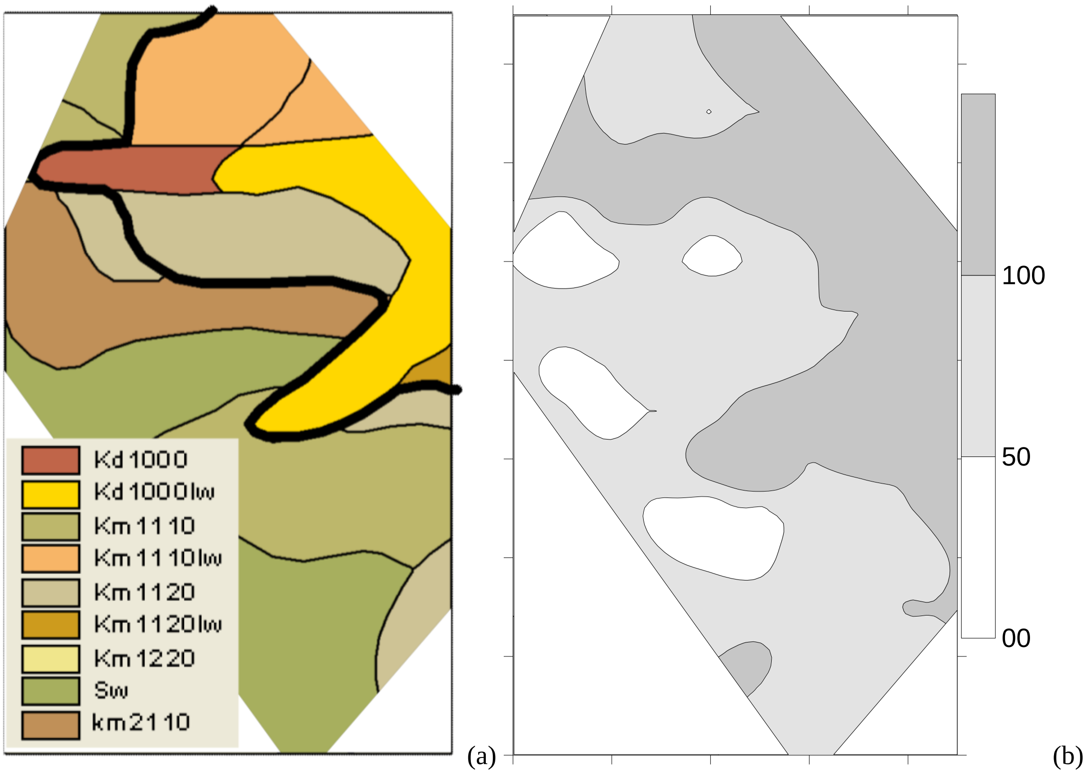


Figure 9.08 A comparison between (a) soil mapping (Soil Classification Workgroup, 1991) and (b) the classified EM38 results of the Glenrosa study area.

The PR and the elevation were also compared (Figure 9.09). Though the R^2 is moderate, it is still highly significant (p = 0.02). What is important though, was that this result showed that PR is sensitive to elevation to the same extent as soil classification is linked to the toposequence concept. Though this is not a workable format, it was felt that with some refinement to the classification procedure, or to allow the EM38 data to be influenced by one of the other defining parameters, the prediction could become better. The rich continuous variability so easily acquired with the EM38 could be used as indication of soil changes which are not detectable using only soil samples and inspection pits.

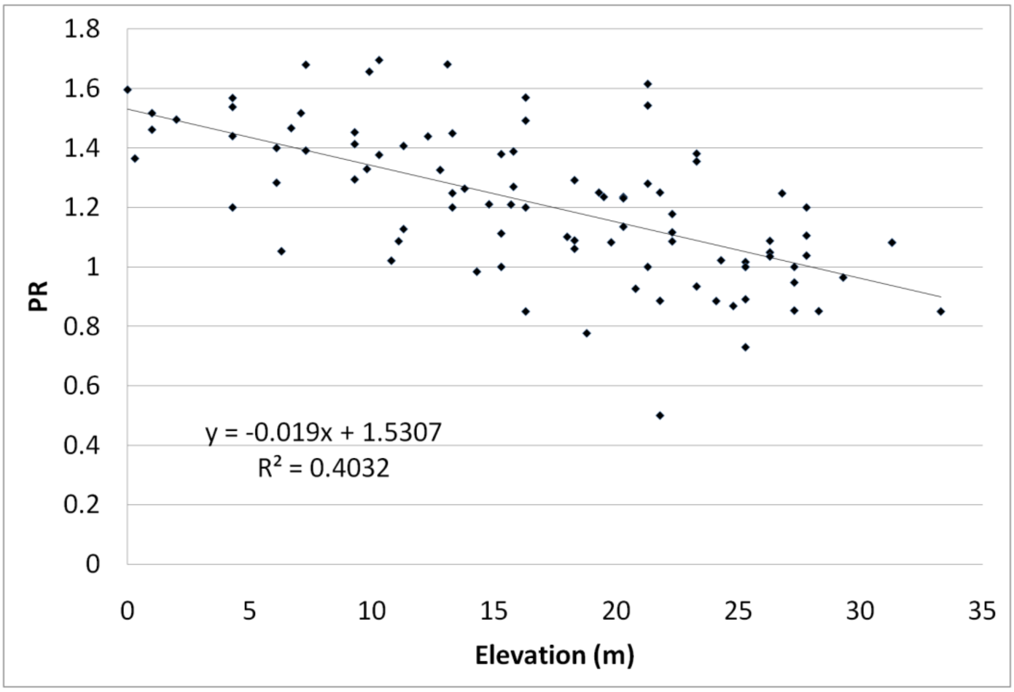


Figure 9.09 Regression between elevation and PR data obtained with the EM38 measurements.

Soil mapping as shown in Figure 9.08 usually overlooks or ignores small deviations in soil type and simply includes them in the larger unit. Therefore a comparison was made between the various reported measurements and the original soil classification information per soil pit, ignoring the generalised grouping of the soil map. It was decided to use the South African classification system (Soil classification working group, 1991) and not translate the information into the World Reference Base System (WRB) because of its local relevance. The South African system uses a name per soil type and family codes to further subdivide within the type. This subdivision was done on the basis of the occurrence of salinity, soil wetness, soil structure and the state of the parent material.

However, the aim was to investigate the link between soil types and the EM38 measurements. It was assumed that in general a relative good correlation existed between soil classification, soil EC and elevation through the toposequence concept. Consequently, the idea was not to use the individual EM38 measurement values, but rather the median of PR values of each soil class and link those to the corresponding classification units. These results are summarized in Table 9.03 and Figure 9.10. The selection process was based on a central PR value in each group. However, the groups were not equally populated, so it was decided not to discard those that had little information, as it may be the case that some soils occurred only in small parts of the study area to be surveyed and that this will always be the case with all such surveys.

Table 9.03 The soil class, form and PR values for Glenrosa farm.

Class No	Form	Family	PR Median	EM Class upper limit
1	Cf	2100	0.940	<0.955
2	Tu	2120	0.969	0.976
3	Sw	2121	0.984	0.992
4	Cf	1100	1.000	1.018
5	Cf	1/2100	1.035	1.042
6	Gs	2/1121	1.049	1.049
7	Sw	2111	1.049	1.150
8	Km	1110	1.250	1.265
9	Km	2110	1.280	1.287
10	Km	1120	1.295	1.317
11	Vf	1120	1.340	1.396
12	Kd	1000	1.453	1.524
13	Kd	2000	1.596	1.7 >

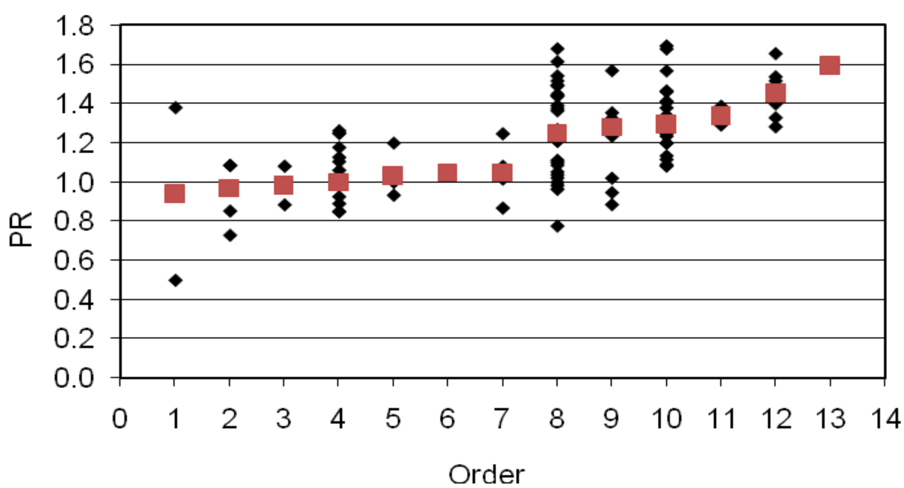


Figure 9.10 The central values (Squares) for each soil group, based on Table 9.03.

The classes indicated in Table 9.03 were selected as central values between the median values used. The results presented in Figure 9.10 offered a new approach in soil mapping. When the median PR value per soil type was taken, mapping of classes based on the median ensured a more reasonable chance that a certain soil type would occur at a certain spot and caused a better indication of the distribution of these soils. The kriged PR values were shown in Figure 9.06. They were reclassified according to the classes of Table 9.03. This result is given in Figure 9.11 as soil classes. However, soil borders appeared as sharp transitions between soil types while it should be clear from Figure 9.10 that the transition should be rather gradual. This map can be compared to the original soil map of the area (Figure 9.08) and a clear communality can be seen, but the lines in general used to demarcate soil groups in the soil survey map are clearly different. In comparing the two soil maps, the largest difference was that in the traditional approach, attention was given to the soils that seemed dominant on the 100 m x 100 m grid scale of investigation.

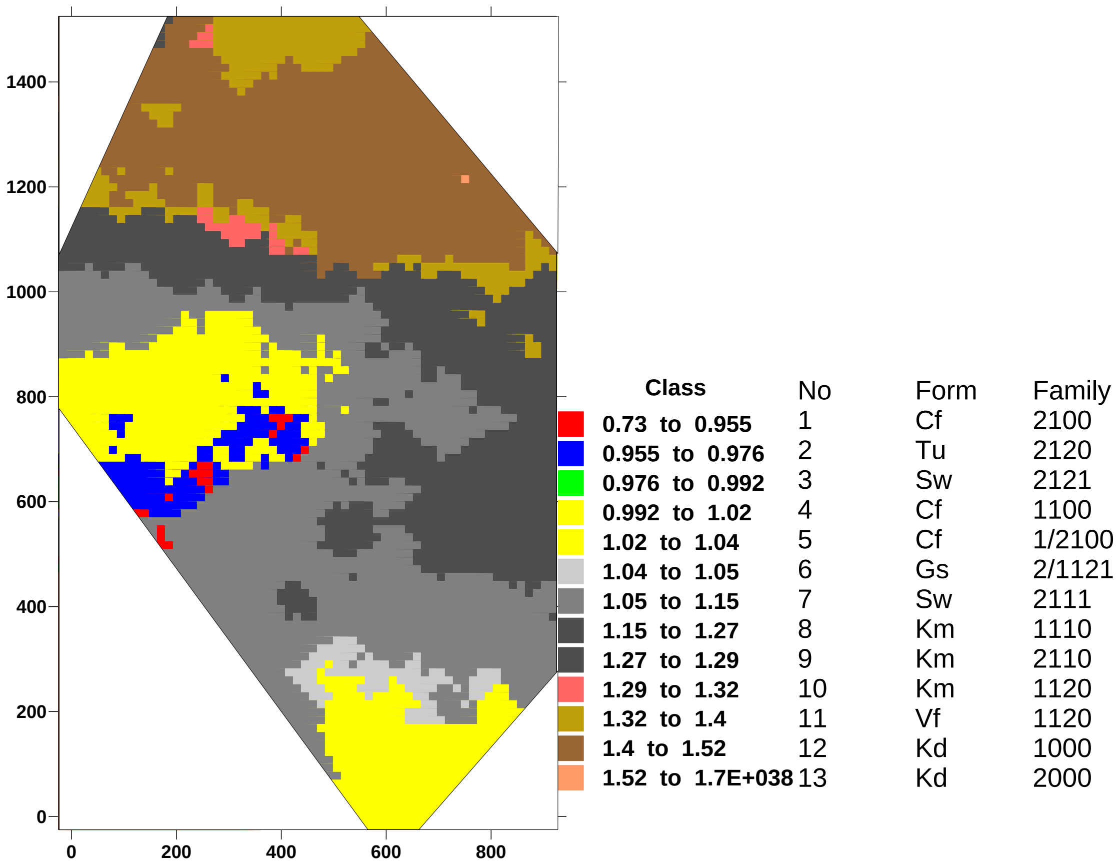


Figure 9.11 A soil map of the Glenrosa farm, based on the median PR values per soil form.

9.5 Conclusions

The EM38 measurements correlated well with a number of soil and landscape variables observed, like EC_e, Na^+, ER, pH, SAR, elevation and to an extent soil type. Soil mapping generally takes mainly elevation and slope properties in consideration since both influence the occurrences of different soil types in the landscape.

The EC_a and the PR maps showed a clear resemblance with the soil survey map based on soil types. It is clear that the EM38 measurements can be a very powerful tool in soil description and characterization. The results remain however to be interpreted by soil scientists and no quick recipe exists for applying the instrument outside its calibrated area.

Not all three EM variables (EC_a-V, EC_a-H and PR) compared equally well to various mapped realisations of soil properties, but all three can provide a useful input to improve soil maps since the variation in a number of soil variables are better presented in the higher resolution of the EM38 maps.

The combination of EM38 information and soil classification information can lead to better soil use maps at much lower survey effort.

10 CONCLUSIONS AND RECOMMENDATIONS

The objective of this final chapter is to highlight the main conclusions of the study, to discuss the extent to which key research questions have been answered and to consider the impact of the findings both in determining future research directions and in affecting the welfare of water users in the study area.

10.1 Recapping the background to the study

Salinity of soil and water in the Western Cape Province of South Africa (WC) is having an increasing impact on the lives of people in the region. A knowledge of how to manage salinity for the benefit of the whole population and the environment is very important. This research was initiated as a result of the foresight that prevailed prior to 1990 when water supply was planned to match the population growth and the expansion of industry and agriculture (Moolman *et al*., 1999).

Agricultural production in many parts of South Africa is not possible without irrigation. In the WC virtually the entire fruit and wine industries depend on irrigation. Agriculture is the largest consumer of water. In 1980 agriculture accounted for 52% of the total water use in South Africa (Dept. Water Affairs, 1986). Although it is expected to decrease to less than 50% in future, irrigated agriculture has remained to date the largest user of water. According to various reports published since 1975, the quality of South Africa's water resources, especially in relation to salinity, is steadily deteriorating (Stander, 1987). Alexander (1980) stated that "*there is no doubt that mineralisation (salinisation) is a serious problem in South Africa - and it can only get worse!*". This is especially true of rivers and storage dams situated in the WC (Fourie, 1976; Stander, 1987).

This research was carried out over an extended period. The saline irrigation experiments commenced in 1992. Most of the work has, however, been published since 2001 in the form of reports, conference proceedings and journal articles.

Based on the earlier indications of the salinity problem a number of commitments were made by water authorities and research bodies to gain and disseminate information that would facilitate water management in the WC. First and foremost, water of adequate quantity and quality had to be supplied to irrigation farmers. Secondly, information was needed concerning the salt tolerance of crops and the economic viability of products from saline environments. Thirdly, it became apparent that managing water successfully required reliable measurements as well as tools (appropriate methods and equipment, as well as models) to monitor, predict and extrapolate salinity data on a regional basis. It was within this framework that the study was carried out.

10.2 Answers to the various research questions

The research objectives of this dissertation were (Chapter 1):

- To investigate the sensitivity of grapevine (*vitis vinifera, L*), to the quality of irrigation water it receives.
- To establish soil water sampling (as opposed to laboratory estimation using a saturated paste) as a preferred basis for measuring the effect of saline irrigation on plants.

- To analyze, from the repetitive sampling of soil water, ways of predicting soil salinity profiles over time, using polynomials of the lowest possible order and to indicate the minimum amount information required to make such predictions.
- To optimize soil sampling positions in view of the fact that partial wetting of soil during irrigation is the norm within the study area. ,
- To explore the positive management aspects of partial wetting in terms of salt storage during the irrigation season.
- To assess and model long-term irrigation and the change in soil salinity on a regional scale and link this to regional sustainability of table grape production.
- To quantify the relationships between soil classification, soil electromagnetic induction measurements and topography as an improved basis for mapping soil salinity on a catchment scale.

In the following a brief overview of the degree to which these aims were met is provided:

It was shown that wine grapes are sensitive to saline irrigation, even under moderate levels of salinity, with a threshold EC_i of 100 mS m^{-1}.

It was indicated that taking soil water samples was beneficial over analysing soil samples, as these allowed better the investigation of the change in soil water salinity status over the growing season. The fact that these measurements could be done repeatedly in the same soil matrix (i.e. in an undisturbed way) proved to be very valuable.

By using polynomials in the prediction of EC_{sw}, it was found that in the study area the EC_{sw} could be predicted satisfactorily using a first order polynomial. Consequently, the minimum amount of information needed to characterize this trend in the soil profile, are only two EC_{sw} measurements taken at two depths.

It was indicated that the partial wetting of the soil also implied that soil sampling needs to focus on the wetting pattern of the soil. The sampling carried out for the study at the Broodkraal farm, took this into consideration and the result was that the local variation in soil salinity could be accounted for by using combined samples from a specific measuring point.

The partial wetting of soil caused the problem that salts tend to be managed only in the wetted volume. But it was shown that also in the non wetted zone the salinity rose during the irrigation season. This non-wetted zone acted as a salt store and was to an extent also flushed during winter by rain and winter irrigation. This situation opens the potential to use the soil as a salt store in a region where leaching of salts poses a problem.

The regional management and monitoring of salinity can be simplified by predicting the contribution of a site to the nearby river system in terms of the salt load lost from the soil profile. This allows to avoid the modelling of complex soil processes in an era and area with limited resources.

Traditionally the mapping of soils, and the occurrence of soil types, is linked to topography. Mobile non-invasive proximal soil sensors, like the EM38, allow the rapid mapping of salinity. A relationship between the degree of soil salinity and soil type in combination with topography could be identified in the study area. The EM38 results could be used to improve the soil map of this region, as the position of soil borders could be much more clearly indicated.

Based on these objectives and observations, a number of specific questions could be formulated, which are given below.

1. Has the problem area been adequately delineated?

The delineation of the soil salinity problem in the study area was achieved with specific emphasis on geographic location, geomorphology, geology, climate, water resources, soils, and land use. Consequently the salinity hazard in irrigated vineyards of SA has also been defined.

2. Has the principal agricultural crop been adequately evaluated in terms of its response to salinity?

After irrigating vines for 8 consecutive years with 6 grades of saline water, it was found that vines were influenced by saline irrigation water, even that with EC lower than 30 mS m^{-1}. A salinity tolerance threshold of 100 in place of the norm of 150 mS m^{-1} was recommended. The yield response could be defined for use by water regulators, and various aspects of plant and soil response to salinity were highlighted. A basis for calculating the potential impact of saline irrigation water on the economy was also established. Salinity was found to have a quantifiable effect on the quality of wine and the quantity of grapes that could be produced. Furthermore, saline water had a cumulative effect on the vines as the salts were found to be stored in the perennial parts of the plant and therefore had an effect on the following season’s yield.

Perhaps the most important finding of the research was that, while the threshold level of saline irrigation required to ensure sustainability remained the same over a number of years of irrigation, the sensitivity of the crop to levels beyond the threshold increased with the number of seasons of exposure.

As an economic indicator, wine quality was also found to be sensitive to saline irrigation. Water quality below 100 mS m^{-1} caused lower yields but slightly better wines. It was found that salinity could be adequately tested in the must, and need not be tested in the wine. Irrigation with saline water inevitably led to over-irrigation on the more saline plots because the vines used less water.

3. Can the measurement of salinity be standardised?

A close relationship was found between the EC_e and EC_i and an equally strong correlation was also found between EC_{sw} and EC_e that allowed the interaction to be explained. A strong relationship was similarly found between EC_i and EC_{sw}, explaining the EC_{sw} reaction to a specific EC_i. The combination of the two forms a basis whereby the best possible circumstances, when irrigating with saline water, can be predicted. Though the EC_{sw} results can be adequately converted to EC_e, there is still a hidden uncertainty in these results concerning the precise relationship between available and unavailable forms of salt in the soil.

A new suction cup lysimeter (SCL) system was designed and successfully implemented during years of field research. Our SCL had the advantage that it could be operated remotely. This allowed sampling at precisely planned times and provided added value in years of monitoring and managing soil salinity. Ease of use is the main characteristic of this system. The soil water samples could also supply information on the soil water content by merely recording the mass of the water sample. This system is fairly inexpensive and can supply more information than conventional SCLs. Since the system allows remote operation, a lot of time can be saved in acquiring soil water samples.

4. Was the salinity behaviour in soils adequately measured and to what extent can salinity be predicted? Can the salinity behaviour in soil over a landscape be predicted from a limited amount of point samples?

The focus was on the prediction of the depth trend in soil salinity within a vineyard after sustained irrigation with saline water. This study provided the opportunity to better understand the temporal and spatial variation of EC_{sw}. The classical trend surface analysis procedure of Davis (1986) provided an answer to the problem of finding a suitable depth relationship that could be used as a norm for the soil studied. This simplified the management of salt in the soil and the quantity and quality of return flow.

Prediction of the depth trend in EC_{sw} with a first order polynomial has distinct advantages. Over- or under-irrigation can easily be evaluated for any irrigated land. Prediction of salt accumulation on the soil surface or deep drainage can readily be assessed. The slope of the first order polynomial indicates directly the general trend and whether an accumulation or a depletion of salt can be expected in the soil. When linked to remote sensing, this approach could be used in evaluating extensive areas of land in terms of salinity and their suitability for irrigated crops. This research further showed that by knowing the date and irrigation water quality and being able to characterize the topsoil EC remotely, one can estimate subsoil salinity conditions in irrigated lands and further estimate the return-flow component from such irrigated lands.

In chapter 7, the variability of EC_e between vine rows was explored. The results clearly showed that the distribution of salts from under the irrigation emitters to a position mid-way between two vine rows, can be highly variable. The inter-row region was subjected to a salt build-up over the growing season and is not always leached by the irrigation. Factors such as density of the cover crop, partial wetting of the soil, the orientation of the vine rows, traffic in the vineyards and the quality of the irrigation water, all play a crucial role in the accumulation of salt in this part of the vineyard soil. This knowledge has important management implications for a saline environment.

5. Can the temporal effect of salinity in vineyards be captured and modelled on a regional basis? Can the regional salinity behaviour be predicted from less intensive data collection?

Both these questions were dealt with simultaneously. The effect of long term irrigation application on the variation of soil electrical conductivity in vineyards was investigated looking at soil sampling technique and time-space modelling. The investigated areas were under table grapes and were subjected to a rigorous irrigation program. The older sites had a lower salt content than the younger sites but the relative variability remained almost constant. So, the data proved that there is a general lowering of salinity in the landscape resulting from irrigation practices. By using a method of predicting change with time using icdf's, and by sampling the irrigation history from the 2nd year to the 5th year, the periods of most dramatic change have been captured. After the 5th year, the soil EC_e tends to be subjected to the irrigation water quality of the past season. The amount of salt removed from the profile over the study period showed a delayed effect in influencing the water quality of the river system.

Two aspects can be highlighted. Firstly, modelling of the temporal behaviour of soil salinity was approached in a unique manner that proved to be a good predictor, but rigorous proof will, however, require resampling after a period of time. Secondly, predicting the contribution of the site to the nearby river system in terms of the salt load lost from the soil profile, proved to be a valuable way of bypassing intricate soil process modelling in a context for which funds, the total land area and skilled labour shortages are limiting factors in addressing these problems.

The regional sustainability in table grape production on saline soils was investigated looking at EC_e and ER, soil pH, soil clay percentage and vine response. By using kriging, soil EC_e, pH, vine age and vigour could be predicted at a high resolution, generating a regional realization or trend. It was shown that modelling the regional trends, and their statistical comparison, produced good results and opened opportunities related to sustainability issues that were not afforded when using point data only. The predictability of the regional variation of EC_e in relation to pH, time and plant vigour could have an impact on the grape/wine industry of the Western Cape.

Over-irrigation, as a means of dealing with salinity in the landscape, did not result in a salt build-up. Gypsum was also used to improve infiltration and control the sodium build-up and this led to a reduced role played by clay content as a growth inhibitor.

Soil pH showed a significant relationship to the long-term, measured changes in trunk circumference of the vines. The EC_e of the upper part of the soil must be considered in the context of up to 10 mm evapotranspiration per day and very little rainfall; hence the dependence on irrigation. It can thus be expected that EC_e will be lowest in over-irrigated areas. In parts that receive less irrigation than the evaporative demand a build-up of salts will occur. In parts that receive no irrigation but that are near to the irrigated area the EC_e will soar. In sites where the soil pH is restricting growth, transpiration is reduced and therefore over-irrigation usually occurs, resulting in runoff and increased drainage that both augment return flow.

Perhaps the most important finding of the research was that vine age, EC_e and pH correlated weakly with trunk circumference. However, in combination, these variables generated an R^2 value of 66 %. The fact that 66 % of the variance was explained by vine age, EC_e and pH in combination, suggested that very little else influenced growth negatively in this environment.

The most important implications of these results are economic. This research showed that the methods applied here could enhance current knowledge in terms of the behaviour and sustainability of agricultural crops on a regional basis through a process that deals with spatial variation. This could increase profitability from these landscapes and it deals with very important water issues.

In Chapter 10, the soil salinity and soil type were characterized using the EM38 proximal soil sensor. The EM38 measurements correlated well with a number of soil and landscape variables. Soil survey generally takes mainly elevation and slope properties into consideration since both influence the occurrence of different soil types in the landscape. The data presented here show a significant correlation with EC_e, ER, pH, SAR, Na^+, elevation and to some extent soil type. From the maps presented, elevation, the PR and soil depth showed a similar pattern. All three of them, as well as the EC_a-V and EC_a-H maps, showed useful comparability with the hand drawn soil map.

It is clear that the EM38-derived maps can be a powerful tool in soil description and characterization. The results remain, however, to be interpreted by soil scientists and no quick recipe exists for applying the instrument outside its designed use. A fair knowledge of modelling semi-variance using geostatistical procedures is also required.

Not all three EM variables compared equally well to various mapped realisations of soil properties, but all three can provide a versatile input to better soil maps since the variation in a number of soil variables are better presented in the higher resolution of the EM38 maps.

The combination of EM38 information and soil classification information can lead to better soil maps with much less survey effort.

10.3 The impacts of the study

This research has contributed in a number of ways:

- A methodology for defining and dealing with salinity hazard has been defined.
- A methodology for prediction of salinity in the soil has been established. This has the advantage of allowing better management of salinity with fewer soil samples.
- A methodology for the economic evaluation of salinity in the study region has been established.
- Various prescriptive aspects for water managers have been described and defined.
- The regional and temporal change in soil salinity has been characterized and assessment methodology has been proposed.

Mapping salinity, i.e. profile salt distribution and regional distribution, brought greater insight into the estimation of salt quantities in the irrigated landscape. Various factors have been highlighted that contributed to the attenuation capacity of a soil. It has also been shown that soil salinity in irrigated landscapes is subject to the specific irrigation practice. The capacity of the soil to retain salts was shown to have a unique threshold value. Furthermore, the unique balance between salt accumulation and salt leaching has been demonstrated.

Methods of measuring soil salinity were discussed and the investigation revealed that measurements of the soil salinity status at field capacity were the most accurate basis for evaluating the state of soil salinity. A suction cup system was developed that allowed the simultaneous sampling of soil water over a large area and numerous treatments.

The Davis (1986) approach provided an answer to the problem of finding a suitable EC_{sw} depth relationship that could be used as a norm for this specific soil. This approach simplified management of salt in terms of both quantity and quality of return flow. This approach will also help to provide rapid assessment in regional soil salinity investigations in the future.

This thesis connects the factors known to influence salinity with ways of measuring salinity in the soil, the description of salinity changes over time, and the assessment of salinity on a regional basis.

Our ability to predict soil salinity patterns on a regional scale is made possible by adhering to simple rules developed in this study. A survey can be done by taking soil samples at only two depths in the profile. Alternatively, a survey can be conducted using an instrument such as the EM38 which can estimate salinity in the soil profile at two depths.

It was also indicated that topography, the occurrence of soil types and the occurrence of salinity in the Berg and Breede River landscapes are closely related. This knowledge can be used in management, in the sense that expansion of irrigated vineyards can be better controlled.

10.4 Future perspectives

This research indicated that irrigated land in the BRC and UBRC is generally close to the river system and closely linked to the river system. It focussed on a number of issues related to soil salinity and its apparent effect on the rivers. These results showed that it was possible that the irrigated areas originally had high salinity, but that after 3 years of irrigation these soils maintained a salt content consistent with the salinity of the irrigation water they received.

The need exists therefore to look wider in the region for situations and conditions that could affect the quality of the water in these rivers. The focus then shifts to dryland salinity as these changes in land use also brings about changes in the behaviour of ground water and the resultant migration of salt towards the river.

This research also indicated that a need exists to further map the irrigated landscapes and bring everything into a hydrological modelling perspective. Land use and soil type are important variables in hydrological modelling and this type of modelling could broaden the perspective and management principles for the region.

More effort needs to go into the detailed mapping of soil types. The possibility of using remote sensing to accomplish this is currently being debated among soil scientists. The study showed that using an instrument such as the EM38 could help in generating better soil maps, containing georeferenced information. This is one aspect of the research that will need further attention.

Land use changes are causing differential changes in the production of salinity that leads to a deterioration of the river systems. A study needs to be conducted where different land uses are compared with respect to their total effect on the environment. This should result in optimal agricultural practices that will minimise the damaging effect of saline seep and low quality return flow on both the rivers and the ecosystems which they drain.

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12 CURRICULUM-VITAE

PERSONAL INFORMATION

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List of previous employment

1984 to 1986	Department of Geography University of Stellenbosch	Research assistant
1987 to 1990	Department of Soil Science University of Stellenbosch	Junior researcher
1990 till now	Department of Soil Science University of Stellenbosch	Senior Researcher

Qualifications

- B.Sc. in Natural Sciences.
- Hons. B.Sc. Natural Sciences. Thesis: A water balance for vines under salt stress.
- M.Sc. Agricultural Sciences (Soil Science). Title: Leaf area changes and transpiration in vineyards under salt stress.

As researcher at the Stellenbosch University, I was supervisor to a large number of students from several departments.

My experience spans a range of field techniques and monitoring systems regarding soils, plants, climate and water.

My position as researcher and my involvement in large research projects taught me to work in a team. My dedication generated research funding for the department of about an average of R400000 per year since 1987.

My experience as researcher is therefore best described by the general topics of the research and training I have been involved in.

- An evaluation of a range of computer models simulating the transport of solutes and water in the root zone of irrigated soils.
- An evaluation of the abilities of several root zone solute and water transport models to adequately predict quantity and quality of water leaving the root zone.
- The use of saline water for irrigation of grapevines and the development of crop salt tolerance indices.
- A pilot study to investigate alternative management options to enhance the use of saline water for vineyard irrigation purposes.
- Establishing the effects of saline irrigation water and managerial options on soil properties and plant performance.
- Water quality information systems for integrated water resource management: The Riviersonderend-Berg River system.
- A pilot study investigating the role of dryland salinity in the quality of the water of the Berg River.

- Leaf area changes and transpiration of vines under salt stress.
- Dryland salinity impacts on Western Cape Rivers.
- Characterization, mapping and modelling dust around opencast gypsum mines of the Northern Cape.
- Mapping (3D) soil salinity in the Western Cape.
- Experience and training in GIS (Idrisi, ArcView, ArcGIS, Surfer).
- Experience and training in Geostatistics.

During the time of this study, I was working as a full time researcher at the Stellenbosch University in South Africa, and a number of activities from this research were logged below. They include a patent, some published articles, reports and conference proceedings.

PUBLICATIONS.

Books

de Clercq, W.P., Ellis, F., Fey, M.V., Van Meirvenne, M., Engelbrecht, H., de Smet, G., 2006. Water and soil quality information for integrated water resource management: Berg River Catchment. WRC Report, TT252/06, (ISBN No. 1770053662)

de Clercq, W.P., Fey, M.V., Moolman, J.H., Wessels, W.P.J., Eigenhuis, B., Hoffman, E., 2001. Experimental irrigation of vineyards with saline water. WRC Reports, 522/1/01, (ISBN No. 1868457753)

de Clercq, W.P., Fey, M.V., Moolman, J.H., Wessels, W.P.J., Eigenhuis, B., Hoffman, E., 2001. Establishing the effects of saline irrigation water and managerial options on soil properties and plant performance. WRC Report, 695/1/01, (ISBN No. 1868457753)

Fey, M.V. de Clercq, W.P., 2004. A pilot study investigating the role of dryland salinity in the quality of the water of the Berg River. WRC Report, 1342/1/04 (ISBN No. 1770053059)

Görgens, A.H.M.; de Clercq, W.P., (eds), 2006. Summary of Water Quality Information System and soil quality studies: Research on Berg River water management. WRC Report: TT252/06, (ISBN No. 1770053670)

Jovanovic, N.Z., Bugan, R.D.H., Frantz, G., de Clercq, W. & Fey, M., 2008. Hydrosalinity fluxes in a small scale catchment of the Berg River (South Africa). In: D. Prats Rico, C.A. Brebbia, Y. Villacampa Esteve (eds.) Water Pollution IX, 603-612. ISBN 978-1-84564-115-3, Wit Press, Southampton, UK.

de Clercq, W.P., Jovanovic, N., Fey, M., (Eds). 2008. Research on Berg River water management. WRC Report, (in press)

International journal articles – ISI-listed journals

de Clercq, W.P., Van Meirvenne, M., 2005. Effect of long term irrigation application on the variation of soil electrical conductivity in vineyards. *Geoderma* 128, 221-233. IF=1.898

de Clercq, W.P., Van Meirvenne, M., Fey, M.V., 2008. Prediction of the depth trend in soil salinity of a vineyard after sustained irrigation with saline water. *Agricultural Water Managment*. In press, doi:10.1016/j.agwat.2008.09.002. IF=1.388

International journal articles

de Clercq, W.P., Van Meirvenne, M., 2005. Regional sustainability in table grape production on saline soils. *South African Journal of Plant Soil*, 23, 2, 113-119.

National journal articles

de Clercq, W.P., 2004. The application of soil electromagnetic induction techniques in aid of soil mapping. Winelands, South Africa

Fey, M.V., de Clercq, W.P., 2004: Die Bergrivier brak probleem. Landbouweekblad, Januarie 2004.

de Clercq, W.P., Kunneke, A., 2007. A protocol for precise mapping of scientific data. PositionIT, South Africa.

Contributions to conferences

de Clercq, W.P, De Smet, G., Van Meirvenne, M., 2001. Mapping of soil salinisation in an irrigated vineyard in South Africa. Workshop on Bilateral (Belgium/South Africa) Workshop on Cartographic modelling and land degradation. Gent, Belgium 2001.

Mongwe, H.G., Rozanov, A., de Clercq, W.P., Fey, M.V. 2002. Methodological aspects of soil organic carbon stock estimation in the Indigenous Forests, Grasslands, Wetlands and Pine Plantations of the Woodbush forestry. In: Proceedings of the 3rd Natural Forests and Woodlands Symposium, Berg-en-Dal

de Clercq, W.P., Van Meirvenne, M., 2003. Effect of long-term irrigation application on the variation of soil electrical conductivity in vineyards. Pedometrics conference, Reading, England (September 2003)

Engelbrecht, H.N., de Clercq, W.P., 2003: A soil irrigation suitability study for the lower Berg River catchment. SSSA Congess, Stellenbosch

de Clercq, W.P., 2004. Remote sensing and spatial description of landscape salinity. WRC workshop. Riebeeck West. 31/8/2004

de Clercq, W.P., 2004. Remote sensing and spatial description of landscape salinity. WRC workshop. Riebeeck West. 31/8/2004

de Clercq, W.P., 2004. Geostatistical Interpretation of point information. Precision Forestry Workshop. Pietermaritzburg. June 2004.

Du Plessis, H.M., Annandale, J.G., de Clercq, W.P., & Fey, M.V., 2004. The Use of Poor Quality Water for Irrigation – the South African Experience. Published proceedings of the ICID, Moscow workshop. September 2004.

Fey, M. V., de Clercq, W. P., 2004. More effects of wheat farming on water quality in a salty landscape: the Berg River basin in South Africa. Eurosoil 2004, Freiburg, Germany. p. 134.

de Clercq, W.P., 2005. Seasonal soil salinity/sodicity dynamics in a vineyard that was subjected to saline irrigation. water . SSSA Conference, Stellenbosch, 2003

de Clercq, W.P., Van Meirvenne, M., 2006. Predicting the change in soil electrical conductivity related to irrigation. SSS of SA conference, Durban, 2006.

Kunneke, A., de Clercq, W.P., 2006. Advanced techniques of measuring and mapping the impact of harvesting operations on forest soils. International Precision forestry conference, Stellenbosch (2006).

de Clercq, W.P., Helmschrot, J., Fey, M.V., Flügel, W.A., Krause, P., 2007: A scale integrated hydrological approach to redefine dryland salinity behaviour in South Africa. Annual Meeting of the Africa group of German Geoscientists (AdG), 6./7. July 2007, Potsdam, Germany.

Patents

A patent (Automated suction-cup-lysimeters) registered in South Africa in my name by the University of Stellenbosch.

Awards

During the 1993 Soil Science Society of South Africa conference (Joint conference with the Agronomy Society and Pomological Society), I received the joint society's medal for best poster. The title was: An automated sample retrieval system for soil water samplers.

Jointly won silver medal for best poster in the junior category at the 2003/01 joint SSSA congress at Stellenbosch for: HN Engelbrecht, and WP de Clercq, (2003): A soil irrigation suitability study for the lower Berg River catchment. SSSA Congress, Stellenbosch.