RESEARCH ON BERG RIVER WATER MANAGEMENT

VOLUME 3

WATER AND SOIL QUALITY INFORMATION FOR INTEGRATED WATER RESOURCE MANAGEMENT: BERG RIVER CATCHMENT

By

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EXECUTIVE SUMMARY
VOLUME 3

INTRODUCTION

The Riviersonderend-Berg River (RSE-BR) system supplies about 80 percent of the water available to Greater Cape Town. A variety of expansion schemes are proposed to meet the growing needs of its water users. Both the expansion to existing irrigation schemes and the development of new schemes are likely, resulting in the extraction of 20% more water from the RSE-BR system.

These developments may exacerbate moderately high salinity levels in the middle-lower Berg River. Firstly, as a result of the removal of more fresh water from the river, its salinity can be expected to rise. Secondly, increased irrigation of the naturally saline soils of the river basin can be expected to mobilize residual salts, and the resulting saline drainage water may contribute to higher salinity in the RSE-BR. However, the importance of the latter process to the future quality of water in the system is unclear.

This study aims to help us understand the influence of irrigated agriculture on salinization of river water in the RSE-BR system. A better understanding of this aspect of water quality will allow improved management of the system and more accurate prediction of the outcome of expanded irrigation in the system's catchment area.

OBJECTIVES

The goal of this component of the project was to develop a sufficient understanding of irrigated soils in the RSE-BR system catchments to be able to:

1) Predict the quality and volume of irrigation drainage from various soil types, and
2) Assess the suitability of soils for irrigation, with regard to their potential to pose a salinity hazard to the RSE-BR system.

The study consisted of two tasks:

Task 1:Plot-scale fieldwork : The objective of the plot-scale field work was to assess the respective salt mobilisation rates and irrigation return-flow processes in two sets of irrigated plots on Malmesbury shale-derived soils, over three irrigation seasons. One set of plots represented a newly-established irrigation scheme and the other land which had long history of irrigated agriculture. Each set was to consist of at least two different irrigation treatments, typical of local practice. Irrigation application rates were to be measured and resultant return-flows gauged and sampled in artificial drain outflows. These drains would be installed at the interface of the soil and the weathered shale layer above the bedrock. Nutrient levels (phosphate and nitrate concentrations) in the drain outflow would also be measured. Soil water content was to be monitored using a neutron probe. Samples of soil water, for salinity measurement, would be collected using soil water extractors. Groundwater observation holes were to be drilled and, if possible, existing boreholes converted to allow monitoring of groundwater level and salinity changes. Estimates of potential evapotranspiration would be made by measuring a set of meteorological variables using an existing automatic recording weather station, strategically placed relative to the two sets of plots. At the end of each season, the data were to be analysed statistically and interpreted to provide input to the other tasks in related projects.

Task 2: Develop generic methods for salinity hazard assessment : The project was to make use of the GIS infrastructure of the DA's Winter Rainfall Region Office at Elsenburg, as well as soil maps, data and the expert knowledge held by this office to develop generic methods for salinity hazard assessment using soils maps, GIS techniques, salinity data from monitored tributaries and the findings of the plot-scale studies described above. The methods developed for salinity hazard assessment were to be demonstrated by identifying zones along the Berg River and its primary tributaries where irrigation may result in a significant increase in downstream salinity.

METHODS

Task 1: Plot-scale fieldwork

The study of irrigation return flow was carried out at two sites, Broodkraal and Rooihoogte, currently hosting vineyards under micro-irrigation. Comprehensive data sets of irrigation and rainfall quantities, weather conditions, drainage water volumes and drainage and irrigation water salinity and ionic composition were collected, over a period of 18 months. Soil moisture measurements were also made on a regular basis.

Samples of soil water were collected from several points on the plots, at the beginning, middle and end of the irrigation season, using suction cup lysimeters to sample the soil solution at shallow, intermediate and deep locations in the soil profile. After making a number of simplifying assumptions, the data were used to model predicted drainage volumes and salt export from the land under irrigation.

A programme of soil sampling was designed with the aim of applying geostatistical methods to describe soil salinity variability. Samples of soil were collected from each plot at the start and end of the experiment, using a 45 m by 50.5 m grid pattern to define sampling positions. In addition, a number of samples (4 x 17) were taken within grid rectangles to allow the statistical description of inter-sample variability. The EC, ER, pH, clay percentage, stone percentage, density and field capacity of these samples was measured.

In addition, the contribution of *heuweltjies* (relict termite mounds) to dryland salinity and the potential consequences of irrigation schemes on lands with high *heuweltjie* density was investigated on areas of the farms currently used for dryland wheat cultivation. Deep (4 m) trenches were excavated into the mounds and inter-mound regions, using a mechanical shovel. The exposed soil profiles were mapped and classified, and soil samples were collected for determination of their pH, ER and exchangeable and soluble cation concentrations.

Task 2: Developing generic methods for salinity hazard assessment

The geostatistical approach revealed a lot of new information. The large spatial variability was dealt with sufficiently and this in itself limited the representativity of samples. The maximum spatial dependence ranged between 45 and 100 m. this result placed a large question mark behind using historic data that is not space and time correlated. Methods were defined with which rapid salinity assessment can be made over large areas.

A GIS-based, 1:50 000 scale map of the soils in the Berg River catchment was compiled by means of field mapping and reference to existing maps and information. Particular attention was paid to areas with potential for new irrigation development. This map was used to produce a crop suitability map and salinity hazard map of the catchment's soils to indicate the change in return-flow hazard when agricultural practice are altered.

SUMMARY OF RESULTS AND CONCLUSIONS

The detailed studies at Broodkraal and Rooihoogte allowed us to compile a comprehensive climate database for the farms. This has been used to calculate actual evapotranspiration for the sites (e.g. Figure 1.1), which is a necessary input for our irrigation return flow model.

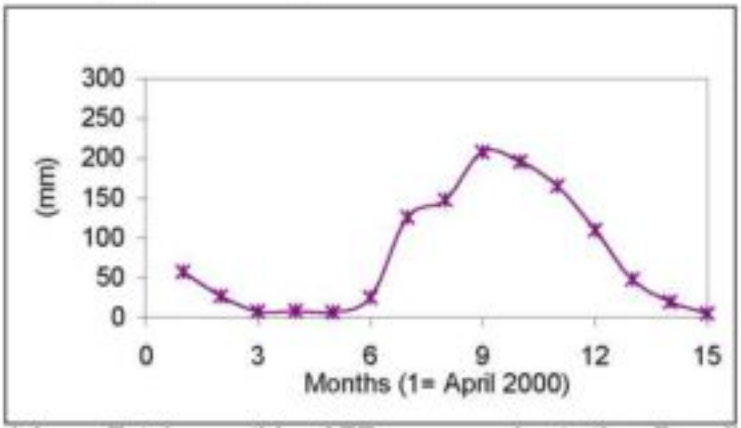

Figure 1.1 : Total monthly AET measured at the Broodkraal Farm using published crop factors for this region

Soil mapping at the sites produced soil maps of suitable resolution. Monitoring of soil water and drainage water quality showed, in the case of Broodkraal, that drainage water salinity generally increased throughout the irrigation season, with a slight decrease in average salinity of soil water as one moves from higher to lower elevations. However, soil water quality showed considerable variation with time (Table 1.1).

Table 1.1: Analytical results of soil water samples taken from position B on the Broodkraal Farm sampled with suction cup lysimeters

Date	Depth	EC	Ca	Mg	Na	K	Total. cations	Cl	NO3	SO4
	(cm)	(mS/m)	(mg/L)							
00.11.29	**20**	180.6	17.8	9.9	98.4	4.1	130.2	192.3		34.8
00.11.29	**40**	114.7	34.4	13.6	141.5	21.0	210.5	317.2	8.5	73.2
00.11.29	**75**	73.2	55.3	24.7	233.2	9.5	322.7			
00.12.07	**20**	153.3	45.8	21.9	195.7	4.0	267.5	328.7	57.4	145.8
00.12.07	**40**	126.8	38.4	15.4	150.0	5.2	208.9	314.8	28.8	88.4
00.12.07	**75**	82.5	19.3	11.6	94.8	4.2	129.8			
00.12.19	**20**	133.5	49.2	22.1	163.2	3.9	238.4	243.1	150.5	91.9
00.12.19	**40**	116.8	37.1	15.2	150.7	3.8	206.8	304.9	22.2	74.5
00.12.19	**75**	74.4	16.7	10.0	94.0	4.3	125.0			
01.01.11	**20**	83.7	27.4	12.8	96.5	3.3	140.0			
01.01.11	**40**	121.3	71.0	123.4	584.4	19.8	798.5	1084.1	8.1	767.5
01.01.11	**75**	90.5	16.8	11.4	110.8	0.0	139.0			
01.01.30	**20**	124.9	42.8	19.8	133.9	4.7	201.2	337.7	2.1	47.5
01.01.30	**40**	169.2	55.1	23.3	203.5	4.0	285.9	516.8	2.2	85.4
01.01.30	**75**	135.5	28.7	18.8	164.5	3.4	215.4	402.3		58.8
01.02.20	**20**	124.0	44.4	21.2	145.6	3.5	214.7	399.1		57.4
01.02.20	**40**	176.4	60.4	25.8	223.0	5.0	314.1			

The relationship between the electrical conductivity of saturated paste extracts (EC_e) and soil water (EC_{sw}) is not simple. EC_{sw} is generally higher that EC_e, but more so at greater soil depths. At Rooihoogte, EC_e of irrigated, deeply-prepared vineyard soils was lower than that of shallowly prepared soils used for dryland wheat farming (Table 1.2).

Table 1.2 : Depth-weighted mean values for pH, EC_e and total dissolved solids (TDS) in vineyards and wheat lands

	pH	EC_e (mSm^{-1}) Sat. extract	TDS (mg/L)	TDS (ton/ha)
Deep cultivated soils Sample taken between rows	7.26	148.8	952	11.4
Deep cultivated soils Sample taken in vine row	7.00	93.8	600	7.2
Shallow cultivated soils (wheat)	5.66	274.8	1758	21.1

The irrigated soils drain rapidly after irrigation (Figures 1.2 and 1.3).

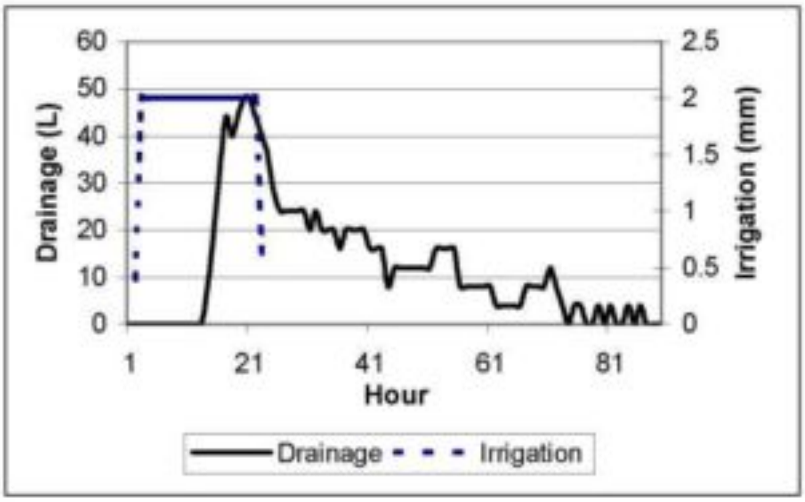

Figure 1.2 : **Drainage response to an irrigation event at Broodkraal Farm**

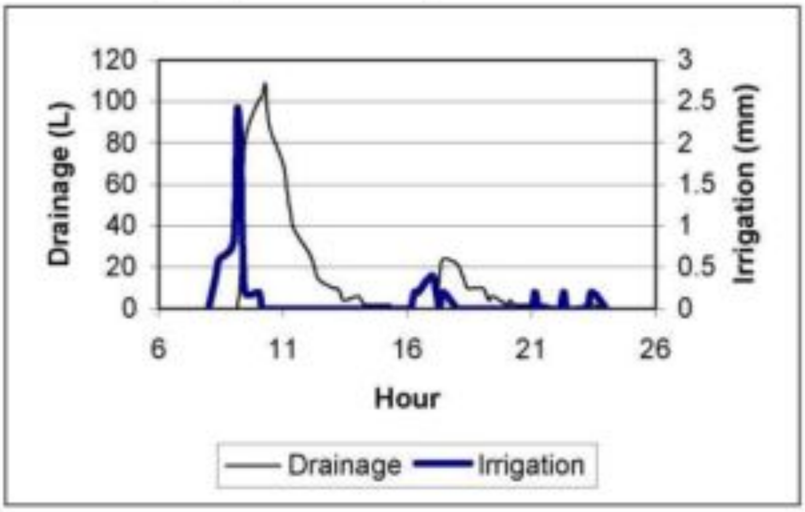

Figure 1.3 : **Drainage response to irrigation in a vineyard on the farm Rooihoogte**

A simple mass balance model was used to predict drainage volume for each soil-water sampling position at Broodkraal (Figure 1.4).

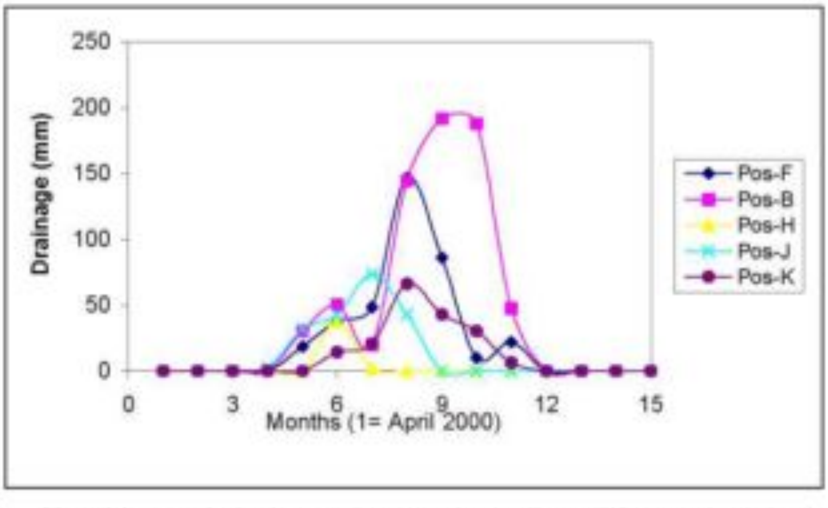

Figure 1.4 : **Monthly total drainage in mm from five different locations on Broodkraal Farm**

Average electrical conductivity ranged between 200 mSm^{-1} and 550 mSm^{-1}. Based on the modelled drainage volumes (Figure 1.4), and assuming a reasonable average salinity, it was possible to model net salt export from irrigated land at Broodkraal (Figure 1.5).

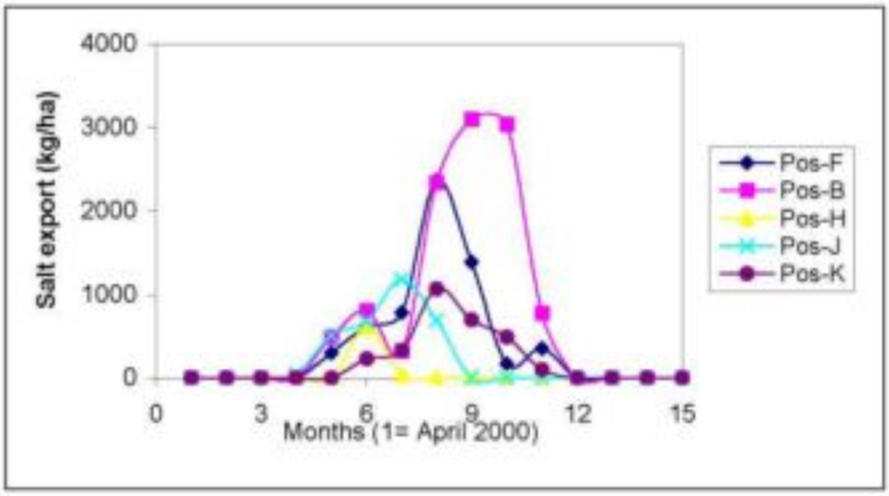

Figure 1.5 : Predicted monthly return flow given as total amount of salt in kg/ha based on a fixed yearly average EC_{sw} of 256 mSm^{-1} below the root zone at 5 sites on the Broodkraal Farm

There is a clear distinction between soils of the Oakleaf and Glenrosa forms with respect to their salinity. The latter sustain higher EC_e values than the former over time in established, irrigated vineyard soils (Figure 1.6).

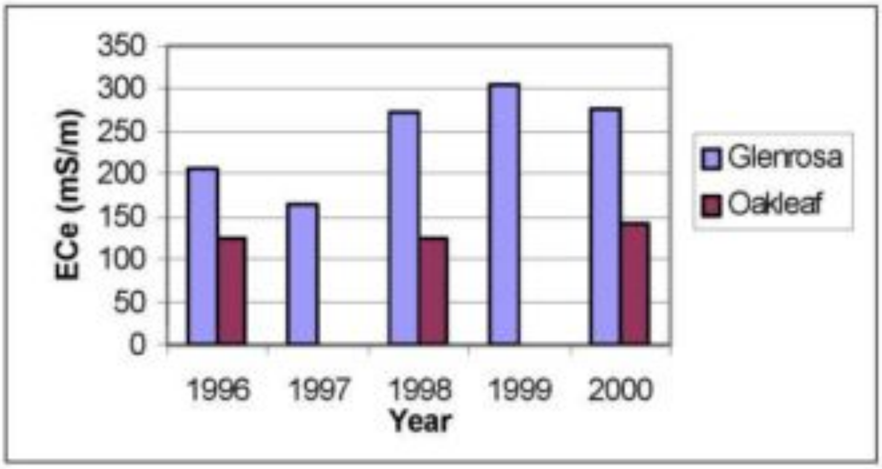

Figure 1.6 : The mean of 4 depth-weighted mean EC_e samples per site from irrigated vineyards. 'Year' refers to year of planting

The study at Rooihoogte of dryland salinity and the role of *heuweltjies* revealed that these termite mounds have a higher base status, pH and salinity than inter-mound areas. In addition, the saprolitic subsoil associated with inter-mound areas also has a relatively high salinity. Prediction of the salinity hazard of future irrigation schemes on *heuweltjie*-pocked soils must take into account the variability in soil chemistry associated with these structures.

A highly significant correlation was found between the stone content of the soil and the SAR on Broodkraal. This suggest that patches of high stone content in the soil constitute preferential flow paths resulting in zones with higher leaching and therefore a lower SAR. Alternatively the stone fragments may constitute a reservoir of the weatherable bases besides Na.

Geostatistical methods proved useful in describing the spatial variation in soil salinity at Broodkraal (Figure 1.7).

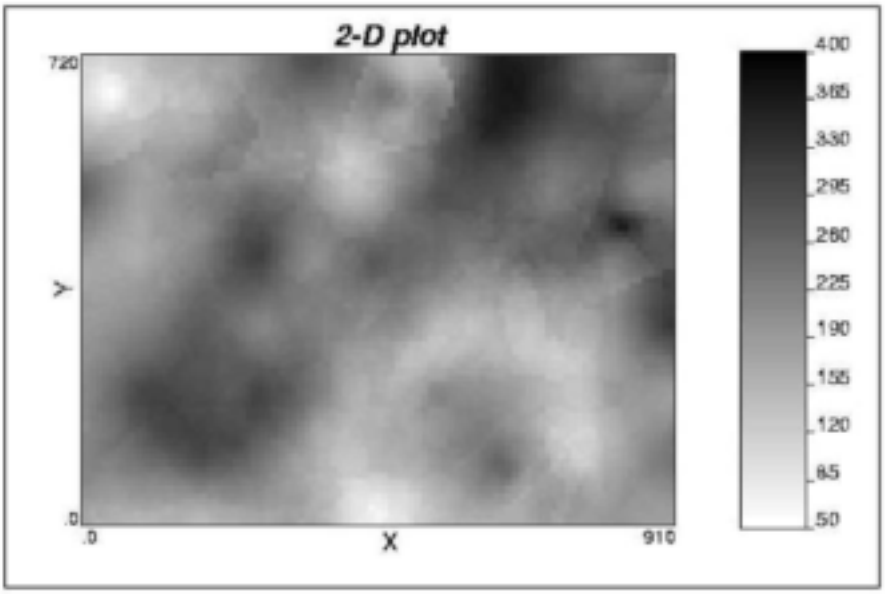

Figure 1.7 : Map of spacial variation in EC_e of Broodkraal produced by Co-Kriging, indicated in metric distance

The lighter coloured areas in Figure 1.7 represent a lower salinity, which is associated with upland areas. This statistical description of the data corresponds with field observation.

Two maps were compiled for the Berg River catchment namely a soils map and a salinity hazard map.

Using old data and newly acquired soil salinity data to predict soil EC change over time, proved to be of little use. The old data weren't geo-referenced. This meant that a number of samples had to be taken in the vicinity of the old sampling positions. Comparing the newly acquired data with the old, variation in the soil proved to be larger between new samples than the possible change over time they were meant to constitute.

MEETING THE RESEARCH OBJECTIVES

Task 1: The objectives of Task 1 were met. However, when this task was formulated, the assumption that the long irrigation history of the catchment would provide new research frontiers was mistaken, as was the view that irrigated agriculture is the dominant contributor of salt to the Berg River. The influence of irrigated agriculture when monitored beneath the root zone could not easily be estimated. When irrigation return flow mixes with the groundwater, the quality becomes unpredictable.

Task 2: The objectives of this task were fully met with respect to the development of generic methods for salinity hazard assessment related to irrigation agriculture. Two factors however prevented application of the methods in sections of the BRC :

1. Two key personnel at the DA's Winter Rainfall Region Office at Elsenburg, resigned during the course of the project, making interpretation work impossible.
2. Modelling of saline seep from dryland areas was impossible, as no approach to do this had been formulated.

Irrigation return flow and saline seep from dryland areas enter the river as a mixture. Surface runoff of salts from wheat lands at the onset of winter rains would constitute an additional source of salts not readily amenable to quantification.

RECOMMENDATIONS FOR FUTURE RESEARCH

As a result of this study a number of pressing research needs have been identified. They are as follows:

There was an attempt in this study to identify the origin of the salts found in the soils of the region. A definite salinity recharge effect was picked up in soils that had remained allow for a number of years. Research needs to be done on the mechanism of this apparent recharge.

The dryland-farming areas of the catchment possibly contribute substantially more salt through cultivation than is currently the case with irrigated agriculture. This needs to be monitored.

The salinity database for the Berg River Catchment needs to be expanded. This must be combined with appropriate data on land-use and topographical features. A new pilot project (K5/1342) has been initiated that will address the problem of quantifying the contribution by dryland salinity to water quality in the BRC.

CAPACITY-BUILDING

Human Resource Development: The following persons from the Designated Group worked on the Project as Laboratory Assistants:

- Ms Kamilla Latief
- Mr Kenneth Davidse

On each of the farms, Rooihoogte and Broodkraal, a local employee from the Designated Group was trained by the Department of Soil Science researchers to do soil moisture readings with both the neutron probe and tensiometers, and also to take and preserve water samples.

Collaboration with Technikons : Mr Pieter Basson, a final year Technikon student in Civil Engineering, worked full-time on this project for a year to meet the Technikon requirements for full-time in-service training.

Technology Transfer: On 28 August 2001 three seminars were held on the farm Rooihoogte:

- *Besproeingsgronde langs Berg Rivier met klem op Rooihoogte en Broodkraal plase*, by Freddie Ellis.
- *Sout voorkoms in besproeiingsgronde van Broodkraal en Rooihoogte*, by Hendrik Engelbrecht
- *Die omvang van brak, bestuur daarvan en die toekoms*, by Willem De Clercq.

The following papers were presented at the Cartographic Modelling and Land Degradation Workshop, Gent, Belgium, 24-25 September 2001:

- *Mapping soil salinisation in an irrigated vineyard in South Africa*, by W De Clercq, G de Smet and M van Meirvenne.
- *Land degradation on old land surfaces affected by termite activity in arid and semi-arid regions of South Africa*, by F Ellis.

Rural Community Interaction: Discussions about this project have been held with representatives of the Saron and Wittewater (at Moravia) communities in the Middle to Lower Berg River catchment.

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WATER AND SOIL QUALITY INFORMATION FOR INTEGRATED WATER RESOURCES MANAGEMENT : THE RIVIERSONDEREND - BERG RIVER SYSTEMS

The Steering Committee responsible for this project consisted of the following persons :

Mr HM du Plessis	Water Research Commission (Chairman)
Dr GC Green	Water Research Commission
Mr OCE Hempel	Water Research Commission (Committee Secretary)
Prof AHM Görgens	University of Stellenbosch
Prof A Rooseboom	University of Stellenbosch
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Mr AS Roux	PAWC : Department of Agriculture
Mr P van Niekerk	PAWC : Department of Agriculture
Mr F Knight	PAWC : Department of Agriculture
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Mr G McConkey	Department of Water Affairs and Forestry
Prof HD van Schalkwyk	University of the Free State

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LIST OF ABBREVIATIONS

A	The Range (semi-variogram)
AET	Actual Evapotranspiration
afm	Salts contributed through fertilisers and soil amendments
C	Concentration
C_0	Nugget (semi-variogram)
C_d	EC ($mS.m^{-1}$) x 6.3 ($mg.L^{-1}$)
CF	Crop factor for every month and specific for crop,
C_o+C_1	Sill (semi-variogram)
d	Drainage
DISA	Daily irrigation and systems analysis model
dp	the salt mass leaching to groundwater
DWAF	Department of Water Affairs and Forestry
ECe	Electrical conductivity of the soil water saturation extract.
ECi	Electrical conductivity of the irrigation water
EC_{ih}	Half the electrical conductivity of the irrigation water
EC_{iw}	Electrical conductivity of the irrigation water
EC_t	Electrical conductivity of the
ET	Evapotranspiration
ET_o	Calculated A-pan evaporation for grass.
FC	Field capacity per profile depth (mm)
GCT	Greater Cape Town
h	The lag (distance in semi-variogram)
hc	The harvest salt removal
i	Irrigation
iwr	Salt removal by irrigation water
M	Mass
M_d =	Mass of salts leached in $kg.ha^{-1}$
$mS\ m^{-1}$	Milli Siemens per meter - measure of salinity
pr	Salt removal by rain
Q_d =	Volume leached (mm)
Q_i =	Volume irrigated according to water meters (m^3) and irrigated area (m^2)
Q_p	Depth of rainfall (mm)
Q_r	Depth of runoff (mm)
RSE-BR	Reviersonderend-Berg River
RY	Relative Yield
SAR	Sodium Absorption Ratio
sd	Precipitation and dissolution of salt
SMC	Soil moisture content per profile depth (mm)
sp	The harvest salt removal
TC	Trunk Circumference
TWK	Teewaterkloof Dam
TX	Mean daily maximum temperature. (ºC)
V	Volume
WQIS	Water Quality Information System
TX	Mean daily maximum temperature. (ºC)
TN	Mean daily minimum temperature. (ºC)
HXX	Highest observed daily maximum temperature. (ºC)
UX	Mean daily maximum relative humidity. (ºC)
UN	Mean daily minimum relative humidity. (%)
R	Mean monthly total precipitation. (mm/month)
W	Mean daily wind-run. (km/day)

CHAPTER ONE
GENERAL INTRODUCTION

The combined catchments of the Riviersonderend-Berg River (RSE-BR) system contribute more than 80% of the total annual water yield of 450 million m^3 available to the bulk water supply system of the Greater Cape Town (GCT) region. The RSE-BR system comprises the Theewaterskloof (TWK) Dam on the RSE River, linked by tunnel to the Berg and Eerste River catchments, and the Wemmershoek and Voëlvlei Dams, both of which are on the Berg River. Sustained growth in water demand of the GCT region will necessitate expansion of the RSE-BR system in the near future. The following schemes are being investigated for imminent implementation: Skuifraam Dam in the upper Berg, Skuifraam Supplementary Pump Scheme downstream of Franschhoek, and the Lorelei Diversion to an enlarged Voëlvlei Dam in the middle Berg. Apart from supplying Cape Town, these schemes will also serve the Reconstruction and Development Programme (RDP) in that they will stimulate the development of a number of communities in the Berg catchment through the establishment of new irrigation schemes. Extensions to existing irrigation schemes will also be possible. The implementation of these schemes will however remove an additional 20% of fresh water from the Berg River and will require a strongly regulated river system between Skuifraam and Misverstand. The likelihood of these developments has sparked three serious concerns relating to water quality and ecological deterioration (DWAF, 1997).

Firstly, the already moderately high salinity in the middle to lower Berg system may be exacerbated through loss of fresh water from the river. The planned irrigation extensions are predominantly on Malmesbury Shale-derived soils, the return-flows from which can be expected to mobilise residual salts of marine origin (Fourie, 1976). Current understanding of salinisation of irrigation return-flows does not allow prediction of whether or not the salt mobilising effects of irrigation on "new" land will be short-lived or long-term (Greeff, 1983). This paucity of knowledge implies a need for detailed field-level monitoring of newly irrigated, shale-derived soils over a number of seasons. For planning and management purposes, information from fieldwork should be spatially linked to knowledge-based interpretation of soil maps of the catchments, to assist in the identification of potential salinity hazard zones where new irrigation development should be restricted.

Secondly, nutrient levels in the middle Berg River may be rising due to an increase in the volume of treated wastewater discharged into the river, and an increase in non-point source loadings related to dry-land and irrigated agriculture. The Lorelei Diversion scheme to augment Voëlvlei may therefore raise the hazard of eutrophication in Voëlvlei. Eutrophication prospects in the Misverstand region may also be worsening. It was until recently not possible to fully understand the nutrient balance of the RSE-BR system, because the only available data were derived from infrequent grab samples taken as part of DWAF's national monitoring programme. There is therefore a need to implement a sampling and source assessment programme including modelling nutrient sources, transport and balance in the system.

Thirdly, there are ecological concerns related to the regulated character of the flow regime. Water released from dams to meet high summer irrigation demands, resulting in flows atypical of a winter rainfall regime, may have unacceptably low temperatures (and possibly low oxygen levels) due to stratification of Skuifraam and Voëlvlei Dams. Apart from such water quality concerns, pre-implementation research is needed to optimise the operation of all the impoundments and diversion points to meet the volumetric In-Stream Flow Requirements (IFR) of the river system, of the wetlands near the Berg River Mouth and of the tidal zone of the estuary. These two sets of ecological concerns regarding river regulation can usefully be investigated via intensive monitoring of ambient temperature and oxygen levels at selected sites to provide baseline data, followed by prediction of post-implementation conditions at those sites for different operating scenarios.

So as to be useful in the planning, management and operation of the RSE-BR system, information from the three monitoring programmes proposed above should be integrated with the historical water quality database, and with land use and soils data, into a Water Quality Information System (WQIS). In addition, an appropriate model, linked with the WQIS, should be established to simulate water quality and flow in the reservoir-river system, for planning and operational scenario analysis. Prototype development of catchment information systems has been taking place elsewhere in South Africa, such as AQCES by DWAF's Institute for Water Quality Studies (IWQS) (Cobban, 1996), or the ICIS developed under the Kruger National Park Rivers Research Programme (Jewitt and Görgens, 1995). Though they were developed in different contexts, the central role of these catchment information systems should be to enhance our ability to understand and manage catchments. The necessity for sound management of the RSE-BR system presents an opportunity to develop an effective information system for the catchment.

An important principle of Integrated Catchment Management is that it cannot be sustainable without the commitment and the participation of the stakeholders and the communities in a catchment. This principle applies equally to water quality management. On these grounds it is necessary to promote an understanding of the importance of water quality management among the communities, water users and stakeholders in a catchment. This need has both an educational and a technology transfer component, and the capacity to meet this need is still limited in the Western Cape and requires further development.

1.1 BACKGROUND

The mean annual precipitation for South Africa is about 480 mm with a runoff coefficient of only 9% (DWAF, 1986). It follows that sustained food production in many parts of South Africa is only possible with irrigation. 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). Although this figure will decrease to less than 50% by the year 2010, irrigation will still be the largest user of water. 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, albeit slowly, deteriorating (Stander, 1987). Alexander (1980) stated that "there is no doubt that mineralization (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 PWV industrial area (Stander, 1987) and in the semi-arid south-western and south-eastern parts of South Africa (Fourie, 1976).

The Berg River system, like many other irrigation systems in South Africa, is coming under increasing pressure from different directions. Over the past 30 years an awareness of salinity levels in the Berg River during summer months has grown considerably. Irrigated agriculture accounts for more than 80% of the total water use in this drainage region. It plays an important role in the economy of the Western Cape and contributes significantly to South Africa's agricultural output. The Berg River catchment has a wide and dynamic crop mix, but is a fast growing wine-producing area, with 40% of the irrigated agriculture area under wine grapes and 25% under table grapes. Other crops produced in the valley are peaches and apricots (13%), citrus (3%), vegetables (3%) and irrigated pastures (7%). The perception of an increase in salinity over time gave rise to concern about the sustainability of using the water for the irrigation of these high values, salt sensitive crops.

Agriculture has a considerable influence on the quality of the water in any catchment. Agriculture demands good water quality, but it is increasingly expected of agriculture to help maintain or prevent unnecessary contamination of the river system, or other water source, and to take account of the needs of water users downstream. One must therefore distinguish between what is needed for sustained agriculture and what is required for the sustainability of the whole system. This is especially the case in a water-poor country like South Africa.

It is reasonable to assume that, in future, agriculture will have to bring about substantial water savings and also have to rely increasingly on water of a poorer quality than at present. However, international research has shown that the effects of salinity on the yield and quality of agricultural crops are very important (Frenkel and Meiri, 1985, Shalhevet, 1994). Problems associated with salinity (principally a decline in yield and 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 and Du Plessis, 1979; Tylcoat, 1985), the Riet River scheme in the Orange Free State, and the Breede River in the Western Cape.

According to unpublished reports of the Department of Water Affairs and Forestry, the salt content of most of the rivers of South Africa is steadily increasing. Furthermore, in some river systems, especially those in semi-arid environments, the salt content of the water increases progressively downstream from a major impoundment. In some cases, the downstream salt content is so high that the water is unsuitable for crop production. In order to supply all the irrigators along the river with water of a sufficiently low salt content, the river has to be diluted periodically by controlled releases from an impoundment. The lower Berg River is one such example. These releases should be regarded as losses and a waste of a scarce and precious natural resource. It is likely that as the demand for water grows in the future, this practice will become uneconomic.

1.2 AIMS OF THE PROJECT

The broad aim of the project was to gain an understanding of the causes of water quality changes in the RSE-BR system. This knowledge can then be applied to managing the quality of water in the catchment as demands upon the catchment grows. In particular, the study was aimed at developing a sufficient understanding of irrigated soils in the RSE-BR catchment, so as to be able to

- predict the quality and volume of irrigation drainage from various soil types and so
- assess the suitability of soils for irrigation with respect to their potential to pose a salinisation hazard.

1.3 SCOPE AND METHOD OF THE PROJECT

This project required a multi-disciplinary research effort, combining plot-scale fieldwork, stream and reservoir sampling, database development, the application of GIS in salinity hazard mapping and educational outreach activities. It was divided into two tasks as follows:

Task 1:Plot-scale fieldwork. The objective of the plot-scale fieldwork was to assess the salt mobilisation rates and irrigation return-flow processes in two sets of irrigated plots on Malmesbury Shale-derived soils, over three irrigation seasons. One set of plots represented a newly-established irrigation scheme and the other, land which has a long history of irrigated agriculture. Each set was to consist of at least two different irrigation treatments, typical of local practices. Irrigation application rates were to be measured and resultant return-flows gauged and sampled in artificial drain outflows. These drains were to be installed at the interface of the soil and the weathered shale layer above the bedrock. Nutrient levels (phosphate and nitrate concentrations) in the drain outflow would also be measured. Soil water content would be monitored using a neutron probe. Soil water samples for salinity measurements, were to be collected using soil-water extractors. Groundwater observation holes were to be drilled and, if possible, existing boreholes needed to be converted to allow monitoring of groundwater level and salinity changes. Estimates of potential evapotranspiration will be made by measuring a set of meteorological variables using an existing automatic recording weather station, strategically placed relative to the two sets of plots. At the end of each season, the data were to be analysed statistically and interpreted to provide input to the other task described below.

Task 2: Develop generic methods for salinity hazard assessment. The project was to make use of the GIS infrastructure of the DA's Winter Rainfall Region Office at Elsenburg, as well as soil maps, data and the expert knowledge held by that office to develop generic methods for salinity hazard assessment using soils maps, GIS techniques, salinity data from monitored tributaries and the findings of the plot-scale studies described above. The methods developed for salinity hazard assessment were to be demonstrated by identifying zones along the Berg River and its primary tributaries where irrigation may result in a significant increase in downstream salinity.

CHAPTER TWO
INTRODUCTION TO THE REPORT

This section provides additional information on the localities at which the research was conducted and the overall research strategy.

2.1 THE TWO FARMS USED FOR DETAILED WORK

The two farms, Broodkraal and Rooihoogte, were chosen for detailed investigations in the lower Berg River catchment, mainly for two reasons. Firstly, the salinity of the water in the Berg River system is mainly a problem in the lower part of the river. Secondly, the soils appeared to increase in salt content in a downstream direction.

Broodkraal was chosen as a result of its position in the lower Berg River catchment, the variety of soil types cultivated and its position at the lower end of the pediment stretching from Koringberg. Broodkraal also has a very recent development history. Since 1996, 50 ha of vineyard per year were cultivated and developed, which made the possibilities for a return-flow study quite promising.

The farm Rooihoogte uses irrigation water directly from the Misverstand Dam and its potential return-flow is also directed to the Misverstand Dam. The farm is situated on an elevated piece of land, i.e. continuity with the pediment away from the river is broken.

2.2 EXPERIMENTAL LAYOUT AT BROODKRAAL

2.2.1 Weather Data

The farm has a weather station that adequately records normal climatic information. Two neighbouring farms also have weather stations with records going back at least 10 years.

2.2.2 Drainage and Suction Cup Lysimetry

Three drains were monitored qualitatively while one was monitored both quantitatively and qualitatively. Two extra outflows from stone drains were also sampled. Daily sampling was not always possible and we had to rely on farm workers to take the samples. At least once a month after an irrigation event, suction cup samples were taken at seven positions in three depth increments.

The farm makes use of an irrigation return-flow dam. About a third of the farm's drainage and runoff water is fed into a dam. The overflow and the EC of the dam were monitored. The return-flow volume was, however, only estimated by inference.

Suction cup lysimeters were therefore used to sample soil water below the root zone after irrigation events.

2.2.3 Irrigation

All irrigation and soil water measurements were logged by the personnel on the farm. Irrigation was also metered. Water meters are installed on the farm giving readings for all irrigation units. These readings were recorded weekly.

Irrigation quantity and quality were monitored at two sites by attaching a 25L water container and a 2L h-1 dripper to one lateral in selected vineyards. Irrigation water quality was therefore measured at the sites with the 25L containers and frequent samples taken in the main irrigation dam.

2.2.4 Soil Surveys

A detailed soil survey was done before development started in 1995. Some new inspection holes were planned near monitoring sites. It was also the intention to inspect the soil in its natural state in localities surrounding the vineyards. As a result of the occurrence of heuweltjies, which made up about 35% of the landscape, it was decided to conduct the investigation in such a manner that more information about heuweltjies could be derived as these features could help clarify the origin of soil salinity.

2.2.5 Soil Sampling

Soil sampling was carried out at the beginning and end of each irrigation season. The soil map of the farm was used to plan the sampling. The two major soil types, Oakleaf and Glenrosa were targeted, and sampling was done as close as possible to the neutron water meter access tubes. Samples were always replicated four times, from two positions within the vine rows and a further two positions centred between the vine rows.

The sampling was therefore conducted in Glenrosa and Oakleaf soils subjected to varying periods of cultivation. Analysis of the data over full duration of the development (Table 2.01) was thus possible. Representativity of sampling sites was ensured by defining semi-variograms and variogram models of salinity for the Broodkraal Farm (as outlined in Section 2.5.3).

Table 2.1 : Comparative ages of the vineyards on Broodkraal Farm

Year of sampling	Year of planting					
	1996	1997	1998	1999	2001	2002
2000	4	3	2	1	0	-1
2001	5	4	3	2	1	0
2002	6	5	4	3	2	1

2.2.6 Soil Water Content

Soil water content was measured with a neutron water meter. Existing pipes were used and farm workers did the metering. Access tubes were installed for all irrigation units on the farm. Irrigation amounts or actual evapotranspiration (AET) were determined from weather station data and neutron water measurements were only used as a control measure.

2.3 EXPERIMENTAL LAYOUT AT ROOIHOOGTE

2.3.1 Weather Data

The farm has a weather station that adequately records normal climatic information. Two neighbouring farms also have weather stations with records going back at least 8 years. Rooihoogte's own weather station has been active since 1993.

2.3.2 Drainage and Suction Cup Lysimetry

One drain was monitored qualitatively and quantitatively. The duration of flow was important since the drains functioned sporadically. The monitored drain was at the lower end of a small catchment on the farm, an area that was fully developed and under irrigation. To supplement this information, water samples were taken frequently from a small tributary of the Berg River, about 50m.

2.3.3 Irrigation, Neutron Soil Water and Irrigation Water Metering

The quality of the irrigation water was monitored at least once a week. The irrigation water was also intercepted at the measuring site by attaching a 2L h-1 dripper to the irrigation system, with the dripper inside a 25L container. This provided information on quantity and quality of irrigation water.

Neutron access tubes were installed to characterize a larger area than that in the immediate vicinity of the drainage outlet.

2.3.4 Soil Surveys

A soil survey was carried out to map the whole area being monitored with neutron access tubes and by drainage sampling. This enabled the determination of the direction of drainage, soil types involved and the total area involved when measuring outflow from a single drains.

2.3.5 Soil Sampling

Soil sampling was carried out along the same lines as those pertaining at Broodkraal.

2.3.6 Soil Water Content

Soil water content was monitored with both neutron water meter and tensiometers.

2.4 INVESTIGATING NATURAL OCCURRING DRYLAND SALINITY ON POTENTIALLY SUITABLE SOILS FOR IRRIGATION DEVELOPMENT ON THE BROODKRAAL AND ROOIHOOGTE FARMS

An investigation into at least two of these possible salt sources (an old land surface underlain by pre-weathered material and the occurrence of heuweltjies) was possible at Rooihoogte and Broodkraal.

We know, however, that many of the more suitable soils for irrigation in new and recently planted areas have developed on older land surfaces. This raises several questions, i.e., will irrigation accelerate the movement of the native salt reserve deeper down the profile and will mineralization processes be accelerated in the solum by irrigation? Also, what are the chances that the irrigation of these soils will be sustainable over time when lower quality irrigation water is used? The widespread occurrence of heuweltjies, with their higher base status than that of the surrounding soils, was seen as another reason to study these features on the two farms.

The following detailed pedological and mineralogical research, on selected modal profiles on and between heuweltjies on dryland (non-irrigated) soils on the two farms, were seen as an important step to materially advance our ability to understand and predict mineralization processes:

- Study of the salt load of the parent material of the more important soils to be used for irrigation purposes (e.g. those below soils occurring on the young, older and oldest land surfaces).
- Study of the salt load of the soils that occur on and between heuweltjies.
- Study of the physical characteristics of soil profiles, starting with detailed field descriptions and sampling, and followed by a study of the structure as shown in thin section and other standard physical (e.g. bulk density, water holding capacity) determinations.
- A chemical characterization of the profiles starting with standard determinations (e.g. CEC, pH, ER, etc.) followed by selective extraction methods (e.g. those to determine the crystallinity of the sesquioxide fraction).
- Mineralogical characterization of the various particle size fractions, i.e. the clay and non-clay fractions.
- Mineralogical characterization of the salt accumulations (any carbonates, gypsum or other salts)
- Resistant mineral studies.

2.5 MAPPING OF THE BERG RIVER CATCHMENT

The initial intention was to map only the soils of the irrigated areas. As the study progressed, however, it became clear that a larger area had to be mapped as the whole catchment played a role in the salinisation of the river. Also, as the tendency toward irrigated agriculture increased, it made no sense mapping only those areas currently irrigated and so all potentially irrigable land was included in the survey.

In conjunction with the preparation of a soil map, the salinity status of the soils and the hazard this poses to sustainable irrigation and to river water quality, also needed to be assessed. To fully evaluate the long-term trends in soil and water salinity requires a historical approach whereby new sampling can be compared with that of much older samples from records of farms and fertilizer companies. For such comparisons to be made, however, requires an appreciation of spatial variability in soil salinity since it is seldom possible to sample again at exactly the same position, that of previous sampling. A systematic grid pattern of sampling was therefore instituted at Broodkraal Farm in order to apply geostatistical methods for analysing spatial variability.

The question of salinity hazard, defined for current purposes as "a condition that might operate against success or safety" and "something risked" (Webster's 3rd new international dictionary), was addressed in the form of a map showing relative salinity hazard derived from a consideration of soil and relevant (e.g. topographic) information.

CHAPTER THREE
LITERATURE SURVEY

This literature survey focuses on recent advances in international and local policy concerning sustainable water supply and sustainable agriculture. Without going into too much detail over policy changes in South Africa, it should be emphasized that the Human Rights Bill of 1995 brought about substantial changes in the approach to water matters in South Africa, forcing a change away from exclusive water rights to the rights of the individual. The review also highlights recent approaches toward water management globally, nationally and on a farm scale.

3.1 CONSIDERATIONS THAT AFFECT POLICY MAKING

In 1886, W Hilgard noted:

"It is hardly necessary to go further into details (of the problems occurring in India) to enforce the lesson and warning they convey to our irrigating communities. The evils now besetting (California's irrigation districts) are already becoming painfully apparent; and to expect them not to increase unless the proper remedies are applied is to hope that natural laws will be waived in favour of California. The natural ways in which the irrigation canals of India have brought about the scourge, are exactly reproduced in the great valley of California; and what has happened in India will assuredly happen there also."

Since the above was written, the San Joaquin Valley has become a focal point of research into countering the damaging effects of modern agriculture on the environment and the development of sustainable agricultural practices.

In the past, the U.S. had a "feed the world" outlook towards agricultural production, and still does in some regions of the U.S. This approach recently lost momentum when economic and environmental concerns came to the fore. The growth in food production over the last 30 years in the U.S. has given rise to increasing food exports from that country. Muller (1999) holds the view that the export of agricultural produce places an unacceptable burden on the U.S.'s non-renewable resources, and that environmental concerns are best addressed when agriculture is rooted in local production and consumption. Thus, the only way to "feed the world" is to promote sustainable agriculture and local consumption around the globe. This represents a vision from the U.S. that says: "our environment first". The environmental integrity of the Berg River catchment is also important, but Muller's approach is clearly untenable here, as the export of agricultural produce underpins the economy of the Western Cape.

Other approaches therefore seem more appropriate here. For example, in Spain, where irrigated agricultural development is experiencing its fastest growth ever, water resources are coming under increasing pressure. Water pricing is being proposed as a method of forcing farmers to adopt water-saving technologies. All taxes on water are to be administered by water user communities (Berbiel and Gómez-Limón, 1999). This approach is similar to that being implemented in South Africa. Likewise, with regard to the salinity problems of the Nile delta, Tarek (1999) writes that laws are being enforced to alleviate the problem.

In general, recent agricultural water conservation actions from around the world have the following elements in common:

- The education of the water users in wise water management.
- The restriction of waste by appropriate pricing and policy measures.
- The restriction of agricultural development, especially on saline soils or soils that have the potential to become saline and therefore cannot support sustained yield.
- The promotion of the use of water saving technology by farmers.
- The education of farmers about appropriate methods for disposal of irrigation drainage water.

On the other hand, quality of agricultural produce and economic considerations complicate matters (Lipton *et al*, 1996). The whole economy of the Western Cape depends strongly on agricultural exports and there is a need to find a locally acceptable compromise between making money and conserving ecosystems.

3.2 HISTORY OF BERG RIVER RETURN-FLOW MODELLING

Looking back on research into return-flow problems in the Berg River Catchment, it is apparent that the complexity of the problem and the turnover of researchers have hampered attempts to develop appropriate modelling strategies.

In 1984, Cass reported the state of research concerning return-flow modelling of the BRC to the Water Research Commission (WRC). In his summary he referred to work done by Van Rooyen (1975) applying first the model of Dutt *et al* (1972) and later the model of Oster and Rhoades (1975) without great success. He later examined the possibility of applying the reclamation model of Schaffer et al (1977) in North Dakota. Following a period of field experimentation aimed at modelling unsaturated hydraulic conductivity, the model of Oster and Rhoades (1975) was used to predict the effect of irrigation water on downstream irrigation water quality (Van Rooyen and Moolman, 1980). This can be considered as the start of the return-flow modelling, currently being used, which conformed to the DISA model approach. No successful model application on the BRC was however achieved to date. All models were tested in smaller catchments with the aim of application it in the BRC.

Fourie (1976) wrote a thesis on the mineralization of the Berg River's water and some attempts were reported later by Cass (1986) to apply the FLOSAL model on sections of the river, using Fourie's data. It was found that the existing database was still insufficient but that the mass balance method of handling chemical processes was satisfactory. Their primary concern was, however, over of the chemical characteristics of the soils, but this information was not available. More modelling attempts were later made by DWAF and the CSIR, but these lacked the return-flow component and a soils database to which modelling could be linked.

3.3 FACTORS THAT DIRECTLY INFLUENCE SOIL SALINITY/SODICITY STATUS

3.3.1 Irrigation Method

Permanent irrigated agriculture requires the sacrifice of some value elsewhere (Van Schilfgaarde, 1990). Shalhevet (1994) came to the conclusion that there is a clear relationship between yield reduction and reduced water consumption, due to salinity increase. He also reported that the bulk of evidence leads to the conclusion that a single unified function may be applied to both water and salinity stress. This implies that salinity and water stress are additive in their effect on transpiration and yield. However, Shalhevet (1994) showed that the quantitative effects of these two stresses are not identical. Meiri's (1984) review of the international literature showed that water stress has a greater weight than salt stress in suppressing growth. From this one can infer that, in times of water shortage, it would be better to irrigate with saline water, rather than to let the crop suffer from water stress.

Shalhevet (1994) was of the opinion that actual transpiration and yield are reduced by salinity in accordance with the production function, which relates relative yield to relative evapotranspiration, and the evapotranspiration - salinity response function. However, it is still unresolved whether reduction in water uptake with increasing salinity is the cause or the result of a reduction in growth. Shalhevet (1994) furthermore argued that salinity reduces evapotranspiration (ET), resulting in slower soil drying than under non-saline conditions. Thus, for the same irrigation interval, the total pre-irrigation soil-water potential may be lower under non-saline than under saline conditions, resulting in a greater damage to the crop. Also, as irrigation becomes more frequent, the evaporation component of ET increases, leading to additional water application and an increase in the salt load. Shalhevet (1994) concluded that the bulk of evidence in the literature shows no advantage of increasing irrigation frequency when irrigating with saline water. There is evidence that increased irrigation frequency with saline water might even increase salinity damage. However, under excessive leaching this may be reversed.

With regard to transpiration, the irrigation method might alter salt tolerance in three principal ways: wetting of foliage, changing salt and water distribution in the soil and applying water at a higher frequency (Shalhevet, 1994). Normally, leaf injury can be reduced by irrigating during the night when saline water does not evaporate from the leaves, leaving a deposit on the leaf surface, or by applying non-saline water at the end of each irrigation cycle in order to wash off accumulated salts (Shalhevet, 1994).

The advantage of drip irrigation when using saline water is twofold. Firstly, leaf contact is avoided and for sensitive crops this may mean the difference between success and failure (Shalhevet, 1994). The second advantage of drip irrigation lies in the pattern of salt distribution under the drippers and the maintenance of constantly high matric potentials. The typical pattern is one of low salt accumulation under the drippers due to high leaching and marked accumulation of salt at the wetting front and between the laterals (Yaron *et al*, 1973, Moolman and De Clercq, 1989). The distribution of water content has a reversed pattern, with a decrease away from the point source. This results in a root pattern in which most of the roots are typically found in the highly leached zone beneath drippers (Moolman and De Clercq, 1989). Shalhevet (1994) concludes that drip irrigation is the best possible way of applying saline water to crops, avoiding leaf injury and at the same time providing optimum soil-water conditions. However, the limited volume of wetted soil might pose problems for fruit and vine crops with larger root systems.

Van Schilfgaarde (1974 and 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.

3.3.2 Soil Properties

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 water-holding capacity of a sandy soil is lower than that of a medium textured soil, which in turn is lower than that of fine textured soils. 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 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 saturation 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.

3.3.3 Clay Percentage and Clay Type

De Clercq *et al* (2001) showed that clay content plays a major role determining the effect that salinity and in particular Na, has on a soil. Tanji (1990) notes that structural degradation of soils depends not only on the levels of salinity and sodicity, but also upon 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_{iw} 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_{iw} is applied. It also becomes a problem when the farmer exploits different sources of water with different EC_{iw} values.

More recent studies have shown the active participation and the role that silt and clay particles play in saline soils.

3.3.4 Stone Content of the Soil

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. Unpublished results (that were confirmed by this study) that illustrate the relationship between the stone, clay and water contents of a soil are given in Figure 3.1. It is clear from these data that the soil water content is influenced considerably by the clay and stone content of the soil. 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,* (1993) have shown that drainage from stony soils commences about 15 minutes after irrigation has been initiated.

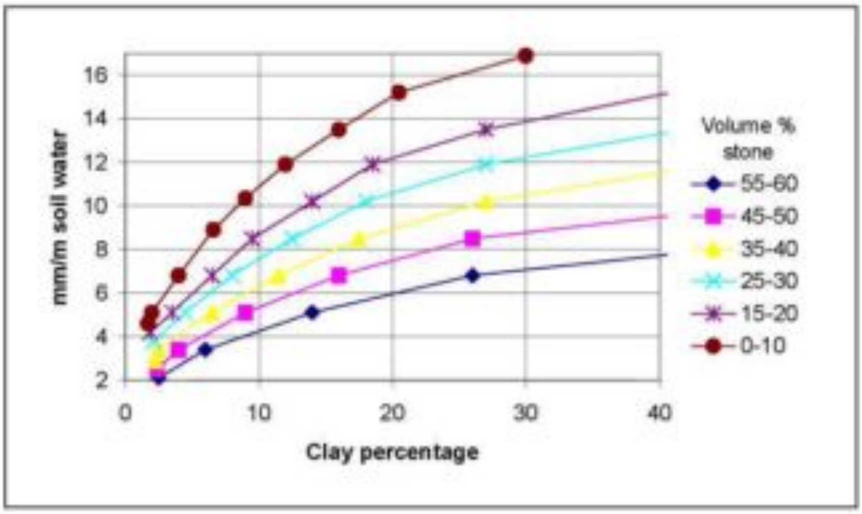


Figure 3.1 Relationship between clay percentage, soil water content and volume percent stone

3.3.5 Climate

Prior *et al* (1992b) in Australia found that symptoms of leaf damage that appeared in December or January were related more to climatic stress than to chloride or sodium levels. Shalhevet (1994) reported that three elements of climate, namely temperature, humidity and rainfall, might influence salt tolerance and salinity response, 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.

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 the much smaller osmotic potential differences.

3.3.6 Time

How long does it take for the soil to deteriorate or for the plants finally to succumb to the effects of soil salinisation? The studies by Moolman *et al* (1999) and De Clercq *et al* (2001) were conducted over a period of 8 years, after which a total reduction in yield was experienced in all treatments. They found that the major impact of ECi on the ECe and SAR of the soil, and yields, only became visible after 7 years of irrigation. At this point, only the two low salinity treatments, namely the fresh water and the 75 mSm^{-1} treatments, could still be considered as economically viable.

After five years of saline irrigation water, Catlin *et al* (1992) found that a three-year time integration of soil salinity better described the effects of salinity on plum trees. The explanation was that two or three years of averaging accounted for the influence of salinity on bud formation and shoot growth in the years prior to the yield year. Five years of saline irrigation and three years of time-integrated mean soil salinity did not substantially change the salt tolerance values inferred after three years of study. Hoffman *et al* (1989) in their study of plum trees, showed that three years of saline irrigation, and a two year time integration, excluding the dormant period, is the minimum time scale to correctly quantify the impact of salinity on plum yield. The interpretation may be that no change occurred in the response of plums to total salinity, or to the combined effects of total salinity and specific ion effects.

Worsening of the salinity effect with time can result from important metabolic processes that are impaired between seasons. 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 and plums was leaf damage that almost killed vines and trees after two, three and four years of irrigation with water of EC_i of 250 - 800 mSm^{-1} (Hoffman *et al* 1989; Prior *et al*, 1992; Moolman *et al*, 1999). In all three 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 mSm^{-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). 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 stone fruits and grapes appear to be more sensitive to salinity as the plants grow older (Francois and Maas, 1994).

3.4 RESPONSE OF SOIL AND SOIL TYPES TO SALINITY

Soil type has a large bearing on agricultural sustainability and management of water resources.

3.4.1 The Response Function as a Means of Predicting Salinity Hazard

Indices of salinity hazard include water salinity, soil salinity and the ionic composition of selected plant organs. Leaf chloride was the most convenient and reliable method of measuring yield response to salinity for peach (Boland *et al*, 1993; Moolman *et al*, 1999). For grapes, high chloride content in the petioles (Christensen *et al*, 1978) and laminae (Walker *et al*, 1981) indicate whether plants have been subjected to salinity. The petiole chloride predicted the yield response slightly better than the laminal chloride in long-term field studies (Prior *et al*, 1992b; Moolman *et al*, 1999).

Fruit trees and vine crops were included in the general model (Maas and Hoffman, 1977) that describes the response to total salinity as a response function where the threshold salinity (EC_t) is the maximum salinity without yield reduction, and S is the slope of the curve determining the fractional decline per unit increase in salinity beyond the threshold. For purposes of generalisation, the data are normalised by relating the yield to the non-saline treatment yield (RY) and using the depth-weighted mean salinity of the saturated paste extract (EC_e) assuming a stable and one-dimensional salt profile:

$$RY = 1 - (EC_e - EC_t)*S \qquad (1)$$

Hoffman *et al* (1989) applied the model to the data of their plum experiment with reasonable success. However, the response function correlated better with the mean root zone salinity to a depth of 120 cm for a two-year time integration than with the mean salinity of the yield year. In the case of a six-year study on salinity effects on grapevine (Prior *et al* 1992a), yield was affected by the salinity of current and preceding seasons. The salinity effects were described better by a logistic function than by the Hoffman- response model. The logistic function was of the form:

$$y = D\left[1+\left(\frac{EC_i}{EC_{ih}}\right)^a\right]^{-1} \tag{2}$$

where y is yield, EC_i is salinity of irrigation water, D is the theoretical yield at EC_{iw} = 0, EC_{ih} is the half-effect EC_i and a is the shape parameter. This model has no threshold value and shows a reduced marginal effect with increasing salinity. The EC_{ih} value for pruning weight in the Prior model was lower than for yield, which suggest that salinity has a larger effect on pruning weight than on yield. Larger salinity effects on shoot growth than on yield were reported also for plum trees (Catlin *et al* 1993). The yield response of vines irrigated with saline water over 5 years found by Moolman *et al* (1999) is shown in Figure 3.2. The threshold EC_e and the yield response to increasing EC_e both indicate a greater sensitivity to salinity than that suggested by Ayers and Westcot (1985).

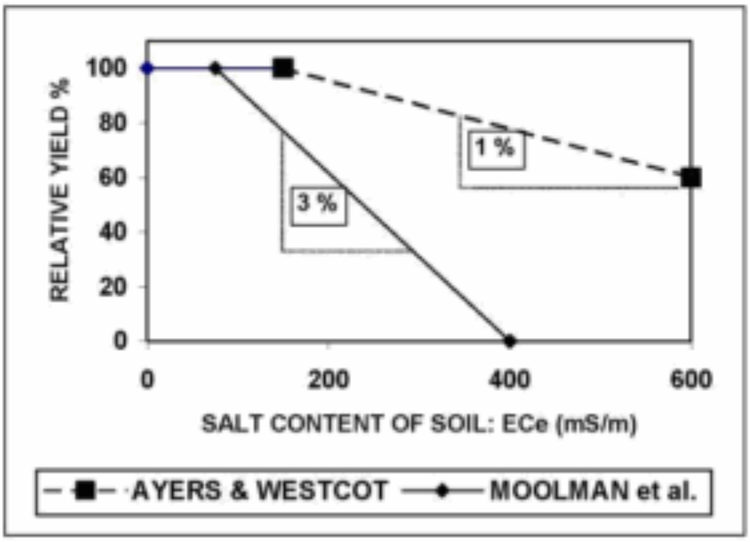


Figure 3.2 : Relative vine yield response to soil salinity by Moolman *et al* 1999 compared with a yield response predicted using data from Ayers and Westcot (1985)

More recent work done by De Clercq *et al* 2001, showed that grapevines tested over a period of eight years were highly sensitive to saline irrigation water and suffered a decline in yield over all treatments and the decline increased in severity over the duration of the study. They reported that all vine yields were better correlated with SAR from soil samples taken at the end of each irrigation season. This can be seen in Figure 3.3.

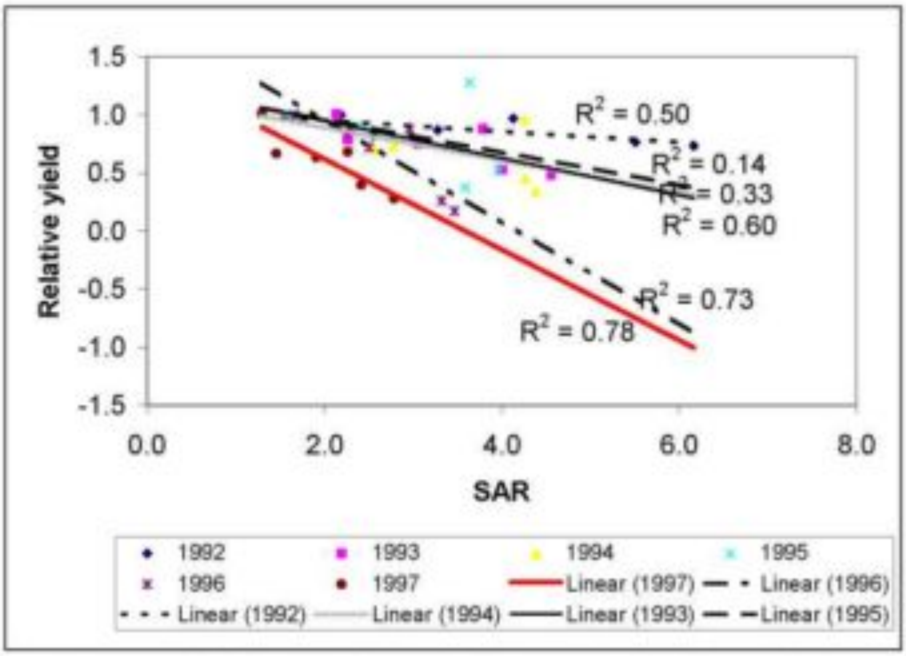


Figure 3.3 : Averaged yield per vine against averaged SAR per treatment of the Robertson main study between 1992-1997

3.4.2 Salinity hazard and sustainability

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 (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 like 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 mSm^{-1}. Irrigation water quality in this case implied high risk for the farmer, but low risk for the environment (the Breede River valley), which was accustomed to higher salinity levels during summer months prior to the institution of water quality management in the Breede River System.

3.5 ENVIRONMENTAL CONSIDERATIONS

Notwithstanding the fact that irrigation is essential for crop production in many climate zones, it can be argued that the introduction of irrigation in an area is one of the most drastic ways in which human activity impacts on the environment. Soil genesis is a slow process and the age of soils is generally measured on a geological time scales. One consequence of the slow rate of soil formation is that soil is in equilibrium with the prevailing climate. For example, in arid or semi-arid regions the chemical composition of the soil is the result of weathering processes, which take place under conditions of a shortage of soil water (relative to potential evaporation), and high temperatures. In most cases such soils contain unweathered minerals and significant quantities of soluble salts. Introduction of irrigation disturbs this equilibrium and weathering of soil minerals and leaching are accelerated. Rhoades *et al* (1968) have shown that increases in salt concentration of 200 to 300 mg/L are common when arid-land soil solutions remain in contact with relatively unweathered soil minerals for substantial periods of time. Also, some or most of the soluble salts are mobilised and transported down the soil profile. Under irrigation, the salts mobilised in return-flow end up in rivers and impact on river ecology. Prior to the onset of irrigation the ecology of the river would have been in equilibrium with the composition of the natural seep from soils typical of a semi-arid climate. The environmental impact of irrigation and return-flow on river ecology can be minimised by intercepting the return-flow and disposing of it elsewhere with specially constructed drainage canals or pipelines. However, because of the additional need to leach when irrigating with saline water, the amount of return-flow that must be disposed of is greater than for non-saline water. This implies that the infrastructure required to utilise saline water for irrigation such as drainage canals, interceptor drains, pipelines, evaporation ponds, etc., will be more expensive in comparison with the non-saline case.

3.6 METHODS OF MEASURING IRRIGATION RETURN-FLOW QUANTITY AND QUALITY

Irrigation return-flow quantities can be estimated with the use of mass balance models, which require the measurement of irrigation rate, evapotranspiration, rainfall, soil moisture and an investigation of soil structure and texture. Drainage rates from subsurface drainage systems can be used as an indication of the drainage rate, but this approach does not account for natural base flow, i.e., water moving through the soil along its natural drainage pathway. Any measurable drainage rate from a drainage pipe is always an underestimation of the actual rate. Therefore the most reliable result is usually to monitor surface as well as subsurface return-flows. Tile drain flow was monitored by Moolman *et al* (1992) at the farm Goedemoed near Robertson with the tipping bucket gauge shown in Figure 3.4.

Figure 3.4 A tipping bucket flow gauge with logging equipment built locally to monitor tile drain flow (De Clercq 1992)

All water and salt balance equations include a measure of the volumes of water in the system. These include the amount of irrigation water applied, rainfall and water lost through drainage and evapotranspiration. The salt balance, which is discussed in the next section, includes all possible removals of salt from the system, whether this is via the removal of plant material, dissolution or precipitation of salts, or the drainage of dissolved salts.

The most basic equation that accounts for irrigation return-flow is given by Aragües (1990):

$$C_d V_d = [C_i V_i + C_p V_p] + [M_{is} + M_{afm} + M_{pr} + M_{sd}] - [M_{hc} + M_{sp} + M_{twr} + M_{pre} + M_{dp}] \qquad (3)$$

where C and V is concentration and volume where subscript *i* is irrigation, *d* drainage and *p* precipitation. The initial quantity of salts present in the system is represented by M_{is}, and M_{afm} stands for the salts contributed through fertilisers and soil amendments.
M_{hc} the mass of harvest salt removal,
M_{sp} and M_{sd} the precipitation and dissolution masses of salt,
M_{pre} the mass of salt added by rain,
M_{pr} and M_{iwr} the salt removed by precipitation or irrigation runoff and
M_{dp} the salt mass leaching to groundwater.

Though this equation is simple and accounts for most relevant variables, it is quite difficult to apply it in practice. It is difficult to estimate dissolution and precipitation of salts in the irrigated soil profile. It is also inappropriate to work with too few measurements, since water and fertiliser are never distributed evenly over the soil surface. Furthermore, as a result of differential heating of the soil surface, evaporation is not uniform, and this non-uniformity translates into spatial variability in the distribution and precipitation of salts in the soil profile. Also, natural soil variation needs to be accounted for.

The dissolved salt content of drainage water tends to remain fairly constant over time, and rarely shows rapid changes. Consequently, drainage quality can be modelled using relatively few samples. Drainage volumes, on the other hand, may fluctuate widely. It is important, in modelling irrigation drainage, to be able to model the changes in net drainage volume that take place on a short timescale.

One of the major difficulties in modelling is dealing with the site-specific conditions and processes that dominate the accuracy of simulation models. It is therefore important to characterise the site-specific conditions for each of the soil types that is being tested, including the time since the previous soil preparation.

3.7 MODELLING RETURN-FLOW

Though it was not a specific aim of this study to model return-flow, data had to be generated to accomplish modelling in another leg of the study. The Conceptual Irrigation Return-flow (CIRF) hydrosalinity model of Tanji (1990) makes use of Equation 3 (above), and has been used as a basis for outlining all relevant variables for modelling of return-flow. The model makes use of the following variables where:

In the hydrologic sub-model the hydrological inputs and outputs are:

Diverted irrigation water
Precipitation
Initial stored soil water
Water inputs to root zone
Water outputs from root zone
Change in water storage
Surface irrigation return-flows
Irrigation efficiency, water application efficiency, leaching fraction.

And in the salinity sub-model the salt inputs and outputs and change in storage involves:

Lateral contributions
Diverted irrigation water
Precipitation
Initial soil water corrected by gypsum solubility
Gypsum, salt pick-up deposition
Salt input to the root zone
Salt output from the root zone
Salt load in irrigation return-flows.

The approach used in the current study is somewhat different from the above and is described in Chapter 5.

3.8 MODELLING VARIATION

It is of very important to know to what extent a single soil sample is representative of the surrounding soils. This assumption led us to a study of the geostatistical methods currently being used in soil science to map the salinity of soils. Since salinity varies in its occurrence within one soil type and between soil types, the task of mapping cannot be linked to soil type only.

3.8.1 The Basic Principles of Geostatistics in Soil Science

We have two needs and these are (1) to describe quantitatively how soil varies spatially, and (2) to predict the values at places where we have not sampled. For this we need a model for prediction and since there is no deterministic one, the solution seems to lie in a probabilistic or stochastic approach (Webster and Oliver, 2001). It is the aim of this section to describe and give the background to the statistics used later on.

A geostatistician models soil as if it was the realizations of a random field (Webster, 2000). Exploratory data analysis is usually performed, as suggested by Webster (2001), for the purpose of determining the form of dispersion, standard deviation, standard error and confidence, i.e., all the elements needed to describe variation satisfactorily. Webster (2001) suggests that the results be presented in table form, with histograms, to show the distribution of the data. Thereafter, all possible interactions and also multiple interactions have to be noted. The data are usually screened again at this stage by drawing location maps to enable the recognition of extremes and patterns. Where necessary, declustering is done using the polygonal method of Isaaks and Strivostava (1989), or the cell declustering method of Deutch and Journel (1992). The latter involves a grid projected over the study area. All measurements in a single grid cell receive a weight inversely proportional to the number of measurements in the cell. The grid is then moved over the whole study area. This evolution of cell averages through the evolution of cell dimensions helps to minimise the effect of outliers in the data surface. Declustering helps to make values in a data surface more representative.

Semivariograms and variogram models are then prepared with, amongst others, the VARIOWIN 2.2 software (Pannatier, 1996) either using the original dataset or the declustered dataset. The concept of variance, as used is classical statistics, is extended in geostatistics to consider the location of the observations separated by a given distance. The spatial variance of a regionalized property Zx, is usually modelled by use of the semivariance $\gamma(h)$ (Journel and Huijbregts, 1978):

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} \left[Z(x_i) - Z(x_i + h) \right]^2 \qquad (4)$$

with $Z(x)_i$ the value of variable Z at location x_i, h is a distance vector (lag) and *n(h)* is the number of pairs separated by *h*. A curve (model) is fitted to these values. The models used here, are mainly exponential and spherical. A variogram model is fitted to the experimental semivariogram. A variogram model is characterised by 3 parameters, namely the sill (C_0+C_1), nugget (C_0) and the range (a) (Equation 5). The variogram models most widely used are linear, exponential, spherical and Gaussian models (Pannatier, 1996; Van Meirvenne, 2000). Only the exponential, spherical and Gaussian models will be given below (Equations 5 to 7) to illustrate the procedure used. These models are described in full by a number of writers (Webster and Oliver, 2001, Deutch and Journel, 1998, Goovaerts,1997, Pannatier, 1996). It is a pity that the notation used by geostatistics authors has not been standardised. The notation used by Goovaerts (1997) will be used in this report.

The exponential model is given by the following:

$$\begin{cases} \gamma(h) = 0 & \text{if} \quad h = 0 \\ \gamma(h) = C_0 + C_1\left(1 - \exp\left(-\frac{3h}{a}\right)\right) & \text{if} \quad 0 < h \quad \text{and} \quad 3h \leq a \\ \gamma(h) = C_0 + C_1 & \text{if} \quad 3h > a \end{cases} \tag{5}$$

The spherical model is given by:

$$\begin{cases} \gamma(h) = 0 & \text{if} \quad h = 0 \\ \gamma(h) = C_0 + C_1\left(\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right) & \text{if} \quad 0 < h \leq a \\ \gamma(h) = C_0 + C_1 & \text{if} \quad h > a \end{cases} \tag{6}$$

The gaussian model is given by:

$$\gamma(h) = C_0 + (C_1 - C_0)\left(1 - \exp\left(-\frac{h^2}{b^2}\right)\right) \quad \text{if} \quad 0 < h \tag{7}$$

These three, or combinations thereof, termed nested functions, are used in the analysis of soil salinity data sets (Bourgault *et al*, 1997). The exponential model shows a linear rise over almost one third of the range, after which the sill (C_1)[1] is reached asymptotically. This rise is much steeper than in the spherical model. A practical range (a) is defined whereby 95% of the sill is reached. The spherical model is used most widely, and is characterised by its initial linear behaviour from the origin (Deutch and Journel, 1998).

3.8.2 Application of geostatistical modelling

Geostatistical modelling opens up methods for rapid and cost effective salinity assessment, mapping and modelling. No current hydrological model incorporates spatial variability on a pixel basis. Geostatistical modelling can be used to prepare maps (soil EC maps) from which return flow can be predicted.

In a parallel study by De Clercq, an attempt was made to define and map the spatial variability in irrigated vineyards on a farm, to map and define the seasonal shift in soil EC. The study was based on results reported on by Moolman *et al* (1999) and De Clercq *et al* (2001). Suction cup data sampled over a period of five years at the Robertson research farm was used in this experiment. It was possible to model the change in EC_{sw} for each of the 6 saline irrigation water treatments with depth. From this model a second was generated with which the EC of the soil water could be predicted, with 90% accuracy, using only data from two depth increments in the upper soil horizons. The implication of this is that the quality of the soil water below the root zone could be predicted quite accurately. The further implication of this is that any soil can be characterized in the same way as a result of a seasonal soil water movement pattern. By only sampling certain crucial elements of the model, soil salinity can be estimated very accurately. The same study also indicates that this approach can be supplemented to easily assess large areas using instruments like the bi-polar EM38 soil electro-magnetic inductance meter. The fact that the results can also be linked to a time of season, opens up the possibility of building a dynamic database in a GIS system that can predict return-flow much more accurately.

[1] The sill is C_1 when the nugget, C_0, is zero, i.e. no nugget effect.

3.9 AN INVESTIGATION OF NATURAL OCCURRING DRYLAND SALINITY ON POTENTIALLY SUITABLE SOILS FOR IRRIGATION DEVELOPMENT ON THE BROODKRAAL AND ROOIHOOGTE FARMS

Previous studies on soil salinity in the Berg River Catchment concentrated mainly on some chemical, physical and management aspect thereof (Fourie, 1976; Cass 1986). Their studies clearly indicated that soil salinity is a problem in many areas of the catchment but that, in general, it was the left bank tributaries which yielded run-off containing unacceptably high salt loads. In addition, downstream from the Misverstand weir (an area where irrigation development is now rapidly expanding) the salinity levels were high in tributaries on both sides of the Berg River.

The questions to ask are *inter alia*, where does the salt come from, can it be mapped to predict its source(s) and how will the soils that are recommended for future irrigation respond to more saline conditions? The salt in the soil profile may have several sources. One of the sources is believed to be the ocean – salt is carried inland by prevailing winds and deposited on the land in rainfall and dust. Over a time scale of millions of years, this process has probably deposited large amounts of salt. Jurinak (1990) states that dry and wet aerosol fallout can contribute up to 100 to 200 kg ha-1 per year and gradually decreasing inland. The older the present-day land surface and the deeper and more weathered the parent material, the greater the chances of salt accumulation in this way. Silcrete occurrences (an indication of an old land surface) are common in certain parts of the catchment and may hold the key to the salt's origin. Some salt in the soil profile may date back even further, to when the parent rocks were formed. These rocks release salts as they weather. Other possible sources of salt are a concentration of bases by biological means, e.g. those that are found in termite mounds or "heuweltjies", common to the area. Other sources might be ancient drainage basins or shallow inland seas that evaporated during arid periods, leaving behind salt deposits that remain today.

CHAPTER FOUR
FACTORS RELATING TO RETURN-FLOW PREDICTION

4.1 BOUND BY THE AIMS OF THE STUDY

It must be borne in mind that this study has two primary legs that limited the investigation to mainly the measuring of water quality and the description of soil type. The two legs can be summarised as follows:

A : Detailed investigations of all variables affecting irrigation return-flow at two sites in different parts of the catchment. Modelling of return-flow will be based on these findings.

B : The compilation of a soil map of the whole catchment in GIS format. Historic soil chemical data will be collected for predetermined sites throughout the catchment. This will enable us to study the effects on soil chemistry of irrigation water quality, by conducting follow-up investigations of soil chemistry at those sampling sites. (It was however foreseen that due to the large variation of soils over short distances, that non-georeferenced data could be worthless).

The general aim is to predict return-flow more accurately and to determine the relative contribution of different soil types to water quality in the Berg River.

4.2 CLIMATE OF THE CATCHMENT

It is important to see the chosen experimental sites' climates in perspective to that of the whole catchment. The study area has a Mediterranean climate. The Swartland and Boland regions have 80% of their annual rain during the months April to September. The climate of the catchment changes as one move inland from the coast and into the catchment's upper reaches. The climatic variation in the whole Berg River catchment can be seen in Figures 4.4 and 4.5. The region is predominantly a winter rainfall region and most water in the catchment is collected in the upper parts of the valley close to the mountains where the rainfall is highest. Toward the coast the rainfall is generally low, erratic and poorly distributed. Rainfall increases toward the Piketberg, and on the Piketberg (i.e., the mountain, 30 km away from the coast), a much higher rainfall is experienced. From the coast the average annual rainfall varies from 50 mm to higher than 1000 mm in the Franchhoek/Jonkershoek/Hottentot's Holland mountain ranges. More than 80% of this region has an annual rainfall of between 200 mm and 500 mm. Strong winds are very common, especially during summer, and lead to severe wind erosion and high ET. Extremely low winter temperatures and frost are uncommon in the coastal zone. Frost and snow are experienced in the higher-lying areas, and frost occurs in the drier, higher regions of the Swartland.

Wind is common in the area, with strong to gale force south-easterly and north-westerly winds in spring - summer and winter, respectively. Wind protection measures are therefore a common practice in the fruit, vine and vegetable growing areas. However, the lower lying areas are mostly protected from the wind.

Tables 4.1 to 4.5 give the ET_o, ET_o/Rainfall balance, long term averaged total rainfall per month and per day, for various weather stations in the BRC (Agrometeorology, Elsenburg, 1989). These variables are important in the assessment of the both the Broodkraal and Rooihoogte climatic conditions in terms of their representativity in the Berg River catchment. Data for Rooihoogte is included, while Broodkraal's climate is assumed to be essentially identical as that at the Koringberg weather station.

Table 4.1 : Monthly average ET_o of selected weather stations of the Berg River (mm per day)

Station	Altitude	Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Langebaanweg	31	10.9	10.0	7.7	6.0	3.8	2.9	2.9	3.5	5.8	9.0	10.8	10.9
Rooihoogte	45	10.2	10.1	6.8	4.8	2.6	1.7	1.4	2.0	3.4	6.6	9.0	9.8
Eendekuil	114	13.1	12.4	8.4	5.9	3.7	2.0	1.7	2.4	4.1	7.4	11.5	12.8
DeHoek/Saron	115	9.9	9.8	7.0	5.3	3.0	2.1	2.0	2.6	4.3	6.6	9.2	10.5
Korinberg	128	11.7	11.4	9.6	6.6	3.4	2.2	2.1	2.8	4.3	6.8	9.7	10.9
Vredenburg	128	11.0	10.0	7.8	5.4	3.3	2.6	2.4	3.1	4.6	7.2	9.2	10.2
BienDonne	138	9.5	9.2	7.1	4.5	2.4	1.6	1.8	2.6	4.0	6.3	8.6	9.1
HLSPaarl	149	10.1	9.8	7.4	4.8	2.8	1.9	1.9	2.6	3.9	6.4	8.7	9.7
Vredehof	154	9.6	9.4	6.5	4.3	2.8	1.8	1.9	2.6	4.1	6.9	9.6	9.4
LaMotte	206	8.1	7.9	5.8	3.9	2.6	1.8	1.9	2.7	3.6	5.0	6.7	8.0
Franschhoek	244	8.1	7.9	5.8	3.9	2.6	1.8	1.9	2.7	3.6	5.0	6.7	8.0
LaPlaisante	260	9.9	9.2	7.0	4.6	2.9	2.2	2.2	2.7	4.0	6.1	8.6	9.5
Heldervue	755	7.4	6.9	5.1	3.6	2.5	2.1	2.1	2.4	3.1	4.8	6.5	7.2

Table 4.2 : Monthly average ET_o values minus monthly average rainfall at selected weather stations of the Berg River catchment (mm per day)

Station	Altitude	Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Langebaanweg	31	10.7	9.8	7.3	5.3	2.5	1.6	1.4	2.0	5.0	8.6	10.4	10.6
Rooihoogte	45	10.0	9.9	5.9	3.4	0.8	-0.3	-0.8	0.1	2.0	6.1	8.6	9.4
Eendekuil	114	13.0	12.1	7.9	4.7	3.0	0.1	0.5	0.7	3.3	6.9	11.3	12.8
DeHoek/Saron	115	9.7	9.3	5.6	3.6	1.3	-1.1	-0.8	-1.2	2.0	5.9	8.5	10.2
Korinberg	128	11.5	11.1	9.2	5.7	1.6	0.1	0.6	1.0	3.5	5.9	9.2	10.5
Vredenburg	128	10.7	9.9	7.4	4.7	1.7	0.9	0.7	1.3	3.8	6.7	8.8	9.9
BienDonne	138	8.9	8.4	6.1	2.2	-1.6	-2.9	-2.2	-1.1	1.7	4.7	7.6	8.3
HLSPaarl	149	9.7	9.3	6.7	3.7	0.6	-0.6	-0.6	0.2	2.3	5.6	8.1	9.1
Vredehof	154	8.9	8.9	4.8	2.5	-0.1	-1.3	-1.6	-0.7	1.1	6.0	8.8	8.4
LaMotte	206	6.8	6.9	4.4	2.0	-1.4	-2.5	-1.9	-0.7	0.6	3.6	5.8	7.1
Franshoek	244	7.6	7.2	4.9	1.6	-1.2	-2.9	-2.6	-1.5	1.4	3.1	5.6	7.4
LaPlaisante	260	9.5	8.6	6.3	3.1	0.2	-1.0	-0.4	-0.2	2.3	4.9	7.8	8.9
Heldervue	755	6.8	6.2	4.0	1.4	-1.3	-2.5	-2.1	-1.8	0.7	3.1	5.3	6.2

Table 4.3 : Average monthly rainfall for selected stations in the Berg River catchment (mm/month)

Station	Height	Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Langebaanweg	31	6.8	4.6	11.8	20.9	39.1	40.1	45.1	46.5	25.3	12.8	12.6	10.0
Rooihoogte	45	6.5	6.8	28.4	42.3	54.9	59.2	69.3	59.9	43.3	15.1	11.1	12.6
Eendekuil	114	3.0	9.3	14.6	35.6	21.7	55.6	37.3	53.1	24.1	14.2	5.2	0.9
DeHoek/Saron	115	7.5	13.6	42.8	49.8	54.2	96.3	86.3	117.9	68.7	20.8	20.2	9.8
Korinberg	128	7.1	7.2	11.9	28.3	54.8	64.0	47.7	54.9	25.0	27.2	15.6	13.4
Vredenburg	128	8.8	4.0	13.1	21.9	49.4	50.0	53.1	54.4	25.2	14.3	12.5	10.3
BienDonne	138	19.5	21.5	30.6	70.1	123.1	135.6	123.7	115.9	67.6	48.4	30.8	24.5
HLSPaarl	149	12.4	12.7	22.4	33.4	67.6	74.1	77.1	75.1	47.0	24.0	18.3	17.3
Vredehof	154	21.1	13.1	52.5	55.1	89.3	93.6	109.0	102.3	89.8	27.7	25.0	32.0
LaMotte	206	39.7	27.5	44.9	57.5	122.6	127.8	116.4	106.7	88.9	42.4	26.3	27.7
Franshoek	244	14.8	20.1	28.3	68.8	117.6	140.4	140.3	130.4	64.9	58.2	33.3	19.4
LaPlaisante	260	12.6	16.9	22.7	43.9	82.4	95.1	81.9	89.0	51.6	36.4	23.7	17.5
Heldervue	755	20.0	20.6	33.7	65.1	117.3	138.0	129.9	129.9	72.8	51.2	35.6	29.9

Table 4.4 : Average monthly rainfall (mm/day)

Station	Height	Month											
		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	1.5	0.8	0.4	0.4	0.3
Rooihoogte	45	0.2	0.2	0.9	1.4	1.8	2.0	2.2	1.9	1.4	0.5	0.4	0.4
Eendekuil	114	0.1	0.3	0.5	1.2	0.7	1.9	1.2	1.7	0.8	0.5	0.2	0.0
DeHoek/Saron	115	0.2	0.5	1.4	1.7	1.7	3.2	2.8	3.8	2.3	0.7	0.7	0.3
Korinberg	128	0.2	0.3	0.4	0.9	1.8	2.1	1.5	1.8	0.8	0.9	0.5	0.4
Vredenburg	128	0.3	0.1	0.4	0.7	1.6	1.7	1.7	1.8	0.8	0.5	0.4	0.3
BienDonne	138	0.6	0.8	1.0	2.3	4.0	4.5	4.0	3.7	2.3	1.6	1.0	0.8
HLSPaarl	149	0.4	0.5	0.7	1.1	2.2	2.5	2.5	2.4	1.6	0.8	0.6	0.6
Vredehof	154	0.7	0.5	1.7	1.8	2.9	3.1	3.5	3.3	3.0	0.9	0.8	1.0
LaMotte	206	1.3	1.0	1.4	1.9	4.0	4.3	3.8	3.4	3.0	1.4	0.9	0.9
Franshoek	244	0.5	0.7	0.9	2.3	3.8	4.7	4.5	4.2	2.2	1.9	1.1	0.6
LaPlaisante	260	0.4	0.6	0.7	1.5	2.7	3.2	2.6	2.9	1.7	1.2	0.8	0.6
Heldervue	755	0.6	0.7	1.1	2.2	3.8	4.6	4.2	4.2	2.4	1.7	1.2	1.0

Table 4.5 : Average monthly temperature

Station	Height	Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Langebaanweg	31	21.9	22.6	20.1	19.7	15.0	12.7	11.6	13.2	14.6	15.1	19.1	20.2
Rooihoogte	45	23.8	24.5	22.1	19.3	16.2	12.8	11.4	12.8	14.5	17.7	21.4	22.5
Eendekuil	114	25.8	25.7	23.3	20.0	17.0	13.2	11.8	13.8	14.9	17.2	22.2	23.9
DeHoek/Saron	115	23.8	24.9	22.7	19.8	17.4	14.1	13.1	14.3	15.8	18.1	21.0	23.0
Korinberg	128	24.6	25.6	23.8	21.5	16.6	14.7	12.9	13.3	15.5	18.3	21.0	23.3
Vredenburg	128	20.2	20.6	19.7	18.6	16.1	14.4	13.4	13.6	14.6	16.3	18.1	19.4
BienDonne	138	22.3	22.6	21.1	17.8	14.5	12.2	11.5	12.3	14.2	16.6	19.4	20.9
HLSPaarl	149	22.7	23.7	21.9	19.4	15.8	13.3	12.3	12.9	14.4	17.2	20.0	21.6
Vredehof	154	22.7	23.5	21.0	18.7	16.1	13.2	12.4	13.9	15.2	17.4	20.8	21.5
LaMotte	206	22.1	22.8	21.3	18.6	15.6	12.8	12.3	13.3	14.8	17.2	19.5	21.2
Franshoek	244	22.2	23.5	21.6	19.0	14.9	13.0	12.1	11.7	13.0	17.0	20.2	20.7
LaPlaisante	260	22.9	23.1	21.5	18.4	14.9	12.6	11.7	12.3	14.3	17.0	19.9	21.6
Heldervue	755	19.1	19.3	18.0	15.4	12.5	10.7	10.5	10.5	11.6	13.5	16.7	18.3

An analysis of the climatic data shows that the climate at the Hoër Landbou Skool, Paarl is closest to the average between highest and lowest for all weather stations, while Franschhoek and Langebaan/Eendekuil represent the two extremes (Figures 4.2 and 4.3). Both Rooihoogte and Broodkraal fall within the higher ET_o - low rainfall regions in the catchment.

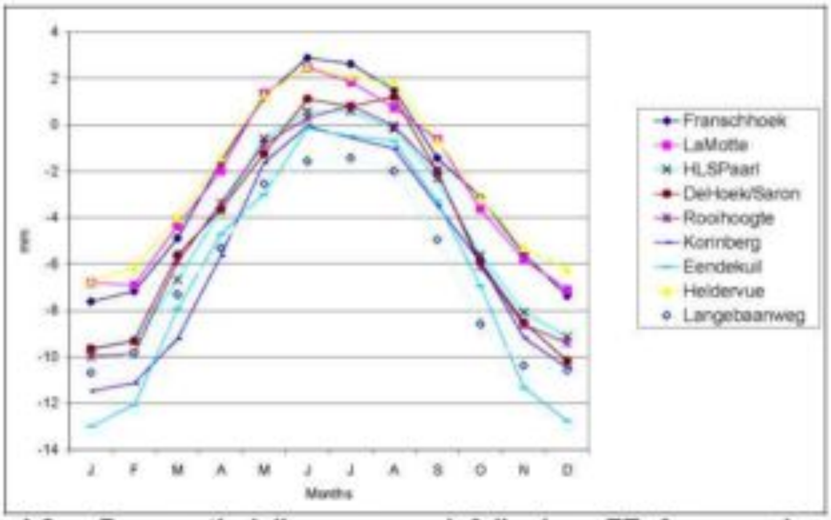


Figure 4.2 : Per month daily average rainfall minus ET_o for a number of weather stations spread over the Berg River catchment

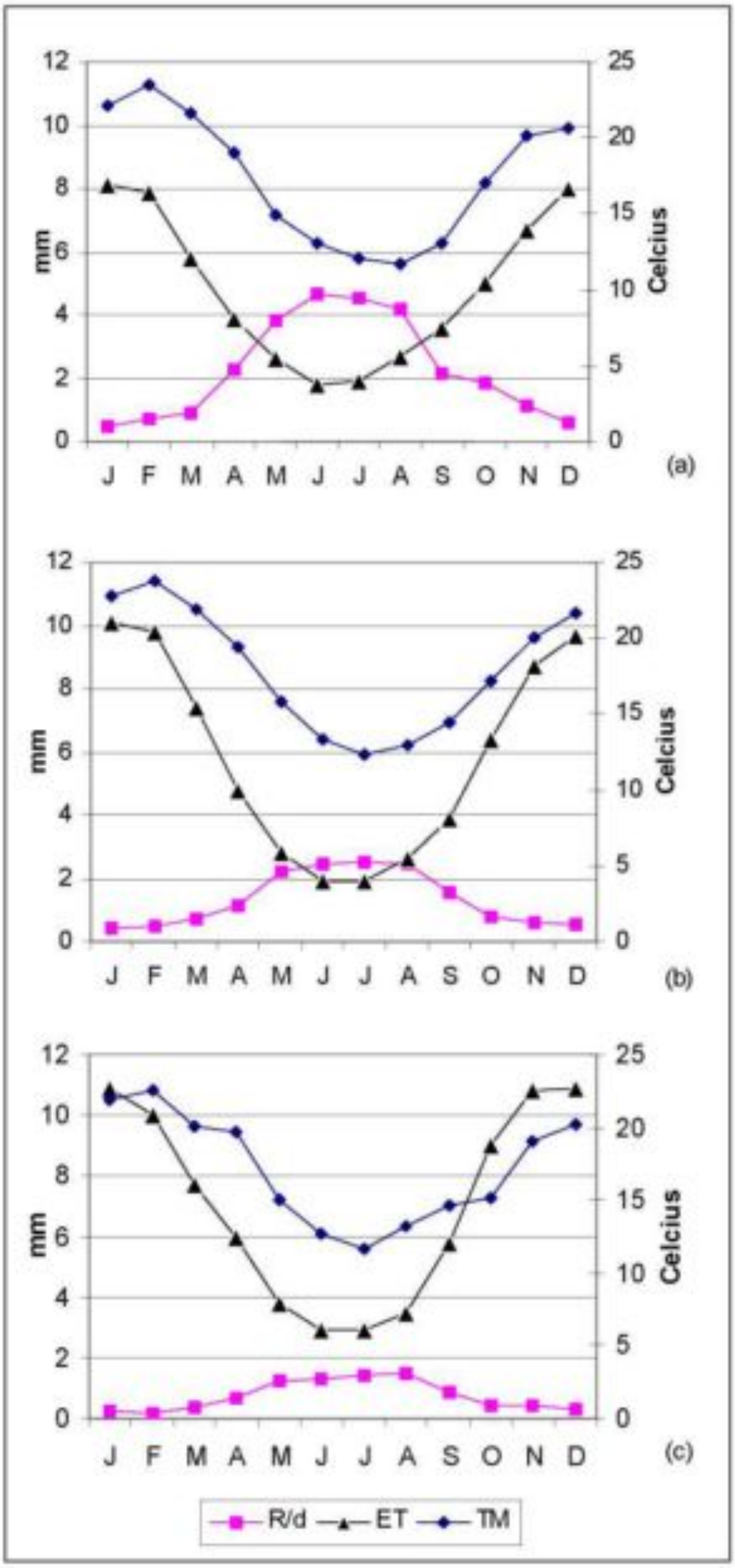


Figure 4.3 : **A comparison between (a) Franschhoek, (b) HLSBoland and (c) Langebaanweg in terms of evapotranspiration (ET_o), average temperature (T) and rainfall (R/d)**

4.3 THE BERG RIVER CATCHMENT GEOLOGY

The geology of the material underlying the irrigated soils is of importance in this study. Of prime interest therefore is the Swartland Subgroup with Formations Moorreesburg, Porseleinberg, Klipplaat and Berg River (in increasing age). The largest section of the Swartland Subgroup falls within the Berg River catchment. The Moorreesburg Formation consists of alternating graywaches and pelitis with some thin and dark limestones. The Porseleinberg Formation consists of mainly quartz-muscovite-biotite schists and chlorite-muscovite phyllites. The Klipplaat Formation has light coloured quartz schist that usually has mica-schists at the base. A few carbonate lenses do occur, in some places large enough to mine. The Berg River Formation has mainly mica and quartz schists with graywache and limestone units. Gradation exists toward the overlying Klipplaat formation. Most of the Malmesbury shales are underlain by the Cape Granite batolith (Kent, 1980).

The age of the Malmesbury Group was determined by Alsop and Kolbe (1965) on Malmesbury pelites and found to be in the region of 550 to 640 million years of age, i.e. late Precambrium. The Malmesbury Group was apparently also deformed and metamorphosed to low grades during the late Precambrium Saldanhian orogenic episode (Kent, 1980).

The underlying Cape granitic complex was dated at about 130 million years making it Cretaceous in age and synonymous with the Gondwana Erathem.

4.4 LAND-USE IN THE BERG RIVER CATCHMENT

Land-use in the BRC consists predominantly of dryland agriculture. Table 4.6 shows land use of the Swartland region and it is clear from the data that the area used for dryland agriculture totally overshadows that of irrigated. From field verification it is also evident that most irrigated land lines the banks of the Berg River. Almost all irrigated land, falls within the immediate 2 km range from the Berg River.

Table 4.6 : Land-use in ha for various crops of the Swartland region (Lipton *et al* (1996))

Dryland crops	ha	Irrigated crops	ha	Vegetable crops	ha
Wheat	267600	Fruit	4260	Potatoes	2234
Oats	30590	Vegetables	7290	Onions	240
Legume pastures	43860	Grapes	16600	Tomatoes	70
Other pastures	66100	Pastures	3690	Peas	900
Other crops	73920	Other crops	460	Sweet melon	160
Fallow land	211330	Vegetables	7290	Other cucurbits	485
				Brassicas	720
				Carrots	220
				Green beans	140
				Sweet potatoes	110
				Beetroot	105
				Other	1900
Total	693400		39590		7284
Percentage	94		5		1

The DA office at Elsenburg has access to a low-resolution satellite image database, from which land-use information could be derived. However, this data was found to be of almost no use to us in our development of a predictive model for irrigation return-flow. It was not an aim of this project to compile updated land-use information for the whole catchment, but this must definitely receive high priority in the future. Land-use was however mapped on the two localities where the detailed work was carried out.
Two experimental sites

4.5 TWO EXPERIMENTAL SITES

Maps of the two experimental sites were compiled (Figures 4.4 and 4.5). They include soil types, the farm layout, position of the experimental equipment and positions of soil sampling. Exact land-use information is also available. Existing information was verified and maps were compiled with the aid of ArcView.

These maps can also be seen in the addendum of this report and can be viewed on the accompanying CD-rom[2].

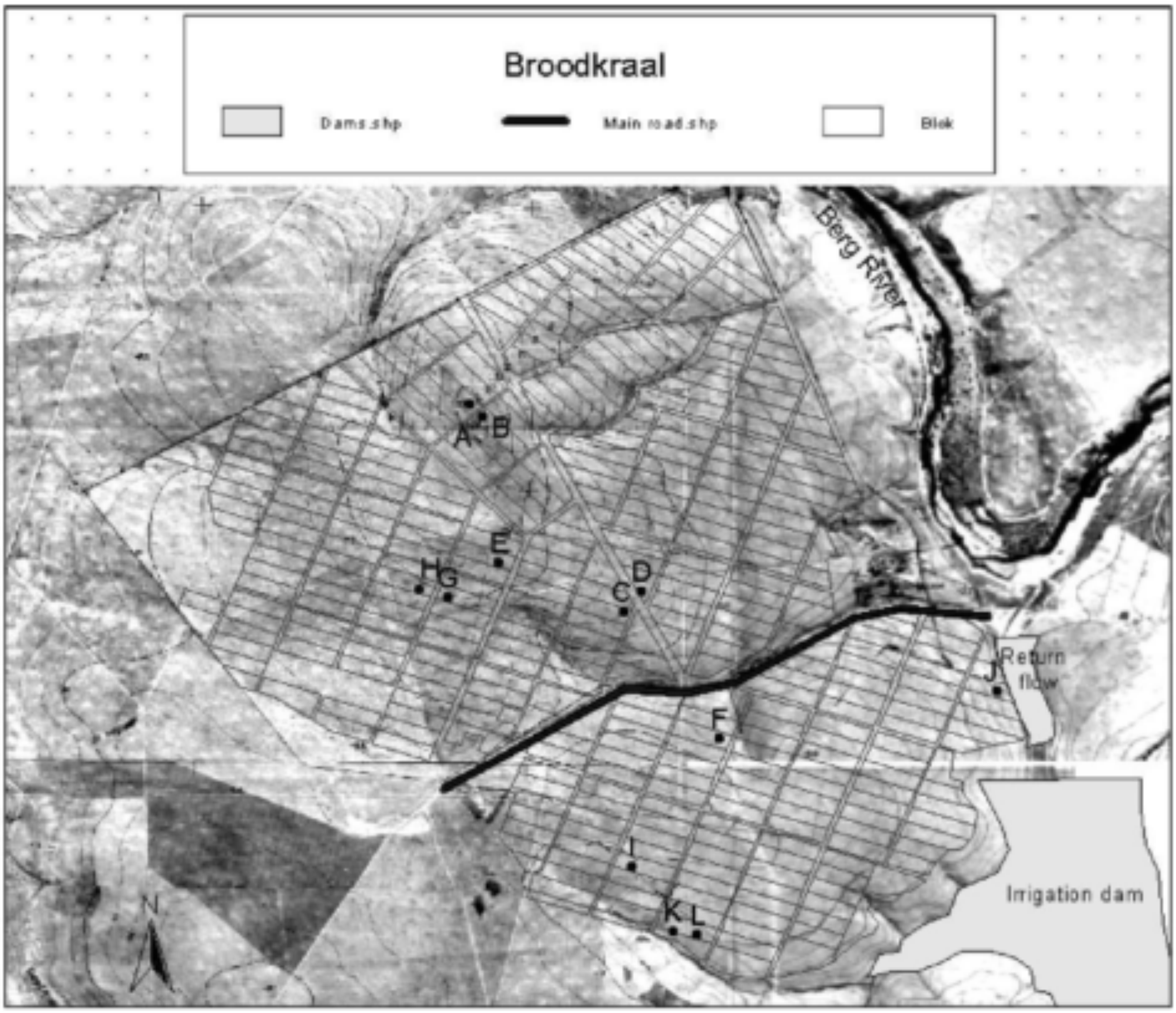


Figure 4.4 : Contour Map of the Broodkraal Farm showing the farm layout (see Appendix B)

[2] For instructions see Addendum B in the appendix.

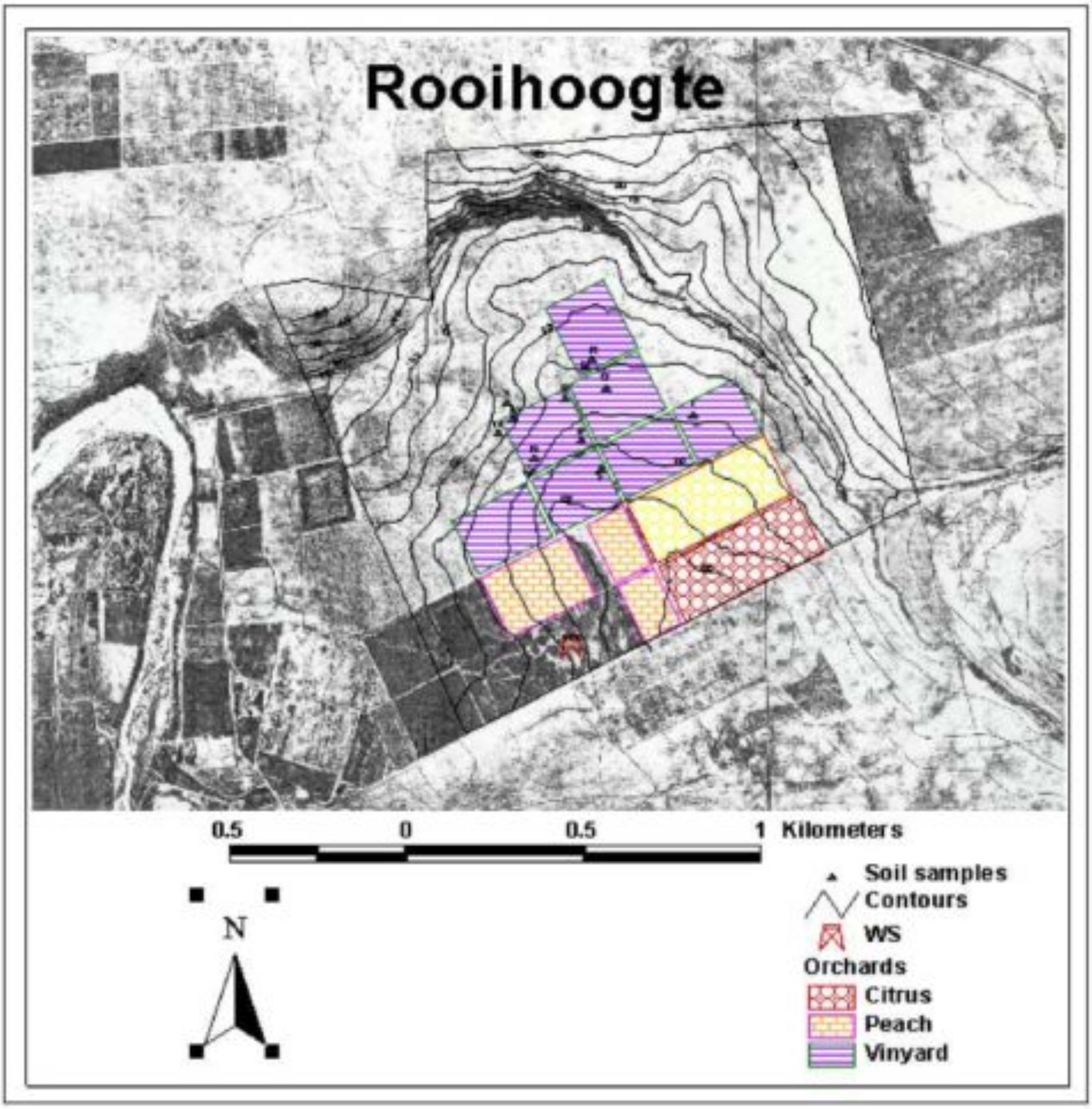


Figure 4.5 : Contour map of Rooihoogte showing the farm layout and observation points for this study

CHAPTER FIVE
METHODS

5.1 VARIABILITY IN THE NATURAL, DRYLAND AND IRRIGATED SOILS

As a result of the large spatial variability in the concentration of solutes in the soils of the Berg River, it is very difficult to distinguish spatial effects from net changes in salinity over time. There are four different categories of variability which influence salinity/sodicity in the landscape. These are:

1. Variability with time, within seasons and years.
2. Variability as a result of an irrigation/ET induced pattern in an irrigated vineyard/orchard, i.e., spatial variability on the micro scale.
3. Spatial variability on the macro scale, influenced by position in the landscape and soil type.
4. The natural spatial variability in the Berg River soils over short distances as a result of biogenic factors, e.g. the occurrence of "heuweltjies".

These factors are of major importance in the assessment of salinity and related variables. It has particularly important implications for research, which requires repeated sampling of soil at the same site to monitor soil salinization trends, for example. It is critical that sampling and analytical methods are used which takes soil variability into account. In this study we made use of geostatistical methods to describe natural variability in soils. All sampling were done to minimize the effect imposed by an irrigation system.

5.2 MAPPING THE SOILS OF THE CATCHMENT

The whole area was carefully surveyed and all areas that can possibly be used for future irrigation development were visited. A soil map of the whole catchment was sketched on 1:50 000 maps during field visits, from which it was digitised. Old information in the form of existing soil maps and maps from farms were used to compile the soil map of the BRC.

From the soil map of the Berg River soils, soil suitability maps for annual and perennial crops were compiled. A salinity hazard map was also compiled using the soils map as basis. The salinity hazard map was based on elements derived from soil classification and the personal experience of researchers/pedologists who are familiar with the area. The derivation of for instance the salinity hazard information is discussed in Section 5.7.

5.3 METHODS USED TO MEASURE IRRIGATION WATER RETURN-FLOW VOLUME

Return-flow can be measured in various ways. It is important that the methods used are cost effective methods and can be used to extrapolate return-flow values to the whole BRC. This study aimed at generating variables and techniques that will lead to a more successful evaluation or modelling approach of return flow in the BRC. It is therefore important to view methods and results against this background. It was not the aim of this project to model the results but to supply a good background for modelling. Methods that were envisaged at the onset of this project will therefore be discussed briefly in this section.

5.3.1 Direct Measurements

Area linked to drainage rates
The total surface area feeding each drainage system was determined. It can also be derived from the accompanying maps of the two study areas. The quantities of irrigation and rainfall were monitored. The quality of the irrigation water and drainage water was also monitored. Estimates could therefore be made of the volume of drainage water per unit area and could in some instances be related to soil type. These drainage measurements naturally include irrigation surface runoff, tile drain flow, irrigation system leakage and seepage, as they were impossible to separate.

Suction cups
Suction cup lysimeters were used to sample soil-water on eight sites on the Broodkraal Farm. Samples were taken from at least three depths in each soil profile. One sampler was installed as deeply as possible at each site, at the base of, or at least in, the weathering zone. Samples from these samplers can be considered as having come from below the root zone, and therefore represent the quality of the

drainage water at that point. These samples were taken shortly after an irrigation event when the soil water status was at field capacity. Since the plant available water in most sites was fairly low resulting from the high stone content of these soils, sampling had to be planned carefully. Sampling was mostly carried out at a matrix pressure of –10 kPa. The method of sampling was fully described by Moolman *et al* (1999) and De Clercq *et al* (2000).

5.3.2 Indirect Drainage Measurements

These include modelling drainage from soil water content, irrigation volumes and weather station-derived parameters.

Modelling PET and AET from neutron probe, irrigation and weather station records and soil samples

Weather station records were used as input data to model irrigation return-flow. It is possible to predict return-flow from ET_0 data, soil moisture data and the irrigation record, but at least one full year of data was needed before a useful modelling effort could be attempted. As a result of disruptions in the monitoring of these parameters during and between seasons, construction of a reliable database over three years, which was the duration of the project, was not always possible.

The salt accumulation rate in dams or streams

There are two dams on the Broodkraal Farm. One is used for irrigation water and the other for the accumulation of return-flow water, before it flows back into the river. Both the quality of water in the irrigation dam and the quality of the return-flow dam's water were monitored. The rate of overflow from the return-flow dam gave an indication of the amount and quality of water that drains from the irrigated area. This rate was, however, not monitored continuously but estimated at the pipe structure when visited.

This could also be done for the irrigation dam, where the salinity increased over the season as a result of seepage and drainage toward the dam. The responses measured at the irrigation dams supplied the opportunity to evaluate return-flow modelling results. However, these accumulations of salt within the dams generate a feel for the total amount of return-flow. For the modeller, it is not easy dividing these EC values generated within the dams into components, namely irrigation return-flow and dryland saline seep.

5.3.3 Soil Salinity Profile Data to Predict Salt Load in the Profile and the Quality of the Soil Water below the Root Zone

For the purposes of predicting the salinity hazard resulting from irrigation, it is important to distinguish between subsurface water movement caused by irrigation and "naturally" occurring ground water. In particular, it would be useful to devise a method to predict leachate quality from readily available soil salinity data, with which the EC in the subsoil could be predicted from the upper soil horizons. The soil saturation conductivity, EC_e, is the most commonly used measure of soil salinity – however, this does not have a fixed relationship with the EC of the soil water (EC_{sw}). EC_{sw} measurements must be used to calibrate EC_e results for useful predictions of leachate salinity to be made. Further, EC_{sw} samples must be taken at field capacity, for the reason that no drainage takes place when the soil water content is lower than field capacity. This means that the water quality at or above field capacity level is of importance. Ultimately, EC_e values from the upper horizons at any sampled point can be used to predict the potential quality of the leachate below the root zone. More detail on this approach can be found in De Clercq (2002).

5.3.4 Geostatistical Modelling and Mapping of Soil Variables

Traditionally, the largest problem in modelling the soils of the Western Cape is how to account for the large variation in soil type, stone content, salinity and the clay content. Geostatistical modelling provides a solution to this problem, since once the semi variance is modelled for any of the mentioned variables, the model can be applied to simulate the sampled area but also as a way of extrapolating the results. Similar soil types elsewhere in the catchment may have similar semi variances.

The approach used involved statistical techniques that allow the prediction of the variability between sampling positions. Soil sampling was therefore carried out with geostatistical analytical methods in mind. The sample set was taken on a 45 m by 50.5 m grid, generating a grid of 15 by 21 samples. Sampling positions that fell on roads and non-cultivated land were omitted. Therefore a total of 60 ha were sampled, generating 264 samples. To be able to describe soil variability between the sampling positions, 4 sets of 17 samples were taken randomly within four of these grid units. The sampling technique also entailed a pooled sample of three micro-positions within a vine row to minimise the effect of the micro-irrigation pattern. These samples were analysed for electrical resistance, electrical conductivity (EC_e), pH and clay percentage.

The trunk circumference (TC) of each of the 16 vines surrounding each sampling position was measured. The age of each vineyard was noted. The spatial co-ordinates of each sampling point were defined.

Geostatistical methods

The maximum distance over which a variogram could be calculated (hmax), was restricted to half the largest dimension of the study area, i.e. its diagonal measurement (L). This distance was calculated using Equation 8. If a larger lag is used, the variogram will lose its representivity, as only the rim of the study area will be used in the calculations.

$$\left[\sqrt{J^2 + K^2}\right]/2 = \mathrm{L} = \mathbf{h}_{\max} \qquad (8)$$

with J and K the dimensions of the study area.

Therefore the maximum lag-distance that could be used in calculation of the experimental semivariogram was 576 m. Generally, a maximum lag distance of not greater than 500 m was used.

All variograms and variogram models were prepared with VARIOWIN 2.2 software (Pannatier, 1996). The spatial variance of a regionalised property Z, is usually modeled in geostatistics by use of the semivariance γ (**h**) (Journel and Huijbregts, 1978):

$$\gamma(\mathbf{h}) = \frac{1}{2n(\mathbf{h})} \sum_{i=1}^{n(\mathbf{h})} \left[Z(\mathbf{x}_i) - Z(\mathbf{x}_i + \mathbf{h})\right]^2 \qquad (9)$$

with Z(x)i the value of variable Z at location **xi**, **h** is a distance vector (lag) and n(**h**) is the number of pairs separated by **h**. Curves are fitted to the semivariance data using various models. Mainly, exponential and spherical models were used to describe the data in this report. A variogram model was fitted to the experimental semivariogram and was characterised by three parameters, namely the sill (C_o+C_1), nugget (C_0) and the range (a) (Pannatier, 1996).

The exponential model is given by the following:

$$\begin{cases} \gamma(\mathbf{h}) = 0 & \text{if} \quad \mathbf{h} = 0 \\ \gamma(\mathbf{h}) = C_0 + C_1\left(1 - \exp\left(-\frac{3\mathbf{h}}{\mathbf{a}}\right)\right) & \text{if} \quad 0 < \mathbf{h} \end{cases} \qquad (10)$$

and the spherical by:

$$\begin{cases} \gamma(\mathbf{h}) = 0 & \textit{if} \quad \mathbf{h} = 0 \\ \gamma(0) = C_0 + C_1\left(\frac{3\mathbf{h}}{2\mathbf{a}} - \frac{1}{2}\left(\frac{\mathbf{h}}{\mathbf{a}}\right)^3\right) & \textit{if} \quad 0 < \mathbf{h} \le \mathbf{a} \\ \gamma(\mathbf{h}) = C_0 + C_1 & \textit{if} \quad \mathbf{h} > \mathbf{a} \end{cases} \qquad (11)$$

Spatial isotropy and anisotropy

Spatial isotropy simply means that the spatial variability is similar in all directions. The reverse is true in case of spatial anisotropy. With isotropy, the semi-variance is determined solely by the lag distance **h** between data points, and is not influenced by the directional vector between the points. The resulting variogram is thus omnidirectional. Thus if the variogram differs for different directions, the situation is anisotropic and directional. In this case, the variogram is calculated with directional windows and the semi-variance is dependant on the directional vectors between data points (Webster & Oliver, 2001; Pannatier, 1996).

Kriging

The aim of Kriging is to estimate the value of a random variable, **Z**, at one or more unsampled points over larger blocks, from more or less sparsely sampled data on a given support. To demonstrate this, discussion will focus on ordinary Kriging, which is by far the most commonly used Kriging process (Webster and Oliver, 2001).

The fitted variogram model determines the weights used for interpolation. The values at all non-sampled locations xo on the surface are given by $Z^*(\mathbf{x}_o)$ and estimated within the local window as linear combinations of data points within the local window:

$$Z^*(x_0) = \sum_{i=1}^{n(b)} \lambda_i Z(x_i) \qquad \text{with} \quad n(b)\, \varepsilon\, n \tag{12}$$

with n the number of data points within the local window, λ_i the weight given to each data point in the local window and $Z(\mathbf{x}_i)$ the measured value of the variable Z at location $\mathbf{x}_i$.

There are two prerequisites for the optimal estimation of the weights (Journel and Huijbregts, 1978):

1. The prerequisite for an unbiased estimator:

$$E[Z^*(\mathbf{x_0}) - Z(\mathbf{x_0})] = 0 \tag{13}$$

2. The prerequisite for a minimal estimation variance $\sigma^2(\mathbf{x}_0)$:

$$\sigma^2(\mathbf{x_0}) = E[(Z^*(\mathbf{x_0}) - Z(\mathbf{x_0}))^2] \text{ is minimal} \tag{14}$$

where $\sigma^2(\mathbf{x}_0)$ is also known as the Kriging variance.

From equation 14, ordinary Kriging (OK) is derived and takes the form of Equation 21:

$$\sum_{i=1}^{n(b)} \lambda_i \gamma(\mathbf{x_i}, \mathbf{x_j}) + \Psi = \gamma(\mathbf{x_j}, \mathbf{x_0}) \qquad j = 1, \ldots, n(b)$$
$$\sum_{i=1}^{n(b)} \lambda_i = 1 \tag{15}$$

and Simple Kriging is defined as:

$$Z^*(\mathbf{x_0}) = \sum_{i=1}^{n} \lambda_i Z(\mathbf{x_i}) + \left[1 - \sum_{i=1}^{n} \lambda_i\right] m \tag{16}$$

where **n** is the number of measuring points within a local window, λ_i is the weight given to each value in the local window, $Z(\mathbf{x}_i)$ is the measured variable, m the known average value and ψ is a LaGrange multiplier.

The procedure then used to apply ordinary Kriging is as follows:

A grid for interpolation is defined (Figure 5.1). The grid is defined in the X direction by **nx** and in the Y-direction by **ny**, with the co-ordinates of the first grid point given in the X direction by **xmn** and in the Y direction by **ymn.** The gridding intervals are given in the X direction by **xsiz** and in the Y direction by **ysiz**.

In this study, these parameters were imported into the KT3D-parameter file of the software WinGSLIB™, which contained the Kriging algorithms (Deutsch and Journel, 1998).

With Simple Kriging, an average of zero is specified. After application of Simple Kriging, a pixel plot is made of the interpolated values, using the GSLIB software. Usually, the average value of the data set is then added to the interpolated values to give a map with true values. This can be done with IDRISI32™ software (Eastman, 1999).

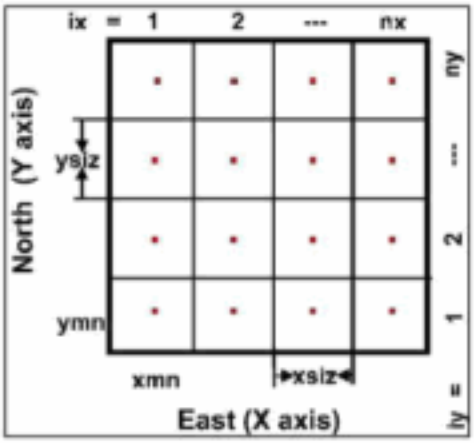


Figure 5.1 : The grid is defined in the X direction by nx **and in the Y-direction by** ny**, with the co-ordinates of the first grid point given in the X direction by** xmn **and in the Y direction by** ymn**. The gridding intervals are given in the X direction by** xsiz **and in the Y direction by** ysiz**. (Deutsch and Journel, 1992)**

Geostatistical interpolation methods were thus used to define regions with similar soil characteristics, and highlight trends in the data that would otherwise not have been easily detectable. The digitised results were analysed further with the aid of Idrisi GIS software. Using the results, it is possible to estimate soil properties for any point on the farm, and highlight differences between the two most prominent soil forms. If two maps of salinity are compared, for the same area, but reflecting sampling carried out on different dates, it is possible to calculate the average rate of change of soil salinity for any point on the map. This makes it possible to estimate the average rate of salt input or output for the region mapped.

5.4 QUALITY OF RETURN-FLOW WATER

As mentioned previously, to enable the successful prediction of return flow, one will have to distinguish between the quality of the drainage water leaving a certain point in a profile below the root zone, and the bulk of the return flow that was generated elsewhere, be it from surface runoff, from higher lying irrigated areas or higher lying dry land areas. In short, the origin of the salt in the landscape had to be established. When the prediction of return flow from the irrigated surfaces did not generate similar values as were measured in some of the drains, there had to be another source of salt and water.

Sampling of drainage water, river water and irrigation dam water was carried out at various points. These samples were considered as being inclusive of all possible water sources that can generate return flow. It is therefore not a good measure of return flow generated by irrigated agriculture *per se*.

A simple model was developed to predict the quality of the soil water beneath the root zone, a model that also accommodates the high stone content found in these soils. It will also be shown that the high stone content and the variability thereof can be seen as one of the main factors leading to high volumes of return flow.

The data acquired consist of the following:

1. Irrigation amounts and quality measurements (EC_i).
2. ET and full weather station records.
3. ECsw of at least three horizons.
4. ECe at the start and end of season.
5. Soil physical parameters: stone %, clay %, density and field capacity of the soil fraction in the soil profile.
6. Drainage water amounts and quality measurements(EC_d).

7. Some water table measurements.

These data sets allowed the use of more than one model, but we found that not all models are suitable for soils with a high stone content, and therefore a very high tendency toward preferential flow. Modelling was therefore attempted using a simple model that accounted for all the relevant volumes and the quality of the soil water below the root zone. Then the DISA model by Görgens *et al* (2001), previously developed for this purpose and applied to the Breede River valley, was tested on this data. However, problems encountered with running the model on a new computer system environment meant that the results had to be omitted from this report. The results will, however, be included in a MSc thesis by H Engelbrecht (2002). DISA was found to be the perfect platform to which to link geostatistically prepared results to and the need exists to upgrade this program as a management tool.

The dynamics of preferential flow was tested by linking tipping bucket flow meters to a data-logger, one measuring irrigation duration and the other drainage from a tile drain (Moolman and De Clercq, 1993). Though this approach was not always successful (as a result of using electronic equipment in a very wet environment), we did manage to capture some results.

For this study it was decided to use the following approach to predict the volumes of water draining from individual sites, and to use the measured quality of the drainage water and/or the quality of the suction cup data from below the root zone to calculate return-flow quality for these sites.

The approach is represented algebraically as follows:

$$Q_d = Q_i + Q_p + SMC_{(previous\ day)} - (PET_{(previous\ day)} \text{ x } CF) - Q_r - FC' \quad (17)$$

where
Q_d = Quantity of water leached (mm)
Q_i = Quantity of water irrigated according to water meters (m^3) and irrigated area (m^2)
Q_p = Quantity of water rainfall (mm)
SWC = Soil Water Content per profile depth ($mm.mm^{-1}$)
PET = Potential evapotranspiration (mm)
CF = Crop factor for every month and specific for crop
Qr = Quantity of water runoff (mm)
FC = Field capacity per profile depth (mm)

with field capacity and soil water content calculated as

$$FC = SWC_{FC} \text{ (at -10kPa) x (1-Stone fraction) x Profile depth (mm)} \quad (18)$$

$$SWC = FC - (PET_{(previous\ day)} \text{ x } CF) \quad (19)$$

Salt leaching was then calculated as follows:

$$M_d = [Q_d \text{ x } 10000 \text{ x } C_d)] / 1000000 \quad (20)$$

and where
M_d = Mass of salts leached in $kg.ha^{-1}$
Q_d = Quantity of water leached (mm)
C_d ($mg.L^{-1}$) = EC ($mS.m^{-1}$) x 6.3
SWC_{FC} = Soil water content at FC, i.e. at -10kPa

From Equation 18 it is evident that the stone content in the soil reduces the soil volume in the calculation. The calculation of the actual field capacity and actual soil water content in Equations 18 and 19 is very important in these soils. This approach is still not the most desirable, but is a way of avoiding the more complex modelling of preferential flow and mass flow. It is worth repeating that this approach uses actual measured drainage water quality, i.e. soil water quality measured below the root zone at all measuring points.

5.5 DEALING WITH THE ORIGIN OF SALT AND THE WATER TABLE

On both farms the whole area was scanned for an old borehole or any sign of standing water that can be linked to a water table. Nothing was found and it was decided to dig deep trenches, down to 5 m deep in places where the saprolite was soft enough. An excavator was used to dig trenches on and between the ancient termite mounts (heuweltjies) found on both farms. This allowed us more flexibility to study the manner in which salt is trapped in this landscape. The trenches ought to have given a good indication of the depth to the water table but no standing water was found. The only reason can be that the water table was much deeper.

An observation showed that certain wet zones exist lining most valleys in the lower BRC as one approaches the river or one of its tributaries. These are mostly outcrops of the underlying Malmesbury shale. Measurements showed that the water seeping from these outcrops were as high as 500 mSm^{-1}. This is seen from outside of Wellington down to Piketberg.

A large degree of horizontal variability in the concentration of salt in the soil was associated with the occurrence of heuweltjies. The profiles in these trenches were carefully mapped and resulted in a change of our thinking toward the movement of salts through these soils, the position of the water table in this landscape and the origin of salts found in the now irrigated landscapes.

Land that is presently used for wheat production under rain-fed (dryland) conditions, on Broodkraal and Rooihoogte farms, was chosen for this study. The areas were selected based on information gathered during various soil surveys conducted in the region and on the two farms. They included the soils that are likely to be used for irrigation development in the near future. Areas with a high density of heuweltjies per unit area were found to be associated with the remnants of an old land surface in the irrigation area. The two farms that were selected for more detailed investigations both have remnants of the old land surface with heuweltjies on them. Monochrome orthophotos (1:10 000 scale) were used to determine the density and distribution of heuweltjies on and in the immediate surroundings of the two farms. A mechanical excavator was used to dig trenches to bedrock or hardpan on and between the heuweljies. Profile wall mapping, soil classification and sampling was carried out at least every 5 m in the trenches. Samples were analysed for pH, resistance, extractable and soluble cations using standard laboratory techniques (The Non-Affiliated Soil Analysis Work Committee, 1990).

5.6 EXTRAPOLATING RETURN-FLOW VALUES OVER THE CATCHMENT

Once the drainage rates and quality of drainage water have been established for certain soil types or certain combinations of soils, it becomes possible to relate these values to similar situations throughout the catchment. Various approaches are possible as will be outlined in the results section. It is of utmost importance to establish the exact origin of most salts in the system, as this has to be included in a catchment scale predictive model. In Section 5, the possibility of mapping salinity with a device like the EM38 soil conductance instrument was investigated. It was, however, not possible to use this instrument in the vineyards as the numerous wires in the vine support system influenced the readings too much. The instrument can be used in the dryland areas surrounding these irrigation farms. It is our understanding that the dryland regions contribute significantly to the salt content of the irrigated areas, whether directly or indirectly. The geostatistical mapping of a small catchment on the Broodkraal Farm opened up possibilities of mapping and predicting salt movement over time in relation to parameters like relative altitude, a growth index, abundance of specific chemical elements, soil physical parameters and soil types.

CHAPTER SIX
RESULTS

6.1 DETAILED STUDY OF BROODKRAAL FARM

6.1.1 Climate

The Broodkraal Farm uses a weather station linked to ADCON software to generate ET_o data and predict the required irrigation rates. This data set starts in 1997. The data are used on a daily basis on the farm for calculation of ET_o and a whole range of management parameters. For the purpose of this report it was decided to include the long-term averages only (Table 6.1).

Table 6.1 : Long-term averages of variables measured at the Broodkraal weather station

	Air Temperature C			Rel. Hum.		Precipitation	Evap	Wind
	Average		Extremes	%		mm	mm/day	(km)
	TX	TN	HXX	UX	UN	R	(PET)	W
Jan	34.5	17.2	41.5	77	27	3	13.1	259
Feb	33.6	17.7	40.2	70	26	9.3	12.4	245
Mar	30.8	15.7	40.6	88	35	14.6	8.4	201
Apr	27.2	12.8	37.8	91	38	35.6	5.9	193
May	23.6	10.4	34.6	89	40	21.7	3.7	170
Jun	19.4	7	28.6	90	44	55.6	2	146
Jul	17.7	5.9	25.2	89	47	37.2	1.7	138
Aug	20.2	7.4	31	92	45	53.1	2.4	158
Sep	21.9	7.8	32.8	93	39	24.1	4.1	171
Oct	25.5	8.8	36.4	87	29	14.2	7.4	200
Nov	30.9	13.5	41.6	78	27	5.2	11.5	250
Dec	32.5	15.3	41.4	73	25	0.9	12.8	268
Tot						274.5		
Ave	26.5	11.6	36	85	35	22.9	7.1	200

TX : Mean daily maximum temperature (ºC)
TN : Mean daily minimum temperature (ºC)
HXX : Highest observed daily maximum temperature (ºC)
UX : Mean daily maximum relative humidity (ºC)
UN : Mean daily minimum relative humidity (%)
R : Mean monthly total precipitation (mm/month)
W : Mean daily wind-run (km/day)

Figure 6.1 shows the actual evapotranspiration (AET or ET_o) at Broodkraal, calculated by making use of published crop factor values and the Penman-Monteith ET derived from local weather station observations. These data constitute an input to our return-flow model.

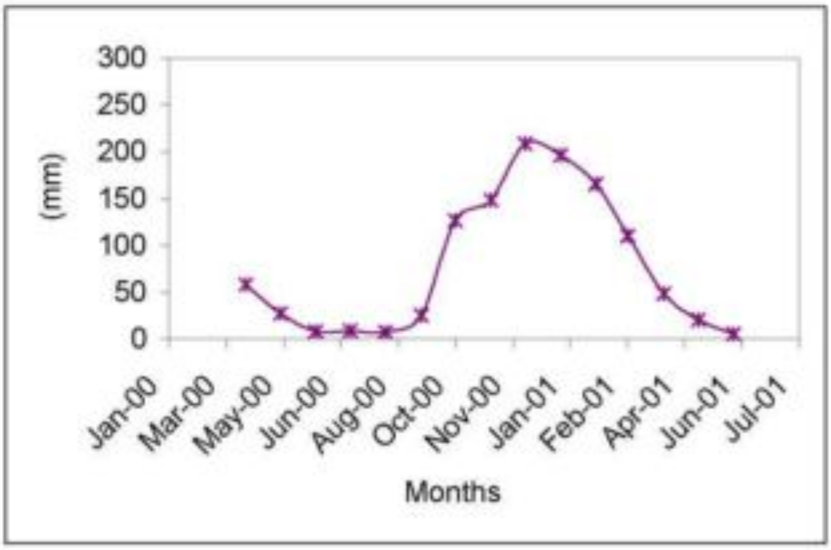


Figure 6.1 : Total monthly AET measured at the Broodkraal Farm using published crop factors for this region

6.1.2 Soil Surveys

A soil map of the Broodkraal Farm is given in Figure 6.2.

Figure 6.2 : Soil map of the Broodkraal Farm showing the sampling positions (see map in Appendix B)

Figure 6.2 also shows the positions of measuring points on the Broodkraal Farm that will be used to monitor soil EC_e and EC_{sw} over the duration of the study. These points are listed here, indicating the soil type and the year the vines were planted (Figure 6.2):

A: Glenrosa planted in 2000
B: Glenrosa planted in 1998 (1999)
C: Glenrosa planted in 1998
D: Glenrosa planted in 1997
E: Glenrosa planted in 1999
F: Glenrosa planted in 1996
G: Oakleaf planted in 2000 (1999)
H: Oakleaf planted in 1998
I: Oakleaf planted in 1996
J: Glenrosa planted in 1996
K: Swartland planted in 1996
L: Glenrosa planted in 1996
Y: Irrigation and drainage monitor site
Z: Irrigation and drainage monitor site

Descriptions of these soils are given in Appendix A.

6.1.3 Survey of Drainage

Drainage water collects at the bottom end of the drains marked from 1 to 5 in Figure 6.4 and from there runs in an open canal, pipe or furrow to the return-flow dam on the farm. The positions of the drains and the EC_d measuring positions are shown in Figure 6.4. Drainage reaction is shown in Figures 6.3, 6.5 and 6.6. In Table 6.2, three EC_d values are indicated for each drain indicated on Figure 6.4, namely the start, middle and end of irrigation season EC_d value. The similarities between the drains are a decrease in EC_d that was found at around December to March each year and an increase from March till the irrigation season started again. This is the most important finding here since irrigation usually decreased during the January/March period. One would expect the EC_d to increase as the drainage volume slows during this period but the fact that the EC_d was lower actually indicates a situation where salts precipitate in the micro pores and irrigation that does occur follows the preferential flow paths through the soil. Irrigation was usually halted from the start of April to discourage excess vine growth.

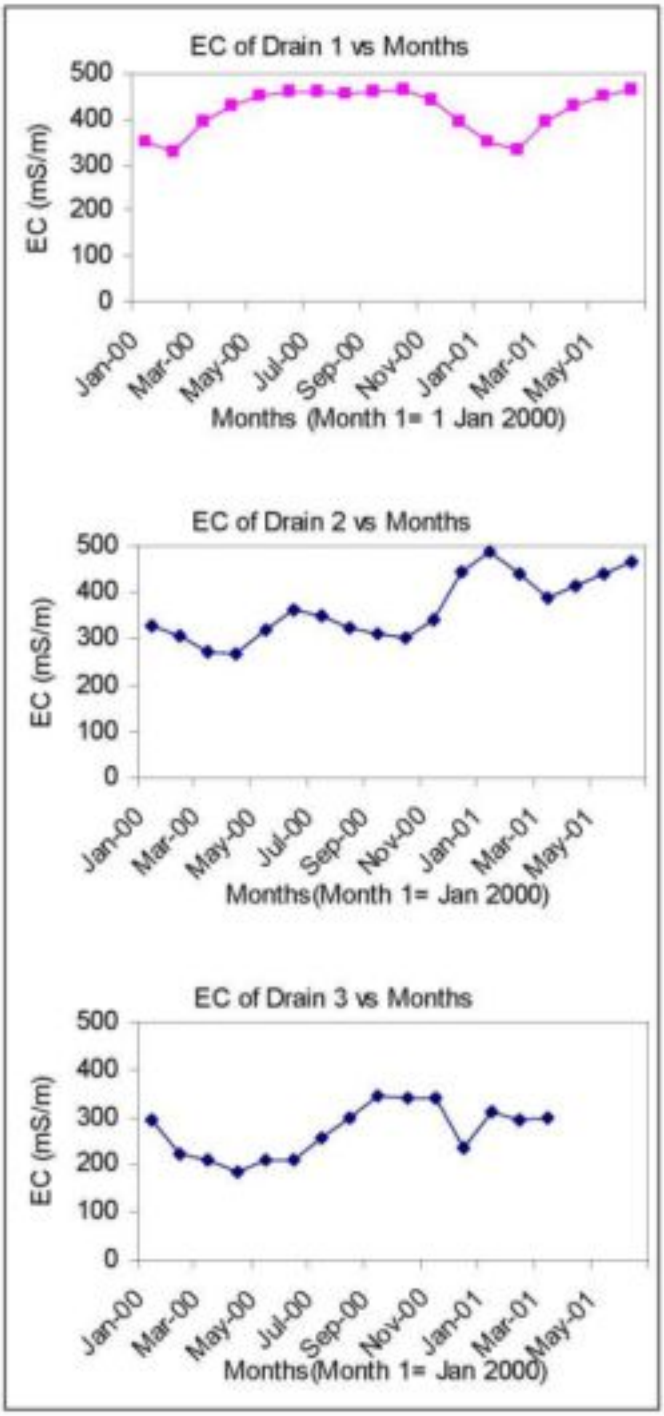


Figure 6.3 : Moving averaged EC_d of three locations on Broodkraal Farm (see maps, Figures 6.2 and 6.4, D1, D2 and D3)

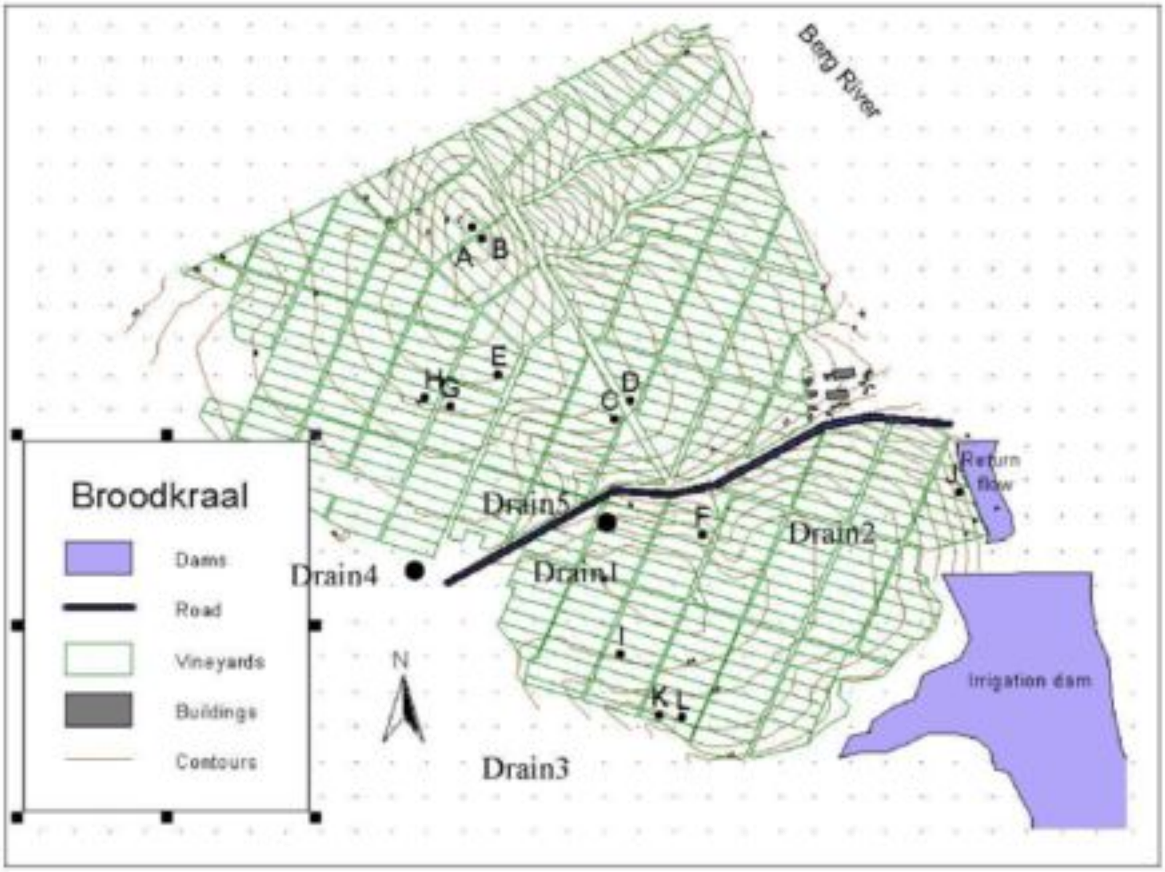


Figure 6.4 : Contour map of the Broodkraal Farm with the farm layout and positions monitoring locations. The contour interval is 5 m and positions A and B are the highest on the farm

Table 6.2 : Start, middle and end of irrigation season EC_d (mSm^{-1}) values associated with drains 1 to 5 indicated in Figure 6.5, the map of Broodkraal Farm

	EC_d (mSm^{-1})		
	Sept	Dec	Mar
Drain 1	347	289	279
Drain 2	390	489	403
Drain 3	298	319	298
Drain 4	139	165	206
Drain 5	193	183	234

Figure 6.4 and Table 6.2 shows an increase in EC_d moving down-slope. This is what one would expect in circumstances where deep drainage does occur. There was a general increase in EC_d at all points during the season. Figures 6.5 and 6.6 show drainage measured at 5 drain outlets on the Broodkraal Farm while Figure 6.6 shows the averaged drainage pattern from these sites. The result presented in Figure 6.6 shows an almost stable general trend. It also shows the lowering of EC_d during January to March each year and the gentle climb in EC_d after March until sometime in December.

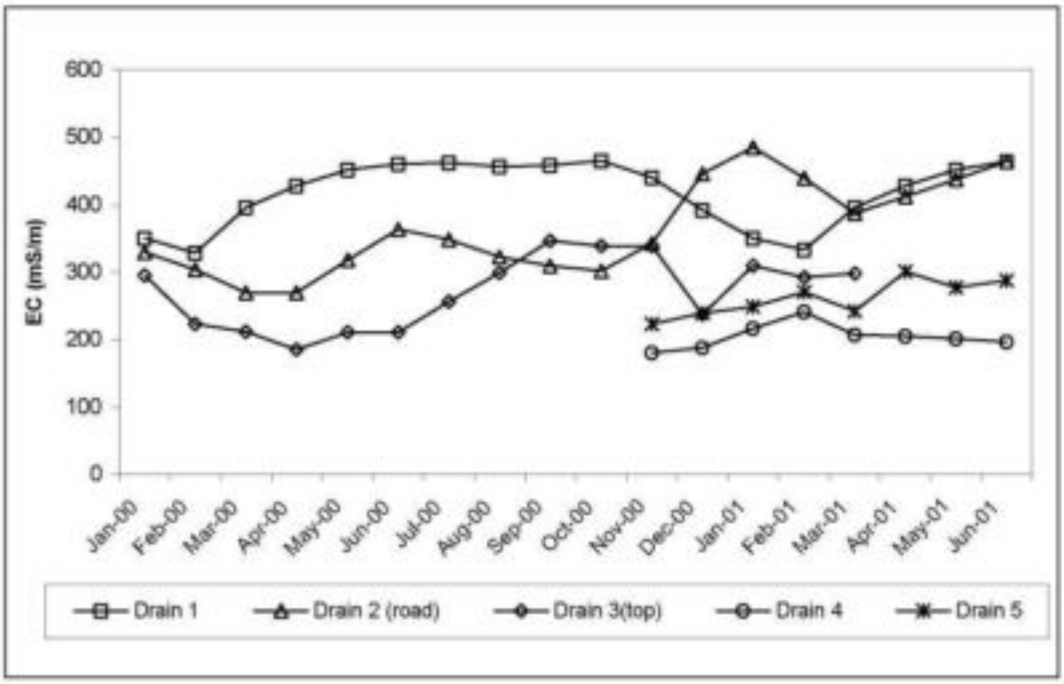


Figure 6.5 : Moving averaged monthly drainage for 5 drains at the Broodkraal Farm monitored since the start and end of 2000. See Figure 6.4 for specific locations

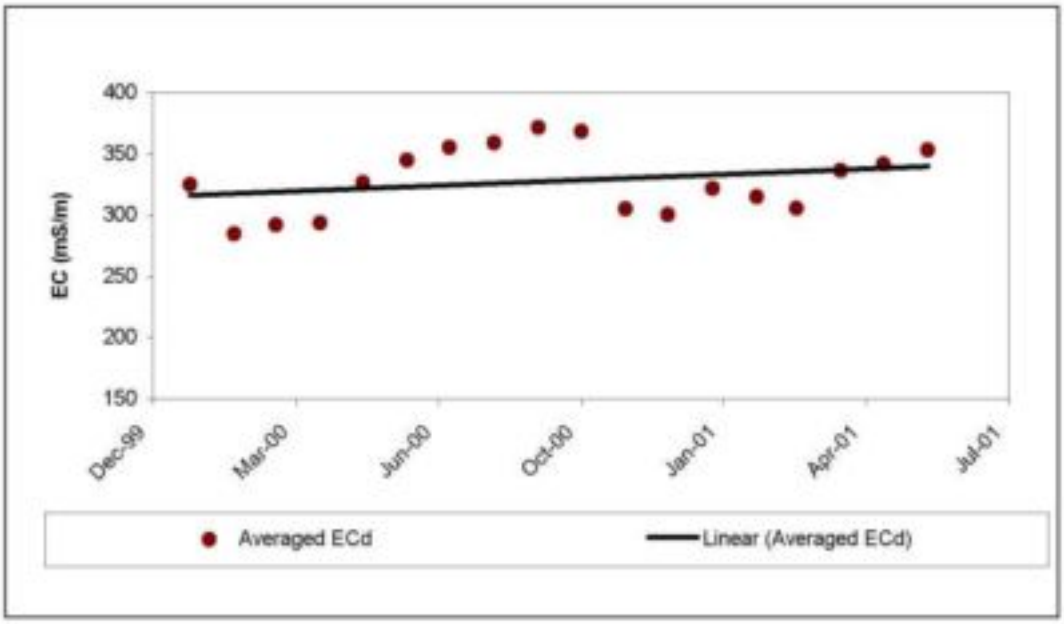


Figure 6.6 : Averaged drainage EC_d (mSm^{-1}) measured at 5 drain outlets on the Broodkraal Farm

6.1.4 Soil Water Measurements

When the project started, neutron probe access tubes were already installed on the farm. The farm management made use of irrigation scheduling techniques using weather station derived parameters and neutron probe moisture meter readings. This database was put at our disposal, but after a year the farm management decided to stop measuring soil water using the neutron probes, since the soil water results obtained from the probes were inconsistent with irrigation rates and plant water use, and showed significant variability. From then on, water meters were monitored and irrigation scheduling done on the basis of ET_o alone. We were thus able to continue monitoring irrigation amounts. However, this study will show that the apparently aberrant neutron probe results were linked to inappropriate irrigation scheduling in saline soils of high stone content.

The ET_o values and irrigation record was used in the water and salt balance calculations shown in Sections 6.1.6 and 6.1.7. The large spatial variability in stone content has a radical influence on irrigation return flow, even within irrigation units. In consequence, special attention was given to stone content and to modelling its spatial variability.

6.1.5 Soil Chemical Properties

Samples from all monitored sites were analysed. These included samples of Glenrosa and Oakleaf soils from the southern and northern part of Broodkraal Farm. Vines in position A were planted in 2000. Position B and C are representative of vines planted in 1998, but B was inoculated with another variety the following year. The vines of position D were planted in 1997, E in 1999 and F in 1996. All of the positions are on the northern part of Broodkraal except F, which is in the southern part.

At each monitoring position, four sets of samples were taken to account for local variability. The four sampling positions consisted of two samples taken within 30 cm of a sprinkler (Tables 6.4 and 6.5, row position 1). The other two were made in the middle between two adjacent vine rows (Tables 6.4 and 6.5, row position 2). At all sites, two holes were thus augured in the vine row and two were augured in the centre-line between two vine rows.

Soil analyses were also carried out on samples from soil monitoring sites in the Oakleaf soils of Broodkraal Farm. The vines of position G were planted in 2000, position H in 1998 and I in 1996. As in the other soils, four sample holes were drilled to account for variability at all the Oakleaf monitoring positions. These positions were located within 30 cm of the sprinkler (Tables 6.4 and 6.5, row position 1). The other two were made between two vine rows, exactly in the middle of the tractor path in line with the two sprinklers on either side (Tables 6.4 and 6.5, row position 2). At all sites, two holes were augured in the grape row and two were augured on the centre-line between two adjacent vine rows.

Table 6.3 : Some analytical results of soil-water samples taken from position B on Broodkraal Farm sampled with suction cup lysimeters

Date	Depth	EC	Ca	Mg	Na	K	Total cations	Cl	NO3	SO4
	cm	(mS/m)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
00.11.29	**20**	180.6	17.8	9.9	98.4	4.1	130.2	192.3		34.8
00.11.29	**40**	114.7	34.4	13.6	141.5	21.0	210.5	317.2	8.5	73.2
00.11.29	**75**	73.2	55.3	24.7	233.2	9.5	322.7			
00.12.07	**20**	153.3	45.8	21.9	195.7	4.0	267.5	328.7	57.4	145.8
00.12.07	**40**	126.8	38.4	15.4	150.0	5.2	208.9	314.8	28.8	88.4
00.12.07	**75**	82.5	19.3	11.6	94.8	4.2	129.8			
00.12.19	**20**	133.5	49.2	22.1	163.2	3.9	238.4	243.1	150.5	91.9
00.12.19	**40**	116.8	37.1	15.2	150.7	3.8	206.8	304.9	22.2	74.5
00.12.19	**75**	74.4	16.7	10.0	94.0	4.3	125.0			
01.01.11	**20**	83.7	27.4	12.8	96.5	3.3	140.0			
01.01.11	**40**	121.3	71.0	123.4	584.4	19.8	798.5	1084.1	8.1	767.5
01.01.11	**75**	90.5	16.8	11.4	110.8	0.0	139.0			
01.01.30	**20**	124.9	42.8	19.8	133.9	4.7	201.2	337.7	2.1	47.5
01.01.30	**40**	169.2	55.1	23.3	203.5	4.0	285.9	516.8	2.2	85.4
01.01.30	**75**	135.5	28.7	18.8	164.5	3.4	215.4	402.3		58.8
01.02.20	**20**	124.0	44.4	21.2	145.6	3.5	214.7	399.1		57.4
01.02.20	**40**	176.4	60.4	25.8	223.0	5.0	314.1			

Tables 6.4 and 6.5 show depth-weighted mean averaged soil results prepared from saturated paste extracts of some of the locations monitored on the Broodkraal Farm. Table 6.4 shows results from the mainly Glenrosa soil types and Table 6.5 shows results from the Oakleaf type soils. It is again important to note the high and very variable stone contents of these soils. It is equally important to note the poor

relationship between EC_e and stone content and pH and stone content. However the relationships will be discussed in a later section of the report.

Figure 6.7 shows the depth relationship of the Ca content and EC_e of the saturated extract from Glenrosa soils. Figure 6.8 was included to show to what extent the Na balance of the Glenrosa soils was affected over time. Figure 6.9 shows the EC_e of the same soils shown in the Figure 6.10, and also shows the effect of irrigation on EC_e of the Glenrosa soils. These results are most meaningful when long-term modelling of soil reaction to saline irrigation water is undertaken.

Table 6.4 : Depth-weighted mean results of chemical analyses on saturated paste extracts from soil samples taken on the Broodkraal Farm in the Glenrosa soils (For positions, see Figure 6.2)

Glenrosa									
Position	Soil depth (cm)	Row position	Stone %	pH (H_2O)	EC (mS/m)	Ca mg/L	Mg mg/L	Na mg/L	K mg/L
A1	90	2	39.6	6.2	269.6	210.8	76.9	295.5	11.7
A2	120	1	35.5	5.7	184.1	50.9	42.6	237.8	5.4
A3	90	2	43.7	4.8	309.5	74.5	62.3	494.9	8.9
A4	60	1	46.1	5.9	344.3	263.5	109.7	336.7	10.9
B1	90	2	53.2	5.0	353.7	158.3	83.0	528.3	12.3
B2	90	1	48.1	4.7	140.4	86.2	34.8	140.6	9.8
B3	60	2	39.6	4.9	349.3	156.3	77.4	473.7	14.9
B4	90	1	42.2	5.2	77.9	29.8	11.0	95.8	7.4
C1	90	1	45.1	7.0	225.7	101.9	64.4	263.3	11.8
C2	90	2	40.6	6.7	242.0	122.3	40.1	329.4	11.2
C3	120	1	35.4	6.5	235.5	64.0	48.6	350.0	8.8
C4	120	2	28.7	7.2	388.5	290.4	91.1	477.8	14.7
D1	100	1	45.2	6.2	132.5	33.9	30.4	161.8	11.1
D2	120	2	48.8	6.4	166.8	35.9	38.2	224.0	12.1
D3	90	1	44.1	6.1	172.4	47.9	45.6	217.9	9.3
D4	90	2	41.3	6.4	186.0	39.8	40.5	205.9	9.8
E1	60	1	55.4	5.2	132.1	101.2	17.9	159.0	13.2
E2	90	2	49.1	7.5	504.7	533.0	94.0	447.2	23.6
E3	90	1	42.2	7.3	190.9	369.8	72.3	318.1	24.4
E4	120	2	46.4	7.2	387.0	271.0	76.4	330.1	15.3
F1	60	2	35.6	5.7	229.1	61.4	63.1	321.1	8.0
F2	90	1	51.9	6.3	154.7	61.1	36.6	172.7	8.6
F3	60	2	53.4	6.8	40.8	41.0	15.0	37.5	0.8
F4	60	1	47.0	6.5	396.8	541.4	127.7	281.9	10.0

Table 6.5 : Depth-weighted mean results of chemical analyses on saturated paste extracts of soil samples taken on the Broodkraal Farm in the Oakleaf soils (For positions, see Figure 6.2)

Oakleaf									
Position	Soil depth (cm)	Row position	Stone %	pH (H_2O)	EC (mS/m)	Ca mg/L	Mg mg/L	Na mg/L	K mg/L
G1	120	1	24.9	5.4	141.9	104.2	42.8	272.2	12.0
G2	120	2	24.6	5.4	157.3	48.9	29.6	205.0	13.2
G3	60	1	34.0	6.0	134.4	64.1	31.3	157.8	8.7
G4	90	2	24.8	6.7	134.6	63.4	52.2	182.2	6.3
H1	90	1	82.7	6.1	88.9	15.2	13.8	119.6	10.9
H2	120	2	84.4	5.8	167.3	33.0	27.5	239.5	6.1
H3	120	1	10.6	6.3	78.9	10.7	9.2	111.0	3.8
H4	120	2	14.6	6.5	166.0	33.1	24.0	242.6	7.8
I1	90	1	57.9	5.4	58.4	23.0	7.7	65.4	13.2
I2	90	2	42.2	6.8	103.6	62.8	12.1	124.7	12.3
I3	90	1	51.9	6.2	114.6	63.9	12.0	123.6	4.7
I4	60	2	47.9	5.0	223.7	169.9	31.4	202.0	17.6

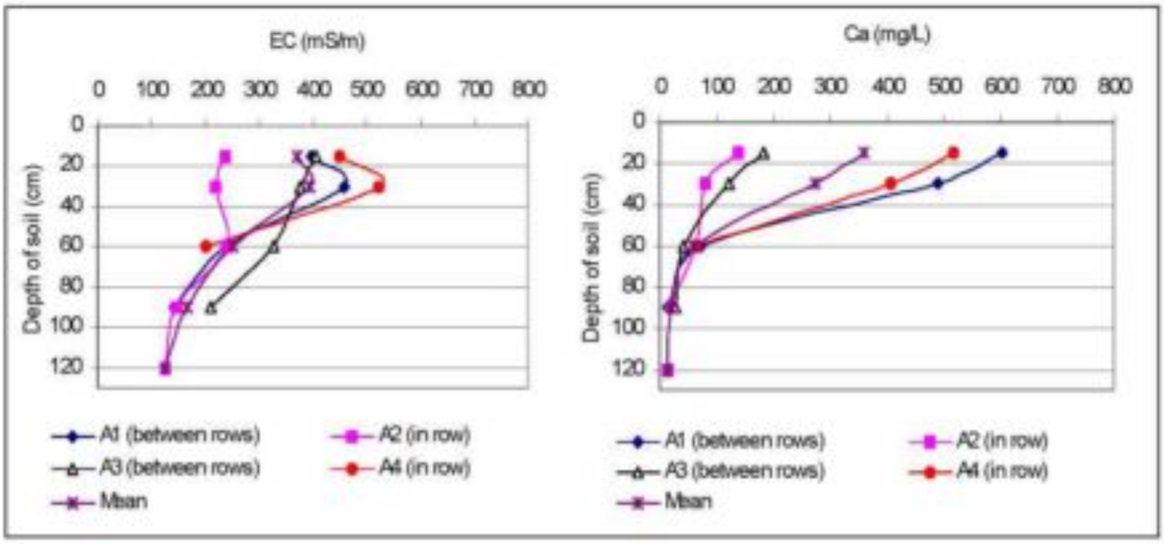


Figure 6.7 : The averaged EC_e and Ca content of saturated paste extracts from samples taken at position A in the Glenrosa soils, year 2000, on the Broodkraal Farm

Figure 6.8 shows a definite downward shift in the high Na zone of the soil. This result is quite meaningful in terms of the salt balance on this farm. It must be kept in mind that Figure 6.8 was calculated from samples taken in the year 2000, from sites that differed in terms of their irrigation history.

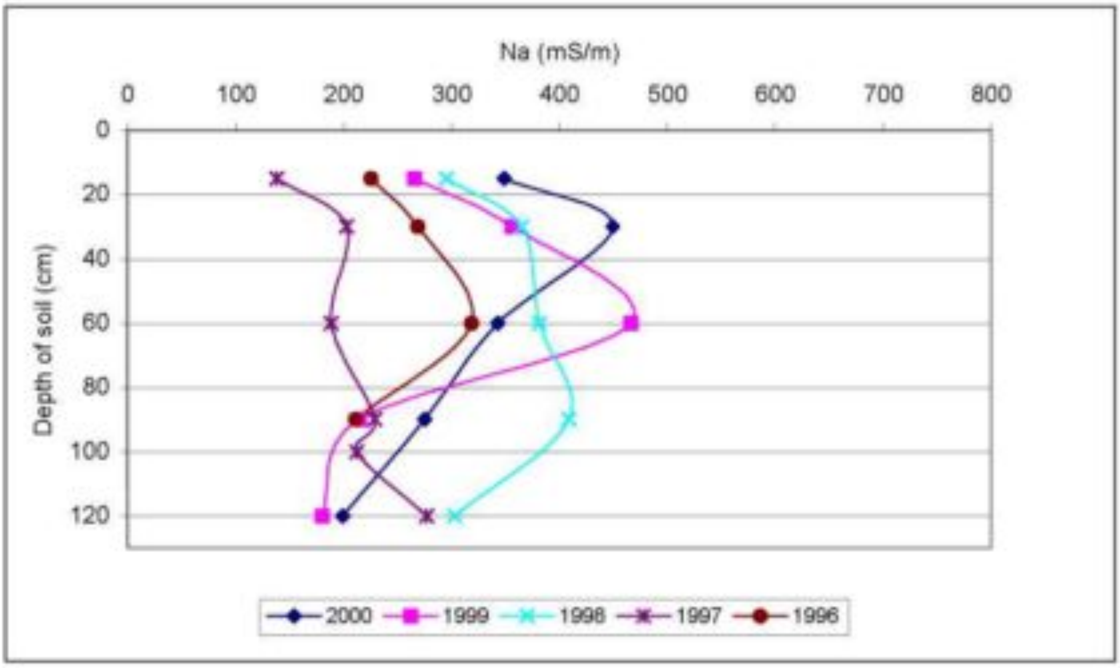
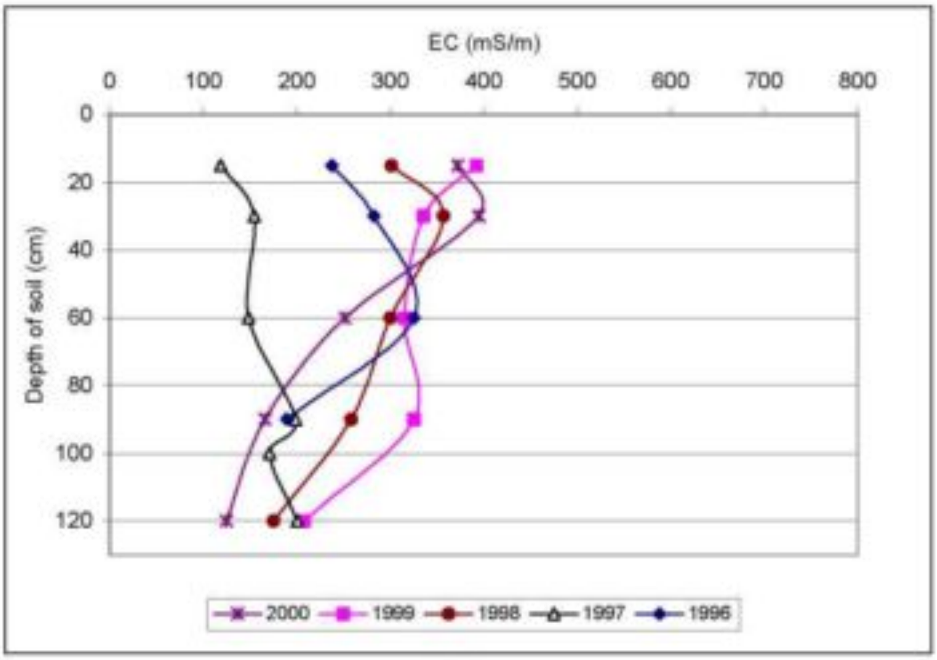
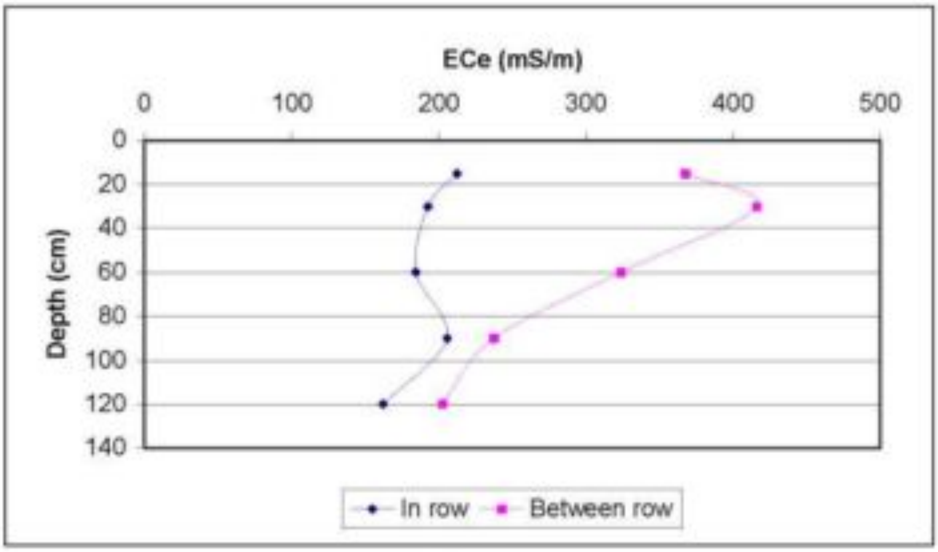


Figure 6.8 : The averaged profile Na content from saturated paste extracts from Broodkraal Farm, measured at positions A(2000) to E(1996) (see map, Figure 6.4)

Figures 6.9 shows the EC_e variation over time taken from the same soil sample results as Figure 6.8. The change in EC_e speaks for itself. It is, however, quite remarkable that all lines except the 1997 line meet in a node 45 cm deep with an EC_e of about 300 mSm^{-1}. The Figure 6.9 (b) result was calculated to show the large difference between the averaged in-row positions and that of the between-row positions.



(a)



(b)

Figure 6.9 : The averaged EC_e of soils at positions A(2000) to E(1996) at Broodkraal Farm of the Glenrosa soils, from 1996 to 2000, with (a) the site average per year and (b) the average in-row and between-row positions over all data

Figures 6.10 to 6.14 show the start and end of season EC_e, EC_{sw} and pH profiles. The relationship between EC_{sw} and EC_e in these graphs is generally soil type-specific. In Figure 6.10, EC_e-EC_{sw} graphs show contrasting EC_e and EC_{sw} behaviour. Very low EC_{sw} in the topsoil while higher EC_{sw} values in the lower horizons were found. Almost the reverse applies to the EC_e values. This difference can possibly be explained by mineralization in the topsoil or the dissolution, during saturated paste preparation, of soil amendments trapped in positions where soil water activity is generally quite low.

The results in Figures 6.10 to 6.14 show the immense variability found in the composition of soil water at sites that were monitored at Broodkraal. It should be borne in mind that the data from each of the mentioned figures comes from only one position in the landscape. Seasonal variations in soil chemistry, as well as differences in soils before and after the onset of irrigation, were detected in all soil samples.

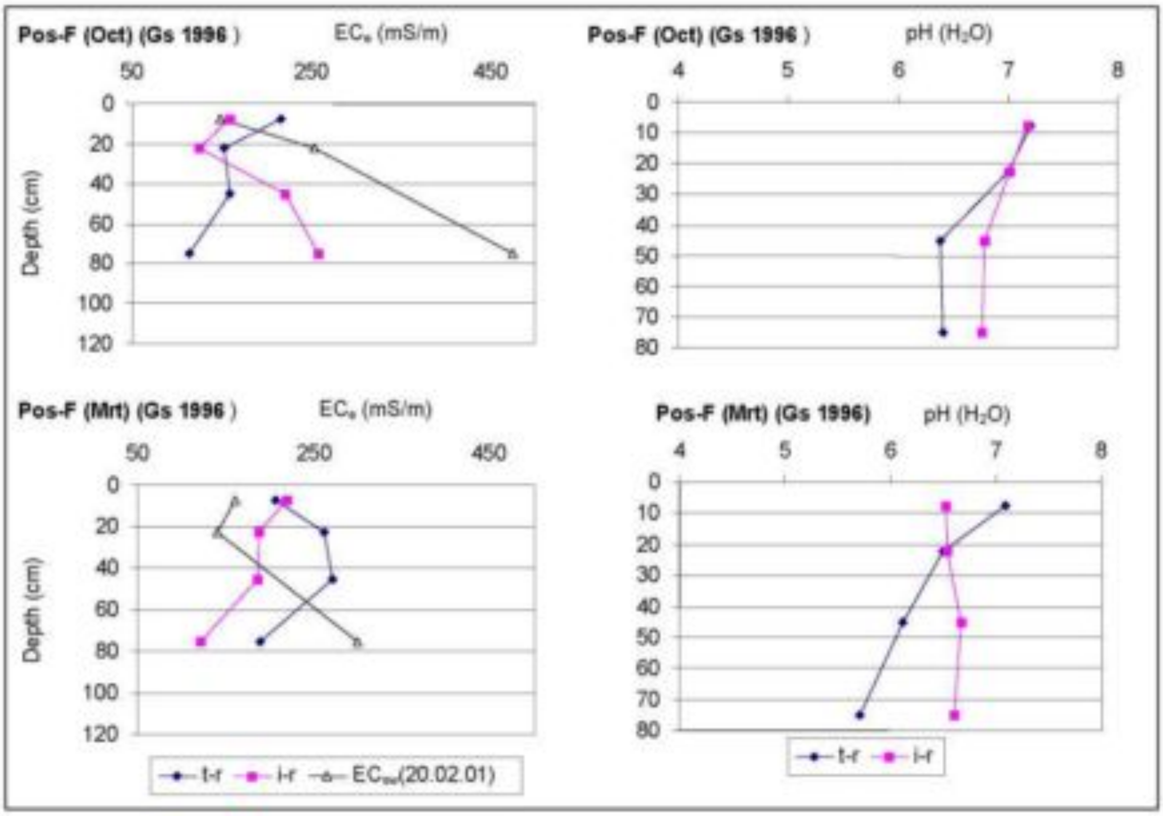


Figure 6.10 : Start (Oct) and end (Mar) of irrigation season EC_e, EC_{sw} and pH measurements taken in vine rows (i-r) directly under a vine and centre between vine rows (t-r) in Glenrosa soils (GS), year 1996

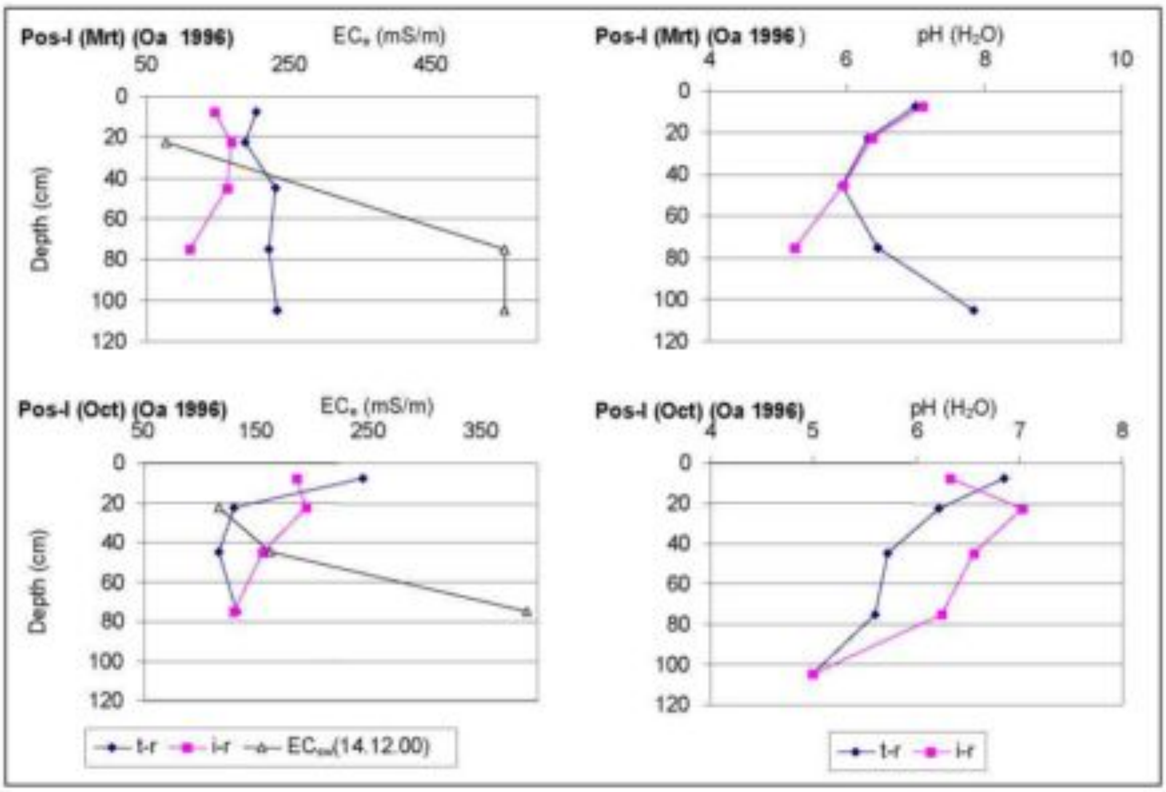


Figure 6.11 : Start (Oct) and end (Mar) of irrigation season EC_e, EC_{sw} and pH measurements taken in vine rows (i-r) directly under a vine and centre between vine rows (t-r) in Oakleaf (year 1996) soils

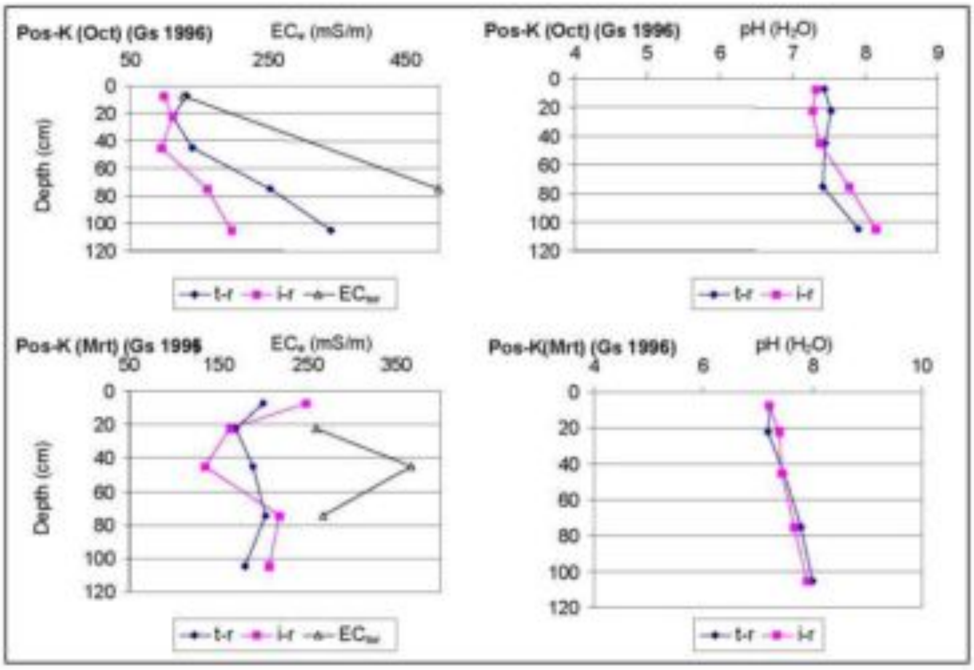


Figure 6.12 : **Start (Oct) and end (Mar) of irrigation season EC_e, EC_{sw} and pH measurements taken in vine rows (i-r) directly under a vine and centre between vine rows (t-r) in Glenrosa soils (Gs), year 1996**

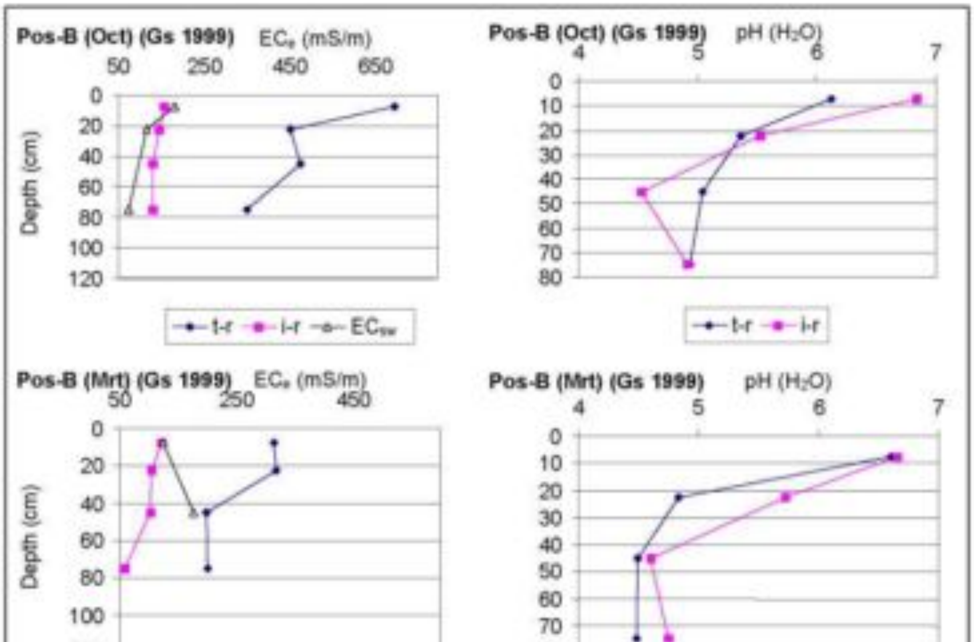


Figure 6.13 : **Start (Oct) and end (Mar) of irrigation season EC_e, EC_{sw} and pH measurements taken in vine rows (i-r) directly under a vine and centre between vine rows (t-r) in Glenrosa soils**

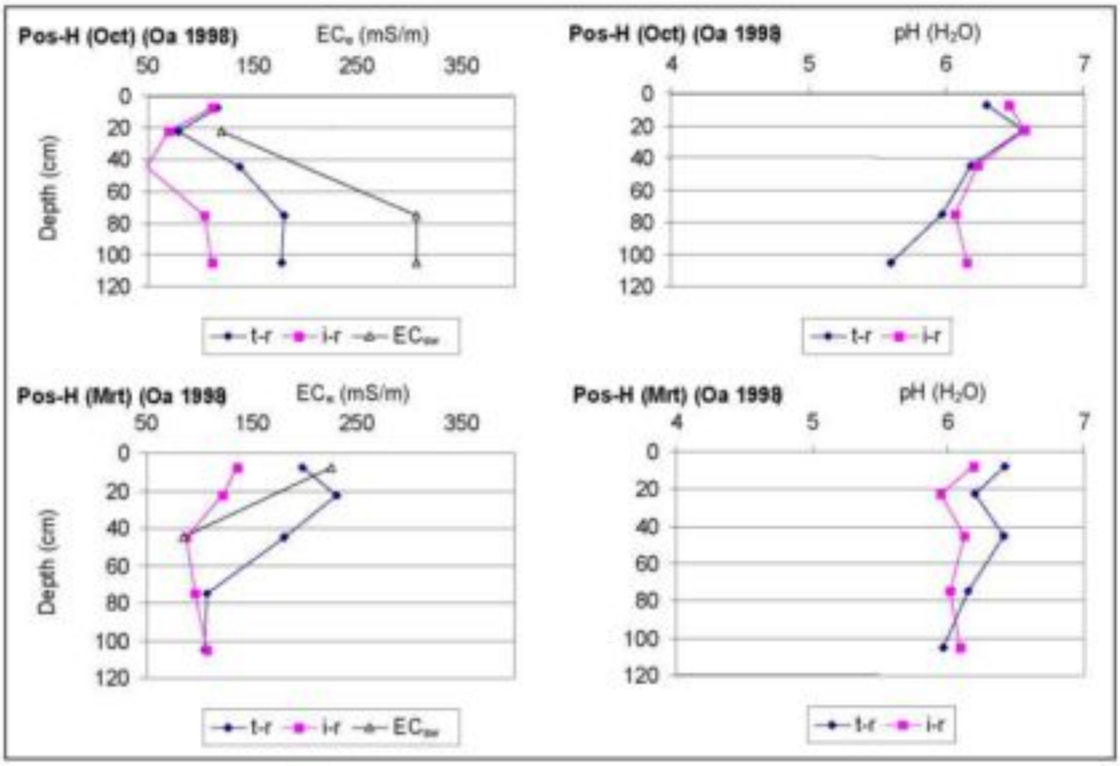


Figure 6.14 : Start (Oct) and end (Mar) of irrigation season EC_e, EC_{sw} and pH measurements with depth (D) taken in vine rows (i-r) directly under a vine and centre between vine rows (t-r) in Oakleaf soils, year 1998

6.1.6 Water Balance and Drainage Rate

A data logger was used to monitor a rain gauge installed under the irrigation system and a tipping bucket flow gauge installed at the outlet of a drainage system. Also used was a 25L container linked to the irrigation system with a $2Lh^{-1}$ dripper installed in the container. This allowed a cumulative and representative irrigation water sample to be taken. It also gave the opportunity to check the amount of applied irrigation.

The irrigation return-flow dam on the farm has an overflow rate of between 2L per second and about 8L per second. This rate falls outside the capabilities of the tipping bucket flow gauge mentioned above. The dam was built to dispose of the drainage water at a downstream position from the pump station that supplies irrigation water from the river. The water from this dam was sampled, and its quality and the rate of overflow could represent very accurate return-flow information.

Some of the drains were sporadic in their reaction. They only flowed for between a few hours and about two days after an irrigation event. Reaction rates measured were similar to that measured at Rooihoogte Farm (Figure 6.15). These measurement were, however, very difficult to make continuously over the whole period, as a result of equipment malfunctions. However, the dynamics of these systems were captured, and reflect the drainage reaction to a normal irrigation event. From these results one can conclude that the fast response of the drainage system is evidence of the high amount of preferential flow that occurs in these very stony soils.

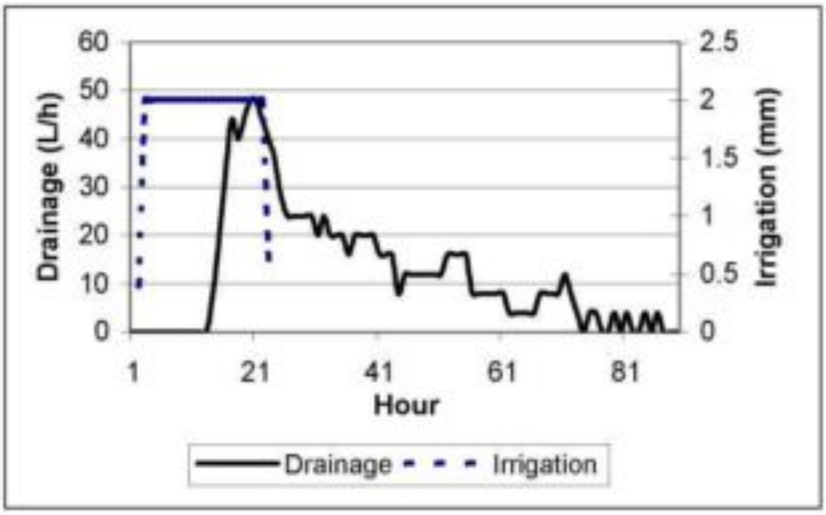


Figure 6.15 : The drainage reaction to an irrigation event at Broodkraal Farm

As a first approximation, a simple mass balance model was developed to predict the volume of water that leaves the root zone, for all soil-sampling positions on Broodkraal Farm (Equation 17). The different positions were modelled and the results for one year are presented in Figure 6.16. It is clear that large differences exist between the different locations, mainly resulting from differences in soil type, stone content and irrigation quantities. When looking at the contour map and soil map of Broodkraal, it is clear that positions B and F are situated in very stony Glenrosa soils and located on a steep incline. These soils also have the lowest water holding capacity. Position J is also a Glenrosa soil but with small vines and consequently a lower irrigation volume. K is a Swartland soil.

As a result of the large variance in stone content, the application of a simple one-dimensional model to account for total drainage from a vineyard can be quite deceiving. Therefore the stone content was implemented in the mass balance equation as a variable and Figure 6.16 represents for each soil type the return flow based on the average stone content for each position. Position B shows the highest volume of leachate, which mainly results from the high stone percentage as well as the high irrigation values. Metered irrigation volumes were used in the calculation and it is possible that the area linked to the irrigation volume was indicated incorrectly. However, position B is located on the edge of a steep incline causing these plants to wilt easily and the soil to dry quickly. In the vineyard itself, signs of over-irrigation were always visible while the vines always seemed close to wilting point.

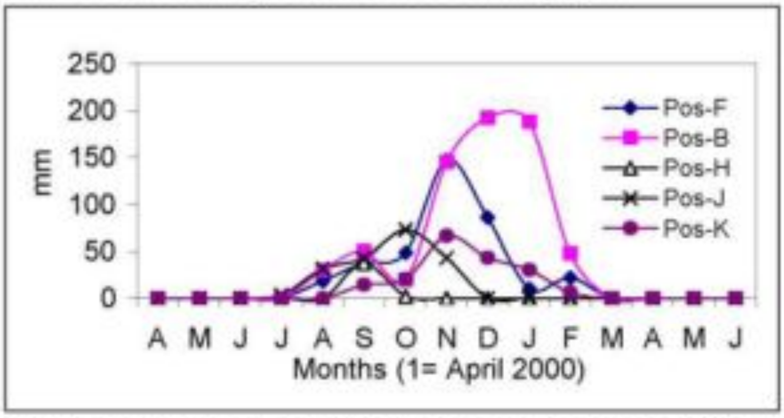


Figure 6.16 : Monthly total drainage in mm from 5 different locations on the Broodkraal Farm

6.1.7 Salt Balance and Salt Movement Rate

EC_d was measured and the results varied between 200 mSm^{-1} and 550 mSm^{-1}. Most seeps in low-lying areas maintained the highest EC_d values measured i.e., 550 mSm^{-1}. The irrigation dam's EC_{iw} was measured during the season. The initial EC_{iw} was 23 mSm^{-1} (September 2000) and rose slowly during the irrigation season to about 150 mSm^{-1} during winter (July 2001). This was ascribed to seepage to the dam from surrounding irrigated land and runoff from surrounding wheat fields during winter rain.

Figure 6.17 gives the results of analyses of soil samples taken at Broodkraal. The samples were taken from both of the predominant soil types on the farm. The idea was to sample soils that differ in irrigation age. It is clear from Figure 6.17 that the Glenrosa soil started off with a depth-weighted mean salinity of 300 mSm^{-1} and thereafter, maintained a salinity of above 150 mSm^{-1}. The Oakleaf soil started off with a salinity of 143 mSm^{-1} and dropped to 125 mSm^{-1}, at which level it has possibly stabilised, depending on future irrigation water quality. The Oakleaf soil displays much more stability with respect to salinity than the Glenrosa soil. This fact is quite evident on the farm in that almost no salinity problems occur in the higher lying Oakleaf soils while Glenrosa soils exhibit salinity problems.

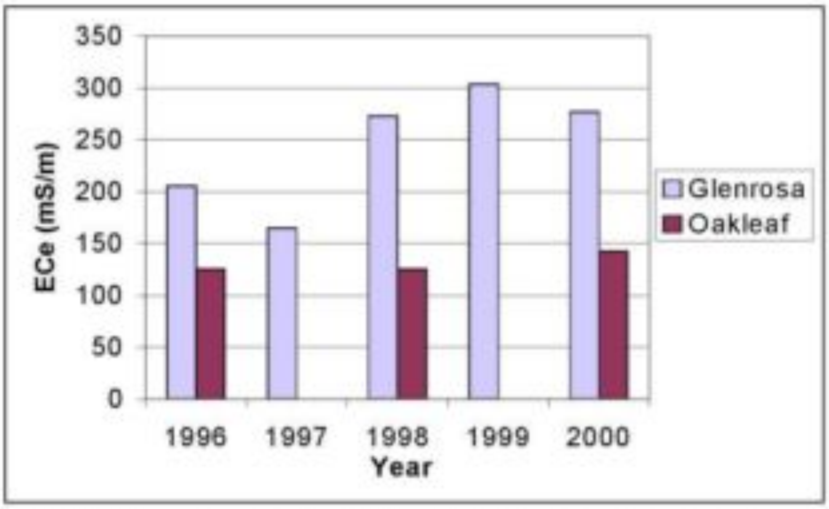


Figure 6.17 : The mean of 4 depth-weighted mean EC_e samples per site of irrigated vineyards. 'Year' refers to year of planting

As a result of the method used to predict return-flow quality, there is a strong resemblance between Figures 6.16 and 6.18. The fact is that Figure 6.19 was prepared with using a constant drainage EC of 250 mSm^{-1}. This means that high volumes of return-flow in this case also imply high salt movement rate. Again position B is more pronounced than the rest. It is, however, the result of high indicated irrigation amounts for this position. To demonstrate the effect when actual drainage EC values are being used, Figure 6.19 was constructed making use of the actual monthly average EC values for drains 1, 2 and 3 (see Figure 6.4 for the actual locations).

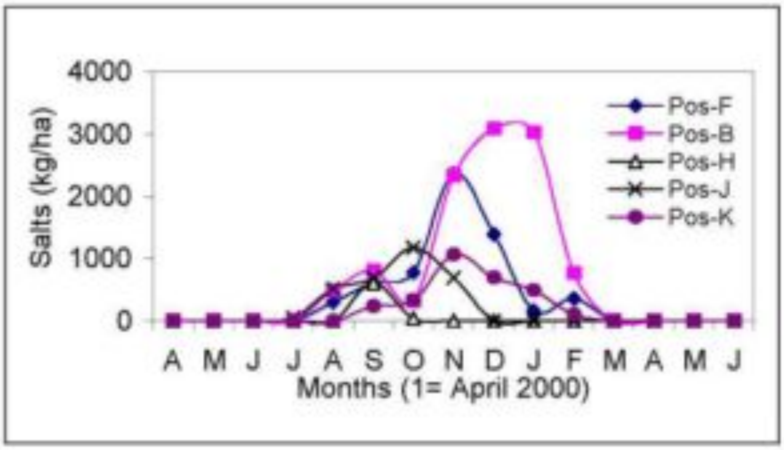


Figure 6.18 : Predicted monthly return-flow given as total amount of salt in kg/ha based on a fixed yearly average EC_{sw} of 250 mSm^{-1} below the root zone of from five different positions on the Broodkraal Farm (refer to Figure 6.4)

From Figure 6.19 it is safe to say that high leaching and the highest salt movement rates were experienced before the end of December each year. Looking at the drainage reaction in Figure 6.3, this period from the end of December coincides with a decline in EC measured at the drains. Though the EC_d is high during the winter months, the volumes are low and sporadic since the main driving force behind drainage during winter relates to the low rainfall occurrence.

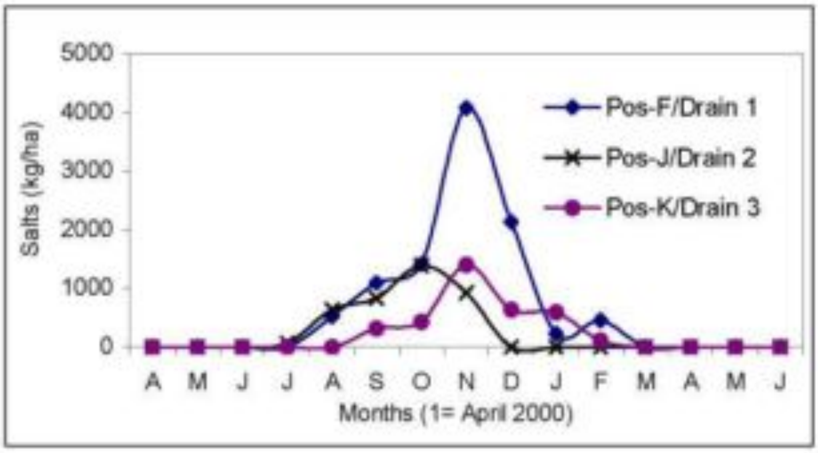


Figure 6.19 : Mass of salt leached from positions F, J and K on the Broodkraal Farm linked to the drainage water quality from drains 1, 2 and 3 (see Figure 6.4)

6.1.8 Applying Models to Predict Return-flow

DISA is currently used in the management of the Breede River system. We also wanted to include SWAP because after comparing various models SWAP handled modelling of stony soils or rather large preferential flow situations best. Literature showed that SWAP has been used quite successfully in other semi-arid and arid regions in Africa. It was, however, not possible to proceed with this modelling mainly due to a time constraint and the fact that both models need, as input, the quality of the seep before mixing with the irrigation return-flow. This meant that only the segment of the model that generates the quality of the water below the root zone could be used. This actually stresses the urgency of a follow-up project that will help characterizing the quality of saline seeps. A modelling attempt will, however, be done using DISA and the results will form part of a MSc thesis (Engelbrecht, 2002).

6.1.9 Discussion

The database created from the work at Broodkraal Farm seems to be more than adequate to be used in very accurate return-flow predictions. The data and predictions included here show that return-flow is mostly site/soil specific. The major obstacle is the large variance in soils when soil ECe data are to be used in modelling of return-flow. The second obstacle concerns the origin of salt in the landscape. How is it possible that the high points in this landscape can be recharged with salts even after six years of over-irrigation? The answer may lie in the salinity of the adjacent dryland farming regions. Broodkraal Farm borders the Berg River itself, implying that the farm is at the lowest end of a large pediment stretching for 15 km to Koringberg.

A survey into the geology of the bedrock (Malmesbury shale), immediately underlying the soils of Broodkraal, showed the angle of dip to be almost 80 degrees away from the horizontal. This is quite common in the Malmesbury shale and makes the prediction of natural drainage pathways toward the river unpredictable. It is often also the reason for saline spots in the landscape, as outcropping bedrock always shows a white salty deposit. The reason is that certain layers in the geologic sequence have better deep capillary attributes, giving an opportunity for capillary rise from possibly deep-seated saline/sodic groundwater. This mechanism is possibly one of the important contributors to salinity in the Berg River resulting from evaporation of soil water from bare soil. The situation at Broodkraal showed that though the salts in the soil profile, in particular the Glenrosa soils, are washed down during the irrigation season, some mechanism of recharge does exist. This recharge possibly results from excess water in the adjacent wheat production areas.

6.2 DETAILED STUDY OF ROOIHOOGTE FARM

In many respects the monitoring at the Rooihoogte Farm was much simpler than that at Broodkraal Farm. The salt content of the soils that were monitored seemed lower and the EC_i was very constant. The farm is situated on a piece of land that is not directly subject to saline seepage from higher lying areas. Again, as was the case with Broodkraal, a number of deep trenches were dug and no standing water was found, except for two excavations close to the tributary, which had standing water only during the winter months. According to the original proposal, this farm and a section of irrigated land were chosen as a result of a relatively long irrigation history. Thus the main purpose of this site was not to duplicate the work done at Broodkraal, but to explore the contribution it makes to the salt content of the tributary and ultimately the Berg River itself.

6.2.1 Climate

The long-term averages of the Rooihoogte weather data are summarised in Table 6.6. Rooihoogte falls within a region in the Berg River catchment having below average rainfall.

Table 6.6 : The long-term averages of the Rooihoogte weather station based on seven years data

Month	Air Temperature °C			Rel. Hum.		Precipitation	Evap	Wind
	Average		Extremes	%		mm	mm/day	(km)
	TX	TN	HXX	UX	UN	R		W
Jan	31.6	16	41.1	88	37	6.5	10.2	195
Feb	32.4	16.5	42	88	37	6.8	10.1	192
Mar	29.3	14.9	40	92	41	28.4	6.8	154
Apr	26.3	12.4	37.6	94	43	42.3	4.8	126
May	22.5	9.9	34.5	95	53	54.9	2.6	112
Jun	19	6.6	29	95	54	59.2	1.7	98
Jul	17.8	5	27.7	96	58	69.3	1.4	90
Aug	19.3	6.2	29.8	96	55	59.9	2	103
Sep	21.1	7.8	33.4	95	48	43.3	3.4	129
Oct	25.3	10.1	39.6	91	39	15.1	6.6	170
Nov	29.2	13.6	42.3	86	36	11.1	9	191
Dec	30.1	15	39.8	89	38	12.6	9.8	188
Tot						409.4		
Ave	25.3	11.2	36.4	92	45	34.1	5.7	146

TX : Mean of the daily maximum temperature (ºC)
TN : Mean of the daily minimum temperature (ºC)
HXX : Highest observed daily maximum temperature (ºC)
UX : Mean of the daily maximum relative humidity (ºC)
UN : Mean of the daily minimum relative humidity (%)
R : Mean of the monthly total precipitation (mm/month)
W : Mean of the daily wind-run (km/day)

Any parameter can be reproduced from the weather station records of both farms. Both make use of modern facilities in this respect.

6.2.2 Soil Surveys

The Rooihoogte soils were studied and compared with the existing soil map of the farm. In essence, no changes were proposed, apart from the fact that the soil information had to be updated to meet the requirements of the new classification system. To be consistent with the Broodkraal study, trenches were dug at Rooihoogte to a depth of 4 m, which enabled us to study the salt distribution with depth and to look for signs of wetness, or a possible water table.

6.2.2.1 Additional soil descriptions of the soil map of Rooihoogte

The only soils described were those where monitoring of soil salinity has been done. The original descriptions and the accompanying soil map are based on the survey done by P A Feyt (April 1983). In that survey, soils were described according to the scheme of McVicar *et al* (1977). This information has been updated for this study and a guide for conversion between the systems is presented in Table 6.7 (Soil Classification Working Group, 1991).

Full profile descriptions of the trial sites were done and are given in Appendix A.

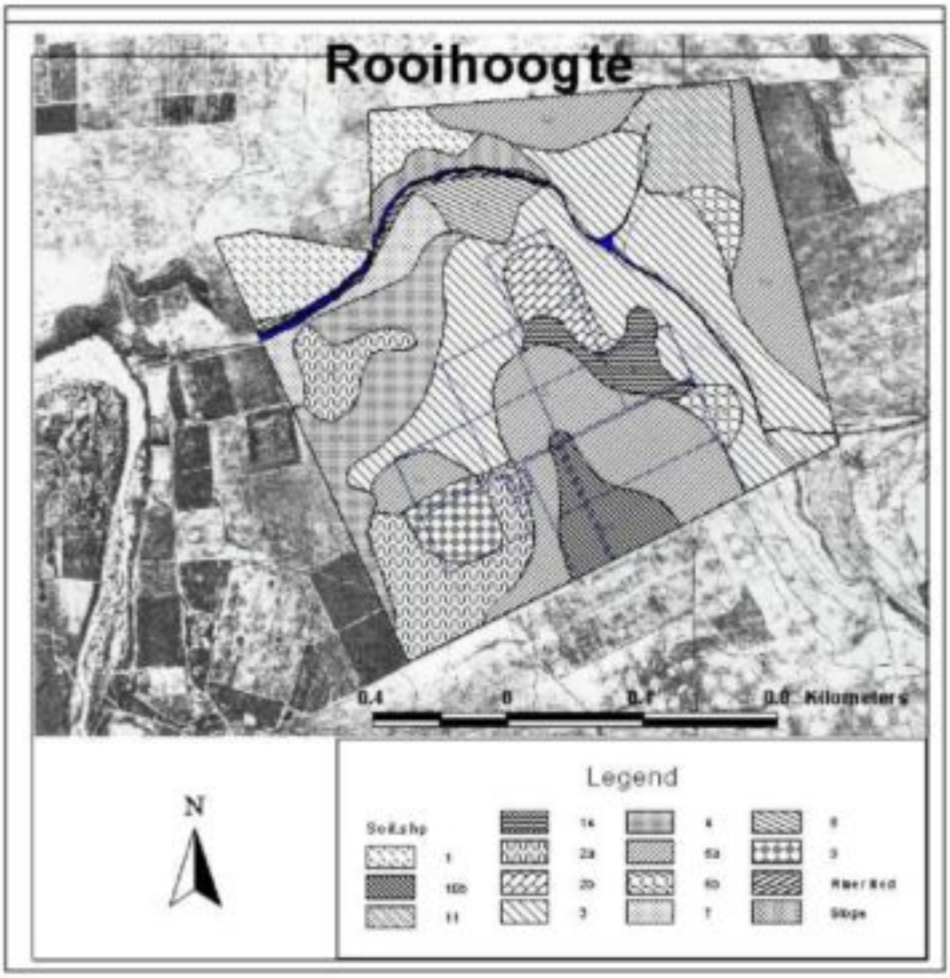


Figure 6.20 : Map of Rooihoogte Farm near Porterville. The tensiometer sites plus the soils and soil sampling positions are shown (for description of the legend, see Table 6.7)

Table 6.7 : Soil map legend of Rooihoogte Farm based on the old and new soil classification systems

Original classification of Feyt (1983) using the Binomial Soil Classification System (MacVicar *et al* 1977)			Correlation and improvement of original classification by Ellis (2001) using Soil Classification. A Taxonomic System For South Africa (Soil Classification Working Group, 1991)		
Soil unit no.	**Soil Form**	**Soil Series**	**Soil Form / family abbrev.**	**Topsoil Texture Class (abbrev.)**	**Brief description of soils of unit**
1	Glenrosa	Williamson	Gs2111	fiSaLm	Shallow soils on shale parent material
2a	Swartland	Swartland	Sw2121	fiSaLm	Shallow non-red duplex without E horizon
2b	Swartlamd	Swartland	Km1120	fiSaClLm	Shallow non-red duplex with E horizon
3	Swartland	Breidbach	Km1220	fiSaClLm	Shallow red duplex with E horizon
4	Shortlands	Glendale	Sw2211	meSaClLm	Moderate deep red duplex without E horizon
5	Valsrivier	Herschel	Se2210	fiSaLm	Moderate deep red duplex without E horizon
6a	Hutton	Portsmouth	Oa2220	meSaLm	Deep red apedal with gravel
6b	Hutton	Portsmouth	Oa2210	meSaLm	Deep red apedal
7	Hutton	Msinga	Oa2220	meSaClLm	Deep red apedal
8	Hutton	Shorrocks	Ou2220	meSaLm	Moderate deep red apedal on dorbank
9	Hutton	Makatini	Oa2220	meSaLm	Deep red apedal
10a	Clovelly	Southwold	Oa2120	meLmSa	Deep yellow apedal
10b	Clovelly	Southwold	Oa2120	fiSa	Deep yellow apedal
11	Clovelly	Newport	Oa2120	meSaLm	Deep yellow apedal
12	Clovelly	Makuya	Oa2110	meLmSa	Deep yellow apedal
13	Clovelly	Denhere	Oa2110	fiLmSa	Deep yellow apedal with gravel
14	Cartref	Noodhulp	Cf2100	meSaLm	Shallow topsoil on shale via an E horizon

6.2.3 Survey of Drainage

Drainage from the site and chosen tile drain was very sporadic. The drain was active for only a few hours after each weekly irrigation event. As at Broodkraal, almost no drainage was measured between the end of December and middle February. Two sites were sampled with suction cup lysimeters, but our success rate was rather low as swelling clays in this soil cause the instrument's contact with the soil to break. Water samples were also taken in the small river below this site and in the Misverstand Dam. Irrigation water was also sampled and so was the drainage from the monitored site. Table 6.8 summarizes the results from three measuring points at Rooihoogte Farm, namely Berg River water quality, the quality of drainage water at one drainage point on Rooihoogte Farm and the water quality of a tributary of the Berg River. This tributary forms a natural cutoff drain for Rooihoogte. It normally has water the whole year round and has water quality usually associated with that of dryland saline seep. There is almost a factor 6 increase in EC between irrigation water and return-flow water at Rooihoogte, and a further 6 fold increase in EC in the quality of the water from the tributary (Table 6.8). Seemingly, irrigation farming on this land would have been almost impossible had the tributary not been there. The PO_4 value of 199 mg/L recorded in the tributary at Rooihoogte (Table 6.8) was verified and seems to be correct. The top end of this stream consists of a small marshy area, which attracts a lot of bird life and is being used as a grazing area for cattle. When this water source shrinks toward the end of summer, some of the naturally occurring fish and frogs die, all of which can contribute to the rise in PO_4 associated with this stream.

Table 6.8 : Long-term averaged results of water sampled from Misverstand Dam, the drainage system at the monitoring site and from the tributary on Rooihoogte Farm

Sampling Site	EC	pH	Ca	Mg	Na	K	Cl	NO_2	Br	NO_3	PO_4	SO_4	F
	mS/m	(H_2O)	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
1. Misverstand Dam	19.4	7.9	5.9	3.8	17.4	2.6	41.1			3.0		7.3	
2. Drain at Rooihoogte	104.8	7.1	26.7	19.2	138.4	11.4	222.4			24.9	10.8	159.7	0.3
3. Small tributary north of Rooihoogte	612.0	7.9	165.4	134.6	719.1	15.0	1926	158.8	51.9	49.7	199.1	375.3	10.6

To a certain extent, the data presented in Table 6.8 answer a lot of questions regarding the aims of this section of the project. Still missing here though, are water volume and the fluctuation in quantity and quality over a normal year.

6.2.4 Soil Moisture Measurements

Soil moisture was measured once a week using tensiometers. Neutron access tubes were installed during the early 2000 and a more accurate account of soil moisture is now possible. For the purpose of this project, neutron access tubes were installed close to each tensiometer position though the aim was to only use the data relevant to the main monitoring site. However, soil moisture measurements did not contribute to the direct aims of the project as moisture readings were not always taken at the lower end of the plant water use cycle and therefore didn't always correlate with the amount of water applied. Recorded irrigation amounts can rather be used for modelling.

6.2.5 Soil Chemical Properties

Since 1999, soil samples have been taken before and after the summer irrigation season. They were analysed for EC_e, pH, Ca, Mg, Na, K, Cl, SO_4 and NO_3 content. The pH and EC_e values are given in Figures 6.21 to 6.24. In Table 6.9 the pH values of the shallowly prepared soil are lower than those of the deeply prepared irrigated soil. The EC_e levels of the shallow soil are higher than that of the irrigated soil. It was also found, as a rule, that the EC_e values are higher in the between-row positions than in the irrigated rows. Table 6.9 gives the depth-weighted mean EC_e averages from irrigated soil and non-irrigated soil, and also gives an estimate of the amount of salt that was leached from the soil by irrigation.

Table 6.9 : Depth-weighted mean values of percentage stones in the profile, pH, EC_e and total dissolved solids (TDS) at Rooihoogte Farm

	%Stone in soil	pH	EC_e (mSm^{-1}) Sat. extract	TDS mg/L	TDS ton/ha
Deep cultivated soils Sample taken between rows	35.4	7.26	148.8	952.4	11.428
Deep cultivated soils Sample taken in vine row	43.8	7.00	93.8	600.2	7.202
Shallow cultivated soils (wheat)	28.2	5.66	274.8	1758.2	21.10

Figures 6.21 and 6.22 show the difference made by sampling position to soil EC_e and pH values. The distance between the two samples taken in the vineyard and that taken in the wheat land is 10 m. As at Broodkraal, at least the tendency to differ between locations and soil types is constant.

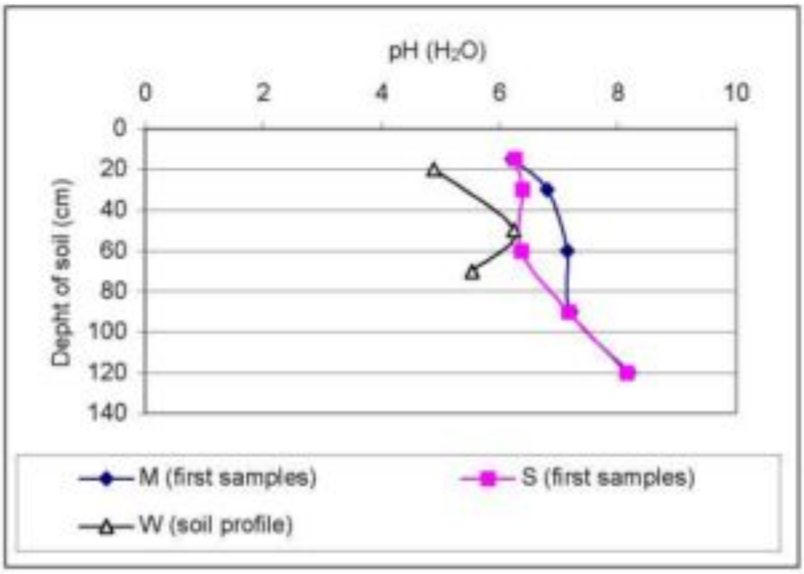


Figure 6.21 : The pH of the first samples taken at Rooihoogte Farm in 1999. M was taken in the in the middle between two rows and S in the vine row. W was taken in the adjacent wheat field, in soil that was never developed

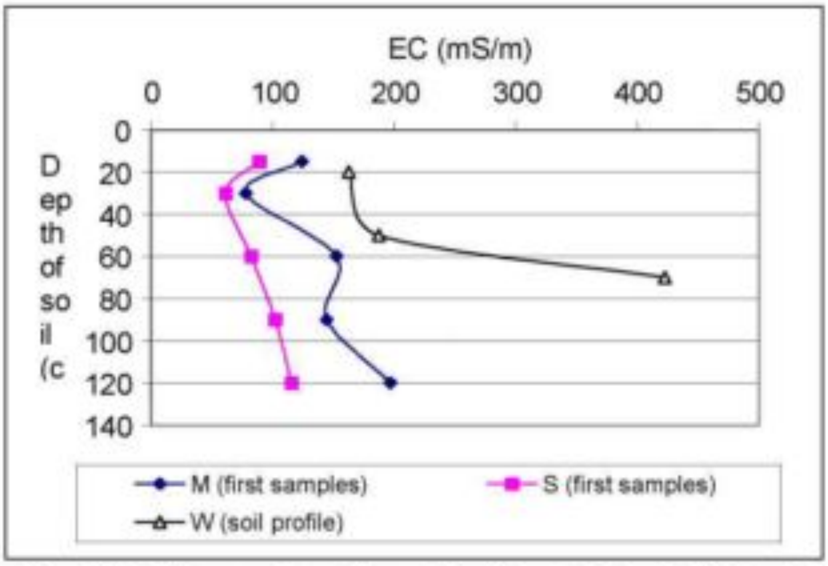


Figure 6.22 : The EC_e of the first samples taken at Rooihoogte Farm in 1999. M was taken in the middle between two rows and S in the vine row. W was taken in the adjacent wheat field, in soil that was never developed before

Figures 6.23 and 6.24 again stress the fact that there is large micro scale variability that has to be taken into account when return-flow modelling is attempted. The between-row positions usually receive less irrigation water and more sun than the in- row positions. The between row positions act as a salt accumulator during the irrigation season, and this has to be taken into account when modelling return-flow. It is possible that irrigation type and its specific water distribution pattern could be implemented as a variable in modelling. Figure 6.24 shows more favourable end winter and end summer results as a result of total surface wetting in Hutton soils.

Figure 6.23, however, could also be evidence of winter dryland recharge in the Swartland soil, which is also associated with Malmesbury shale.

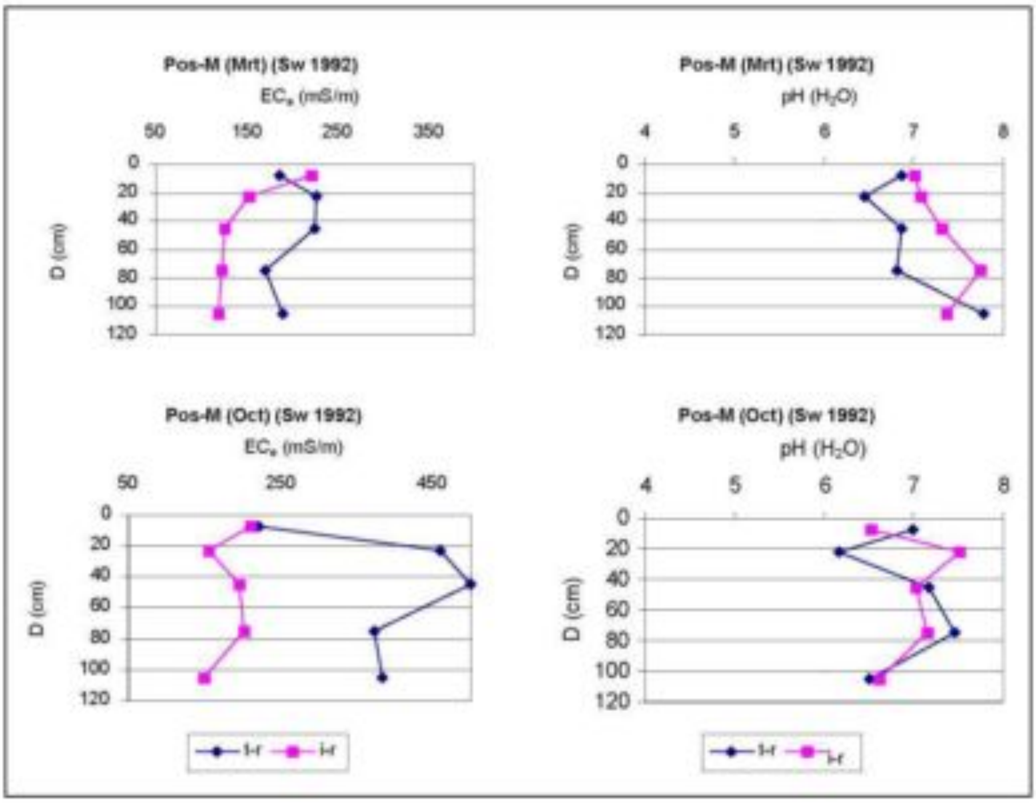


Figure 6.23 : Start (Oct) and end (Mar) of irrigation season EC_e and pH depth (D) trends, taken in vine rows (i-r) directly under a vine and centre between vine rows (t-r) in Swartland soil (Sw 1992 is Swartland soil in year 1999)

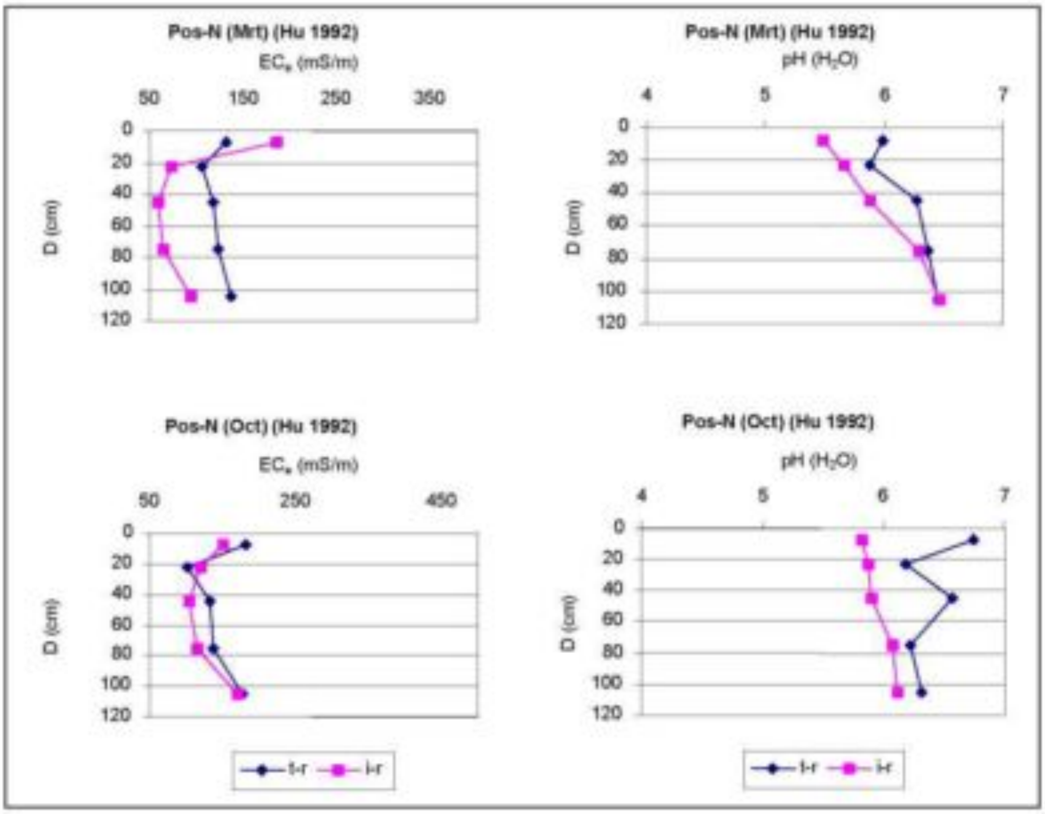


Figure 6.24 : Soil EC_e and pH over depth (D) for the months October and March at Rooihoogte Farm (HU 1992 = Hutton soil in year 1999)

6.2.6 Soil Physical Properties

Several physical properties of the soils have been measured to enable a successful description of the soils' ability to store salt, and the mobility thereof when the soils are irrigated.

Firstly, the stone content of the soils contributes greatly to reducing soil volume, and, when these soils are cultivated, the disturbance of stone in the soil profile leads to the development of preferential flow paths. This concept of high stone content with problems associated with it, has to be accounted for in return-flow modelling.

Apart from the stone content, the remaining soil volume was defined in terms of its water holding capacity and its density. Some of these will be listed in the Appendices and will be used in predictions of return-flow quantity and quality from this site.

6.2.7 Water Balances and Drainage Rates

A rain gauge installed under the irrigation system, a tipping bucket flow gauge connected to the drainage system and an irrigation water sampling container linked to the irrigation system, were used to monitor all water-related parameters. Apart from that, the farmer logged the irrigation amounts and helped to collect the water samples. The water from the container and drainage system was analysed on a regular basis.

We were not able to capture the drainage rate continuously. The logger got wet twice, and no data could be extracted. The equipment had to be removed several times per year as a result of farming operations that could have damaged the instruments. We did however capture the irrigation/drainage balance. We also managed to take water samples at regular intervals, but the discontinuity in water samples indicates the sporadic activity of the draining system. Figure 6.25 shows an example of the drainage reaction rate captured for two irrigation cycles.

Return-flow measured from a drainage system is always regarded as an under-estimation of the actual flow. The drainage values given in Figure 6.25 are more the result of a localised rise in the water table near the drainage system and do not account for any base flow or deep percolation that may occur. It is also not necessarily the result of over-irrigation but rather the fast accumulation of water related to preferential flow and possibly a perched water table.

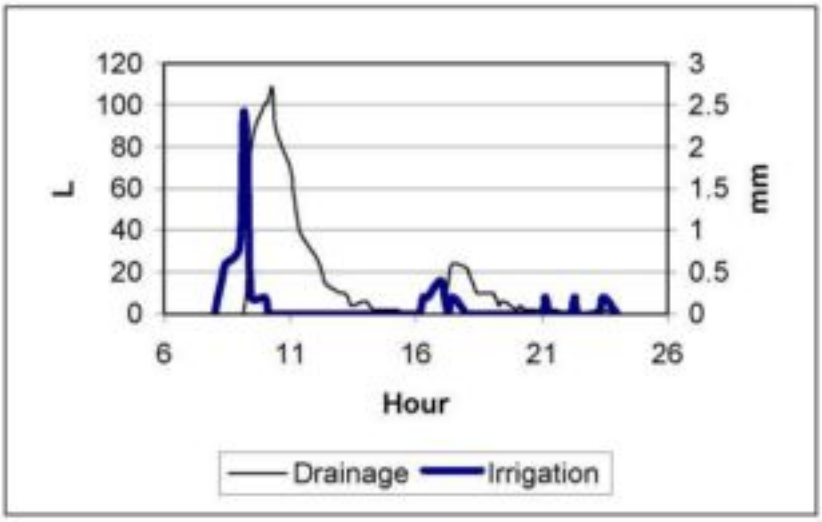


Figure 6.25 : The drainage rate and irrigation duration at a vineyard on the Farm Rooihoogte

6.2.8 Salt Balances and Movement Rates

Various attempts were made to model return-flow from the Rooihoogte Farm through mass balance equations (Figure 6.26). By changing crop factors and the field capacity levels, all led to the same tendency. The fact is that irrigation amounts were maintained at a low level through the season. Though the soil water content was maintained between 85 and 45 percent, no leaching during summer could be found. This could in fact be confirmed by an adjacent drain outlet. The drain never ran for more than a few hours after an irrigation event and then stopped, while in winter there was continuous activity.

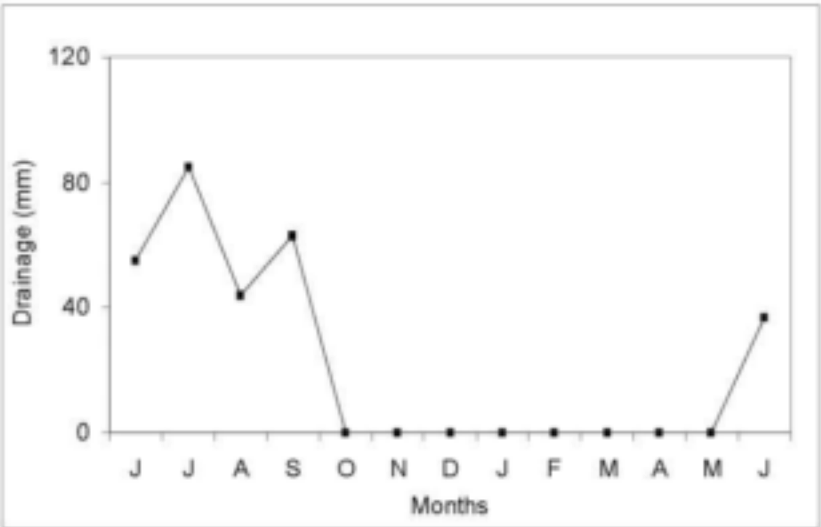


Figure 6.26 : Mass balance predicted irrigation and rain induced return-flow from the Rooihoogte Farm for 2000-2001

6.2.9 Discussion

The information database that was developed to model return-flow seems to be sound. This part of the study also emphasises the fact that though return-flow can be predicted from these irrigated surfaces, it does not add up to the total amount of solutes measured in the Berg River tributary bordering Rooihoogte Farm.

The situation at Rooihoogte Farm differs in one important respect from that at Broodkraal. The area at Rooihoogte that was subjected to this investigation is the typical site favoured by farmers for irrigation agriculture. This site is separated from the inland pediment by a small tributary and is elevated enough to have a deep water table. This was not the case at Broodkraal. This is why the farmer at Rooihoogte can irrigate successfully in Swartland soils. Salinity problems that occurred were mainly due to improper drainage.

This study led to improvement in the irrigation practice on the farm as neutron probe readings indicated that under-irrigation occurred as a result of over estimation of the soil water storage capacity. The soil water storage in turn was under-estimated as a result of not taking the large stone fraction of these soils into account.

Also worth mentioning is that the research on Rooihoogte Farm helped the farmer toward a successful Eurep-GAP evaluation. This in turn directly benefits everyone working on this farm.

CHAPTER SEVEN
SALINITY HAZARD ASSESSMENT

7.1 INTRODUCTION

From the outset of this project it became clear that irrigated agriculture at present plays a minor role in the salt flux of the Berg River. Sections of land that were developed for irrigation had an initial three years of substantial salt contribution to the river system, but stabilized after that with a fairly predictable return-flow. The two detailed studies also showed that other sources of salt existed in the landscape, which potentially could generate far worse return flow scenarios. This indicated that the aim of the study to investigate irrigation return-flow was a little shortsighted. Further investigation into the dryland agricultural areas showed that large accumulations of salt exited below or close to the "heuweltjies" (predominantly in the Malmesbury shale) in this landscape. Since most irrigation development currently is close to the river, it is not easy to distinguish between irrigation return flow and return flow that is generated by "natural" saline seep toward the river system. It is not yet known how the change from natural Renosterveld to wheat lands and the resulting change in the water budget of the wheat land soils has affected the salt budget of the river system, and how to assess and manage this.

Although this project did not have as aim an investigation into the dryland regions and their contribution to the salt content in the river system, an investigation was launched to characterize the underlying Malmesbury shale material of the weathering zone in some wheat fields associated with heuweltjies. The primary aims therefore were to define soil suitability for irrigation expansion and to shed some light on the possible source of salt affecting this area.

In order to find methods that can be applied in salinity hazard assessment, geostatistical methods were explored as a possible approach to mapping and modelling salinity in the BRC. This approach has the benefit that it can be applied in a GIS environment with the added possibility of 3 dimensional modelling. This is also the only method of dealing with the large variability found in these soils. Once described, the variability of a given soil property, within a certain soil type, at a specific location, can be used to predict that property's variability in the soil type at a different location, if certain sampling criteria are met.

Lastly, the mapping of the BRC soils made use of all possible resources including the knowledge gained in the detailed studies, previous soil maps, consultation with soil scientists familiar with the area and field verification. Four maps were compiled: a soils map, a salinity hazard map, a map of soil suitability for perennial crops and a map of soil suitability for annual crops. From the point of view of water quality management, the latter three maps are a valuable resource. The salinity hazard map refers to the risk of crop damage by excessive soil salinity and the risk of detrimental effects on river water quality caused by saline return flow. The crop suitability maps rank soils in terms of their suitability for annual or perennial crops, with regard to both the risk of crop damage by salinity and the risk of saline return flow.

7.2 NATURAL OCCURRING DRYLAND SALINITY ON POTENTIALLY SUITABLE SOILS FOR IRRIGATION DEVELOPMENT ON BROODKRAAL AND ROOIHOOGTE FARMS, AND THE LARGE VARIABILITY INDUCED BY THESE PHENOMENA ON SOIL CHEMICAL COMPOSITION IN IRRIGATED SOILS

7.2.1 Introduction

It almost goes without saying that the origin of the large amounts of salt present in the BRC had to be found and/or defined. If not, all future attempts to model the evolution of water quality in the BRC would have been flawed. The same applies to the large spatial variability in, for example, clay content, stone content and the occurrence of heuweltjies. Not only are heuweltjies associated with the highest EC values measured in the landscape, but soil structure and pH also tend to be different in these spots. Heuweltjies make up about 15 to 45 % of the landscape.

7.2.2 Results and Discussion

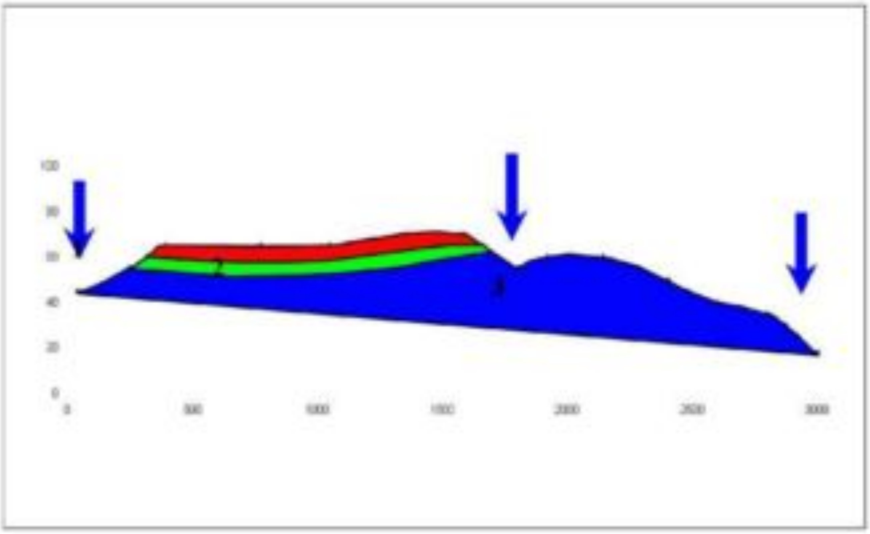
The distribution of heuweltjies (or Mima-like earth mounds) in the Western Cape was reported by Lovegrove and Siegfried (1986). According to them the origin of the mounds was likely to be the result of the harvester termite, Microhodotermes viator and the mole-rat, Cryptomys hottentotus. It was postulated that these animals were responsible for the mound formation, soil burrowing and soil translocation. In this study it became clear that heuweltjies were most prominent on the remnants of the silcrete/ferricrete capped land surface. We also observed at least two types of heuweltjies. The most common one on both localities seems to be a relic feature, as no active termite nests were noticed, and is characterised by a hardpan (mostly dorbank) at shallow depth. The second, less common one, appears to be semi-active, especially in the centre of the heuweltjie, and is characterised by soft calcareous, mostly stone-free soil (neocarbonate and soft carbonate diagnostic horizons), and was only observed in an undisturbed area where ferricrete outcrops occur (No 5, Figure 7.2) on the Rooihoogte locality. The silcrete/ferricrete surface was correlated with the African Surface of Early Tertiary age by Partridge and Maud (1987). The surface is characterised by a layer about 1.5 m thick of reddish transported material (most can be classified as a diagnostic neocutanic horizon (Soil Classification Working group, 1991)) lying almost abruptly on deeply pre-weathered shale/schist at both localities (Figure 7.1). Details about the distribution and size of heuweltjies, as determined from orthophoto maps, are given in Table 7.1.

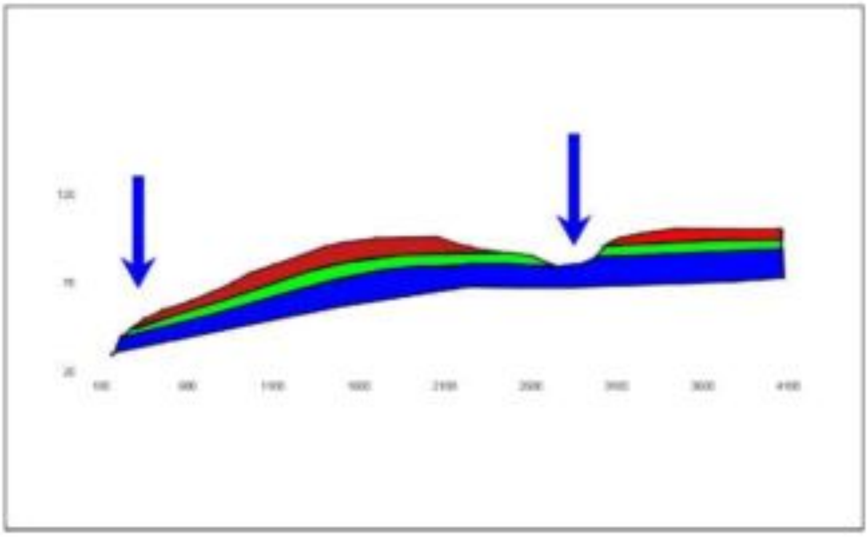
Deep trenches were dug through several heuweltjies on both farms. The positions and numbers of those investigated at Rooihoogte are indicated on Figure 7.2. At least 35 – 40 % of the total area underlain by a heuweljie is not visible on the soil surface, which means that their influence on the landscape is expected to be much greater than indicated by the surface area figures given in Table 7.1.

Table 7.1 : Statistical results of distribution and size measurements of heuweltjies at two localities (two sample areas per locality) using air photo interpretation

Locality	Broodkraal (south)		Broodkraal (north)		Rooihoogte (south)		Rooihoogte (north)	
Parameter	Area (m^2)	Radius (m)	Area (m^2)	Radius (m)	Area (m^2)	Radius (m)	Area (m^2)	Radius (m)
Mean	612	13.4	698	14.2	1258	19.5	1293	20.0
Median	494	12.5	735	15.3	1229	19.8	1331	20.6
Standard deviation	364	4.0	433	4.5	531	4.5	432	3.7
Range	1892	20.1	2863	26.3	2258	20.8	1794	15.3
Minimum	76	4.9	56	4.2	148	6.9	382	11.0
Maximum	1968	25.0	2919	30.5	2406	27.7	2176	26.3
Count	75	75	63	63	38	38	27	27
Total cover (%)	13.08		12.26		14.72		13.30	

The physical, morphological and chemical properties of heuweltjies were found to be totally different from that of the non-heuweltjie areas. Soils of heuweltjies have a higher base status (some are even calcareous), especially towards their central parts, compared to the lower base status of between-heuweltjie areas. Biological sorting is probably responsible for the difference in texture of material on and between the heuweltjies. The breaking-up of these ancient "biological cities" for intensive irrigation practices, might cause the release of more unwanted salts to the surrounding irrigation lands or to the nearby Berg River.





(a) (b)

Figure 7.1 : Schematic cross-section through the landscape at a) Broodkraal and b) Rooihoogte showing the different materials (1 = highly weathered material with heuweltjies; 2 = weathered zone) on the old (1 + 2) and young (3 = fresh to partly weathered shale/schist) land surfaces. Arrows indicate stream or river incisions in the landscape. (Vertical and horizontal scale in meters)

In the following section a discussion of the properties of materials associated with specific heuweltjies and inter-heuweltjie areas is given. Figure 7.3 gives a generalised schematic view of the relative position and type of materials associated with heuweltjies on Broodkraal Farm. The relative positions of materials indicated here also applies in general to heuweltjies on Rooihoogte Farm, with the difference that hardpan formation was generally not so pronounced, and that on some heuweltjies, no/limited hardpan formation was noticed.

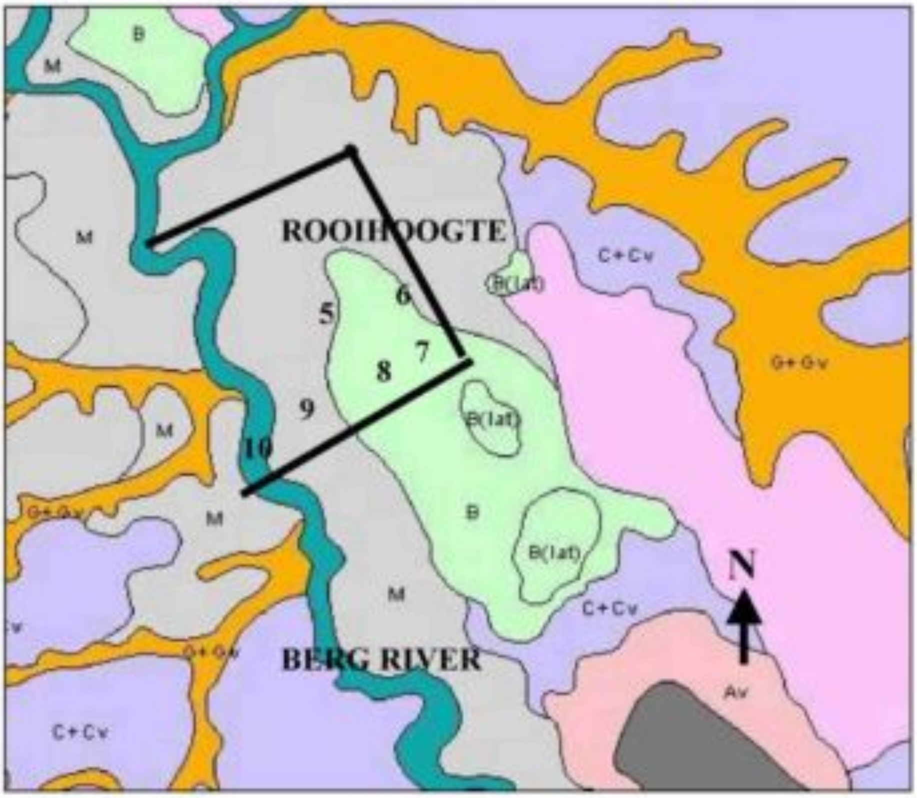


Figure 7.2 : Part of the soil map of the Berg River showing Rooihoogte Farm and the positions and numbers (5 – 10) of the trenches dug through and between some of the heuweltjies that are referred to in the report. Similar trenches were dug at four positions on Broodkraal Farm (see Appendix B)

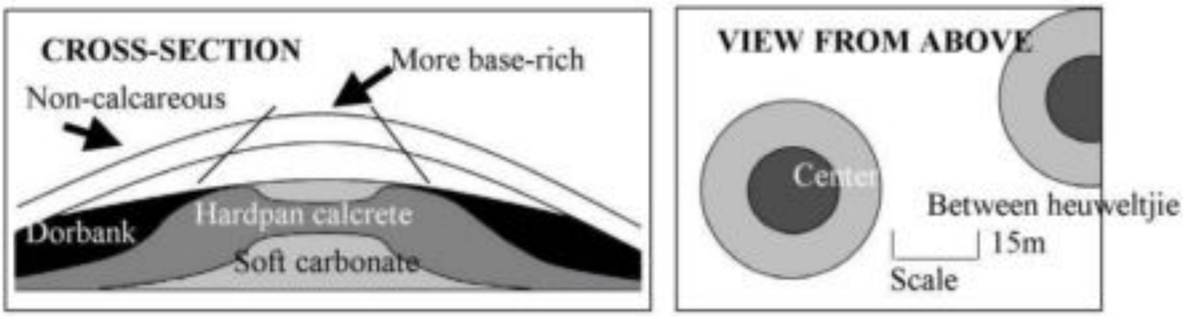


Figure 7.3 : Drawings showing schematically the relative positions of heuweltjies in the landscape and horizons/materials on heuweltjies

Table 7.2 gives results of chemical analyses of horizons/materials in the heuweltjies, moving from the centre towards the periphery of heuweltjies. The (yellow) neocutanic horizons occurred on heuweltjies where termites are no longer active (relic mounds) and where the mounds seem to be totally decalcified. They occur on specific old terraces on the farm Rooihoogte and only the dorbank and a relic hardpan ferricrete horizon remain in places. The high pH of the (red) neocutanic and even higher pH of the (red) neocarbonate horizon is conducive to the mobilization of silica. The much lower pH (therefore lower silica mobility) in similar material (Table 7.2) for the surrounding inter-heuweltjie area could be an explanation for the absence of dorbank horizons there. It is also clear that of the diagnostic horizons analysed, most of the salts are concentrated in the neocarbonate and dorbank horizons, and to a lesser extent in the red neocutanic horizon.

Table 7.2 : Means of variables determined for different diagnostic horizons/materials sampled in cross-sections through 8 heuweltjies in the Rooihoogte and Broodkraal areas

Horizon/ Material	Variable	Distance (m) from center of heuweltjie				
		0	5	10	15	20
Neocutanic	Resistance (ohms)	957	1165	1110	1396	1019
	pH(water)	5.5	5.6	5.3	5.0	4.7
Neocutanic	Resistance (ohms)	721	989	558	949	254
	pH(water)	7.0	7.4	7.4	6.8	7.7
Neo-carbonate	Resistance (ohms)	193	93	512	782	
	pH(water)	7.8	7.8	8.1	7.9	
Dorbank	Resistance (ohms)	387	588	381	528	290
	pH(water)	7.2	7.0	7.5	6.2	6.4

Table 7.3 indicates that for diagnostic horizons or materials that occur on both the heuweltjie and inter-heuweltjie area, it is those on the heuweltjies that have the highest salt load and the highest pH. However, for the saprolitic material (the upper part of the deep pre-weathered zone, indicated in Figure 7.1), a high salt load seems to characterise both heuweltjie and inter-heuweltjie areas.

Table 7.3 : Means of variables determined for different horizons/materials sampled in soils that occur on and between heuweltjies in the Rooihoogte and Broodkraal areas

Horizon/ Material	Variable	On heuweltjie		Between heuweltjie	
		Mean	Std. dev.	Mean	Std. Dev.
Orthic A	pH(water)	6.3	0.8	5.5	0.6
	Resistance (ohms)	1145	535	1816	1547
Neocutanic	pH(water)	7.3	0.7	5.4	0.1
	Resistance (ohms)	770	529	1230	1206
Neocarbonate	pH(water)	7.7	0.2	None	None
	Resistance (ohms)	703	584	None	None
Unconsolidated material[1]	pH(water)	6.4	1.3	5.6	0.4
	Resistance (ohms)	841	588	1384	1224
Saprolitic material[2]	pH(water)	7.3	1.3	5.1	0.5
	Resistance (ohms)	209	114	324	245

1 Pooled samples
2 Pooled samples from pre-weathered shale/phyllite

Figure 7.4 gives the depth-weighted averages of pH and resistance for two heuweltjies (No's 6 and 7) on Rooihoogte. These two heuweltjies represent the more base-rich mounds that occur in presently cultivated wheat lands. From the results it is clear that the highest salt load and the highest pH can be expected towards the centre of the mounds. In Figure 7.5 (heuweltjie No 10), both pH and potential salt load are much lower. This heuweltjie represents the relic variety of heuweltjies where termite activity has stopped long ago and where decalcification has taken place. These heuweltjies are therefore more like the inter-heuweltjie areas.

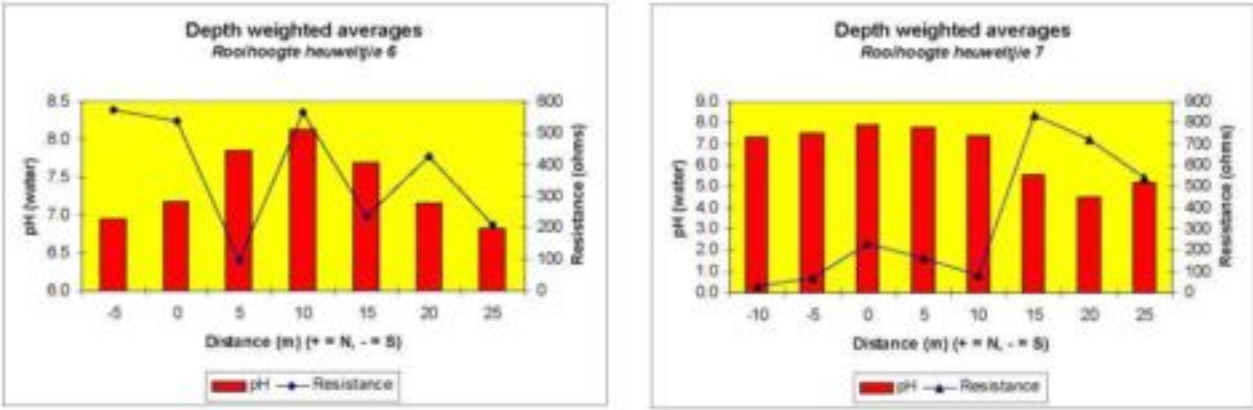


Figure 7.4 : Depth-weighted averages of pH and Resistance for Rooihoogte heuweltjies No.6 & 7

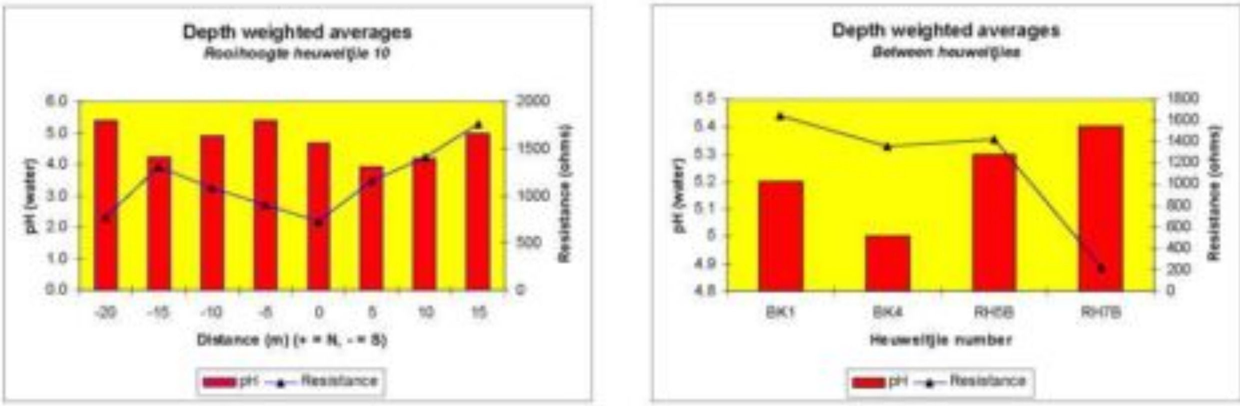
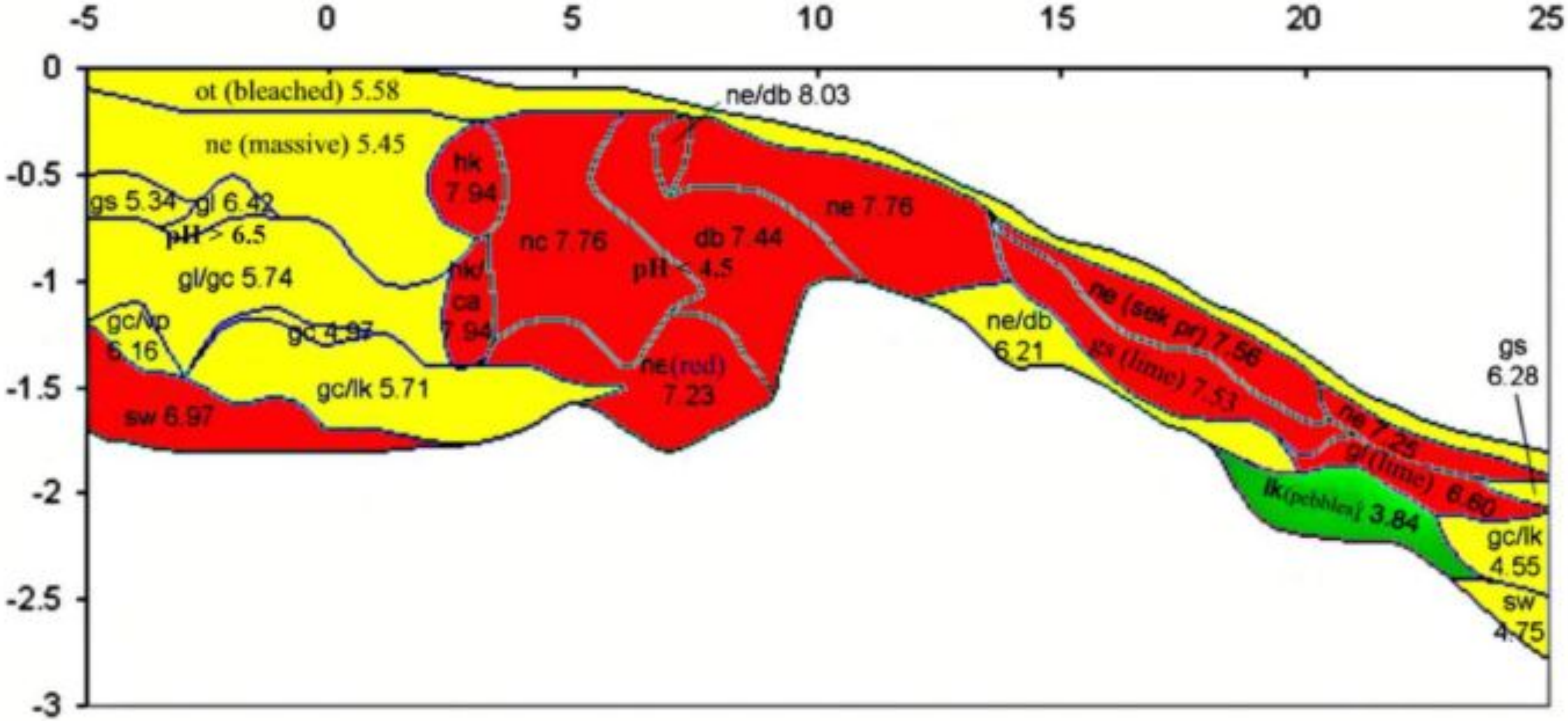


Figure 7.5 : Depth-weighted averages of pH and resistance for a relic heuweltjie on Rooihoogte Farm (heuweltjie No 10) and for inter-heuweltjie areas on Broodkraal (BK1 and BK4) and Rooihoogte (RH5B and RH7B)

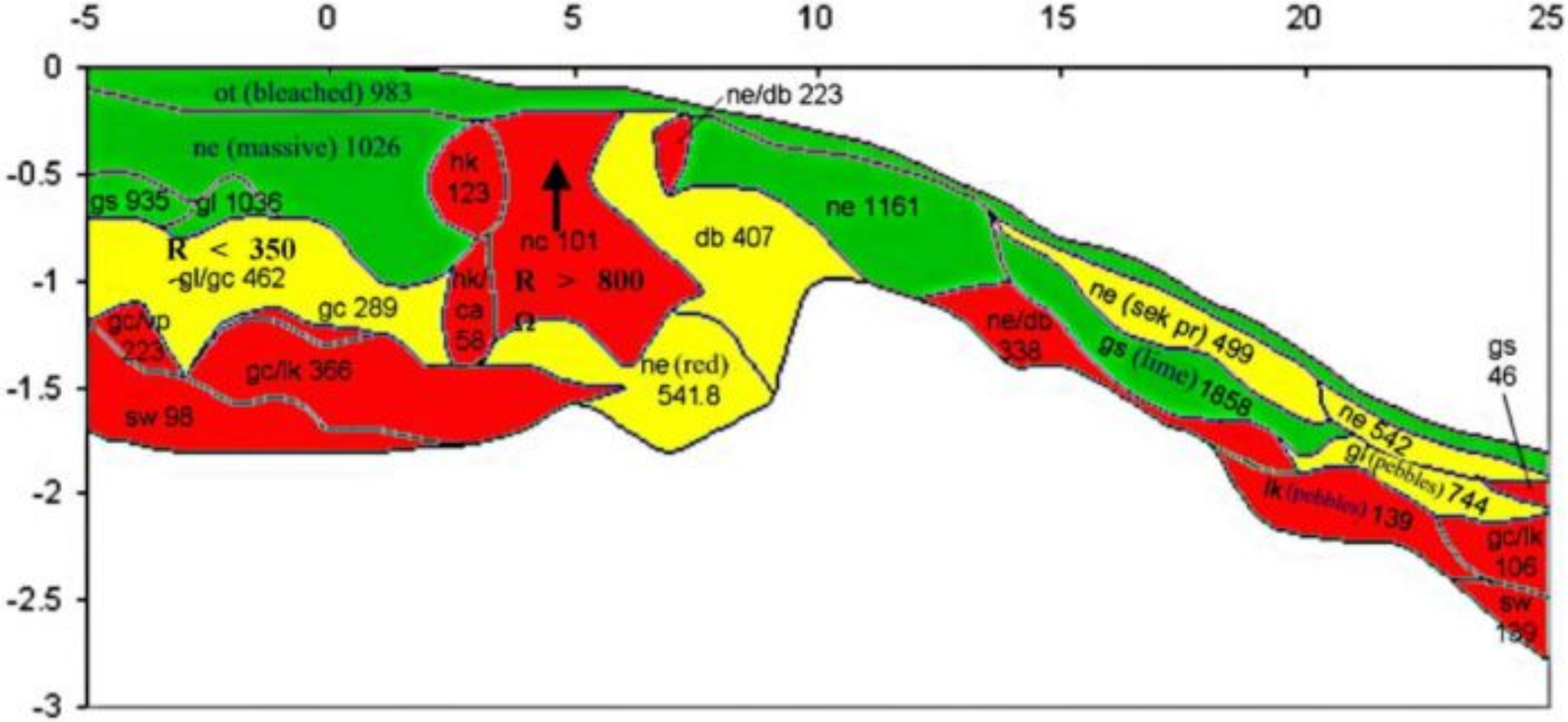
Figure 7.6 is an attempt to illustrate the three dimensional nature of variation in pH and resistance in heuweltjies. Here the analysis of pH and resistance was used and expressed per diagnostic horizon for heuweltjie 6 on Rooihoogte. The zones of higher pH and lower resistance are clearly visible with the tendency to be most pronounced towards the center of the heuweltjie.

In Figure 7.7, depth-weighted averages of pH and resistance values for topsoils and deep subsoils (representing the pre-weathered saprolitic material) are given for two inter-heuweltjie sites sampled next to No.'s 5 and 7 on Rooihoogte. This data confirms the earlier statement that a high salt load can be expected to occur in the saprolitic (weathered zone) material. The composition of the salts was not considered in this study, but high levels of Na are expected. Irrigation development should influence the mobility of these salts.



-5
0
5
10
15
20
25
0
-0.5
-1
-1.5
-2
-2.5
-3
ot (bleached) 5.58
ne (massive) 5.45
ne/db 8.03
hk
7.94
gs 5.34
gl 6.42
pH > 6.5
gl/gc 5.74
hk/
ca
7.94
nc 7.76
db 7.44
pH < 4.5
ne 7.76
gc/vp
6.16
gc 4.97
gc/lk 5.71
sw 6.97
ne(red)
7.23
ne/db
6.21
ne (sek pr) 7.56
gs (lime) 7.53
ne 7.25
gl (lime) 6.60
lk(pebbles) 3.84
gs
6.28
gc/lk
4.55
sw
4.75

(a)



(b)

Figure 7.6 : Plot of the profile wall using diagnostic horizons for a) pH and b) Resistance for heuweltjie 6 on Rooihoogte (horizontal and vertical scale in meters)

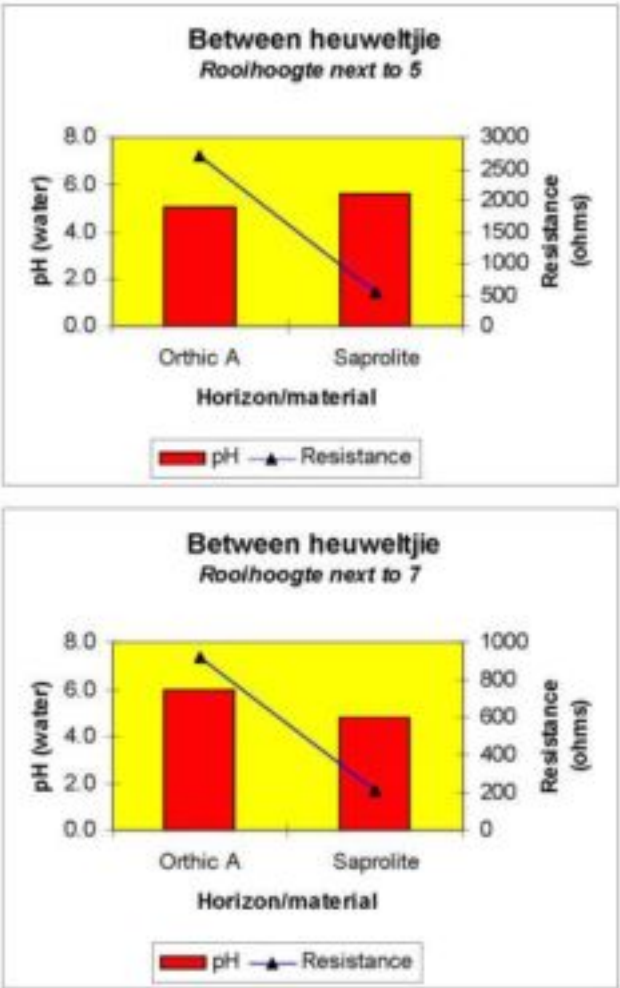


Figure 7.7 : **Depth-weighted averages of pH and Resistance of topsoils and deep subsoils (saprolite) on two between heuweltjie areas (next to No's 7 and 5) on Rooihoogte**

7.2.3 Conclusions

This study revealed two points that are important for further irrigation development of the area:

1. Despite the availability of suitable soils, presently under dryland cultivation, for further irrigation development along the Berg River, a potential problem with a high salt content exists in most of these soils. Such soils are mainly related to the old geomorphic land surfaces where a pre-weathered zone occurs in or just below the soil solum. The salinity hazard of these (and other) mapping units where salinity is already, or might become a problem under dryland conditions in future, have been identified and indicated on one of the maps that accompany this report. Further research is therefore necessary to establish the geographical distribution, quality and quantity of the salts that are presently in the saprolitic material.

2. The influence of the biological factor, manifested in the occurrence of numerous mounds, called "heuweltjies" in the region, is important, as it has caused the development of higher base status (i.e. salt concentration) with resultant higher pH in profiles. These conditions are conducive to a situation of higher mobility of salts both vertically down the profile or horizontally down slope to lower lying areas. These factors could lead to increased salinisation, especially under new irrigation development, if not managed properly.

7.3 DEFINING AN APPROACH TO SALINITY HAZARD ASSESSMENT AT BROODKRAAL FARM

At Broodkraal Farm, 368 positions were sampled at two depth increments (Figure 7.8). Each position was sampled at two depth increments. In Figure 7.8 it can be seen that the area was chosen to cover a small catchment. The area consists of mainly two soil types, namely Oakleaf and Glenrosa. The vineyards that were sampled ranged (at the time of sampling) between 5 years and 1 year in age. A lot of work was done analysing the data. In this section and the next, some of the more meaningful results that have a bearing on this project will be shown.

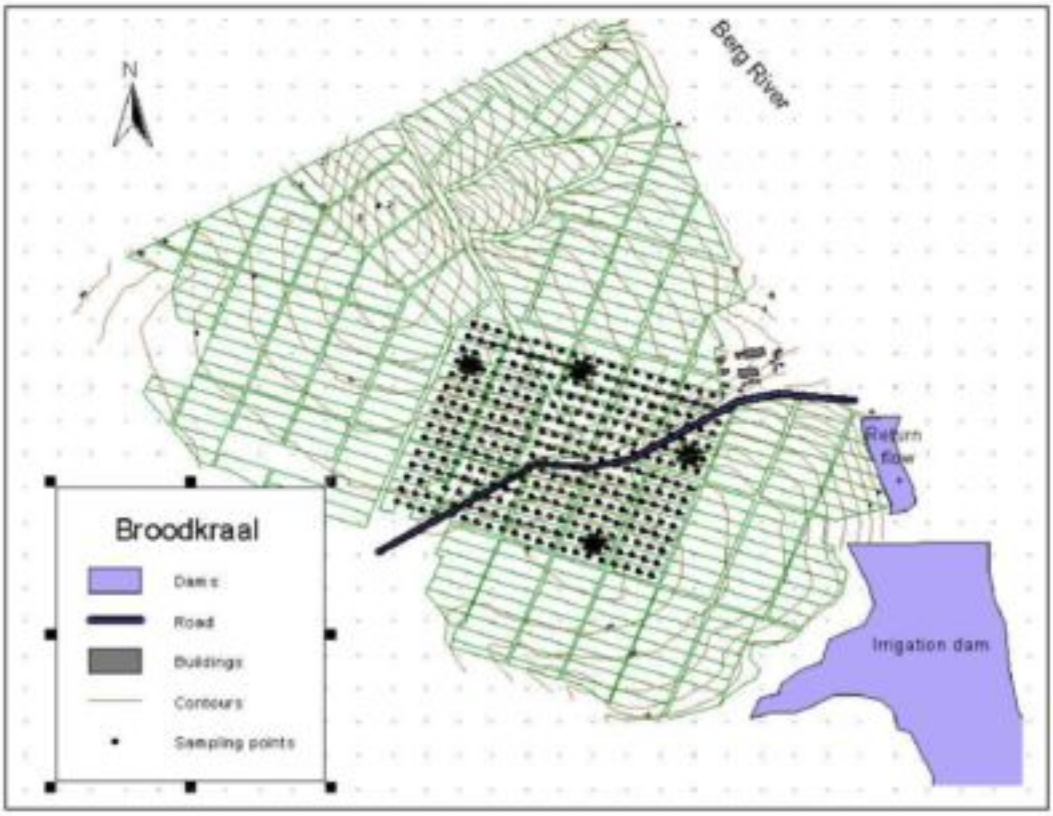


Figure 7.8 : Map of Broodkraal Farm showing the soil sampling positions for geostatistical analysis

The descriptive statistics are given in Table 7.4 and a correlation matrix in Table 7.5. Judging from Table 7.5, the correlations between variables is rather low except between EC_e and ER, which is not surprising. It is also better to value the significance values in Table 7.5 above the R2 values. In large datasets the R2 values tend to be a bad measure of spatial dependence as only a few outliers dramatically reduce the R2 values. This is not the case with the significance values (Table 7.5). In Table 7.5, the relationships between pH and EC, pH and TC and stone content and EC, were indicated as highly significant.

Table 7.4 : Descriptive statistics of variables stone content, pH, ER (electrical resistance), Ec_e and TC (trunk circumference) from the Broodkraal Farm

	Mean	Std. Deviation	Analysis N
Stone	36.37	6.81	173
pH	6.47	.62	173
EC	226.17	63.86	173
TC	11.20	2.93	173

Table 7.5 : Correlation Matrix of variables measured at Broodkraal Farm

Correlation		STONE	PH	EC_e	TC	SAR
R^2	PH	0.127				
	ECE	-0.157	-0.333			
	TC	0.282	0.406	-0.157		
	SAR	-0.407	0.071	-0.054	-0.145	
	CLAY	0.069	0.019	-0.105	0.234	0.037
Sig. (1-tailed)	PH	0.074				
	ECE	0.037**	0.003*			
	TC	0.011**	0.000*	0.103		
	SAR	0.000*	0.213	0.271	0.124	
	CLAY	0.272	0.434	0.178	0.029**	0.374

** Significant, *highly significant

The results in Table 7.5 are rather remarkable. The SAR-stone relationship is highly significant. This implies that in stony soils or stony patches, more leaching takes place. There is also significance in the relationship between clay percent and trunk circumference values. This implies that growth is limited by more clay in the soil. All of these relationships can be used to characterize differences between soils in terms of their sustainable use. In other words, these are important findings as they relate to water use in these vineyards.

The relationship between SAR and stone content of the soil needs more attention. Judging from the R^2 values, the relationship is inverted, implying that a low SAR is related to a high stone content. This supports the finding that the stones are not distributed evenly and form patches of high and low stone content. This has a marked influence on irrigation management. To optimise irrigation in these soils, the irrigation frequency must be determined by the water holding capacity of the stony patches and the irrigation amount by the patches with least stones. This will ensure that leaching is minimized and that the patches with least stones are leached as well. The patches with least stones tend to become more saline than the rest when this irrigation practice is not applied, and result in poorer plant performance as can be seen from the significant relationship between trunk circumference values and stone content.

Some of these relationships will be explored and modelled in the next section.

7.4 GEOSTATISTICAL ANALYSIS OF VARIABLES PH, EC, ER AND TRUNK CIRCUMFERENCE AND THEIR INTERACTION

Due to the significance in the relationships between the mentioned variables, the variance of each variable was modelled and mapped. A model was then developed that can be used to indicate whether a soil can be considered for sustainable irrigation agriculture.

The model also presents the opportunity to do quick and cost effective salinity hazard evaluations. It is important to note that this approach highlights the importance of the correct soil EC and soil pH for sustainability, both variables being measurement of soil water quality.

7.4.1 pH

The pH may have an important effect on growth as shown by the good correlation between trunk circumference and pH.

The histogram of the weighted averages of the pH was drawn (Figure 7.9). It shows negative skewness (<0), kurtosis smaller than 3, and a mean pH of 6.6 while the maximum and minimum are 8.3 and 4.4, respectively. The fact that the pH varied this much provided the opportunity to correlate these values with the other measurements and to map pH successfully. In Figure 7.11, a map of pH in the study area is given.

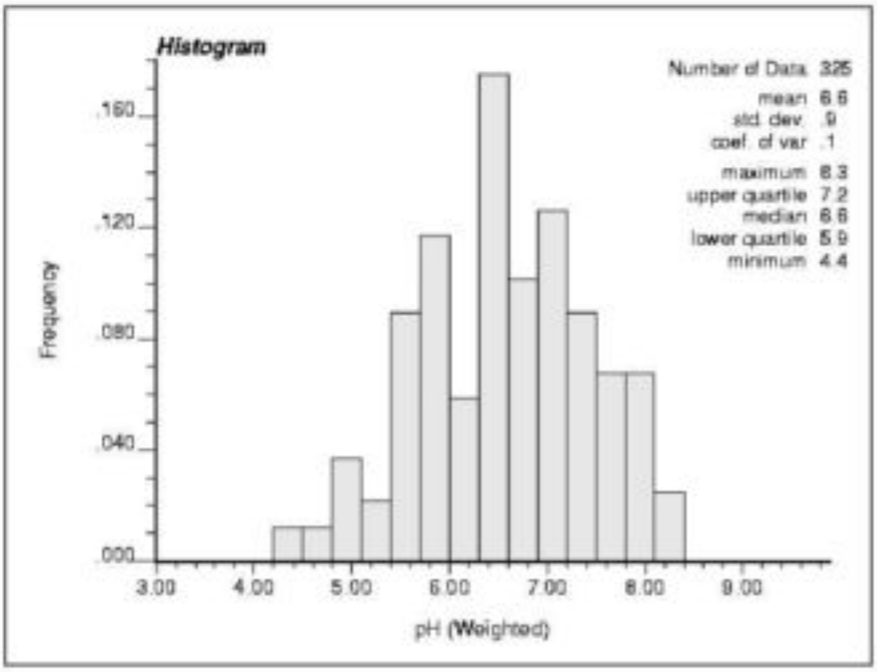


Figure 7.9 : Histogram of weighted average pH data (0 to 40 cm soil depth)

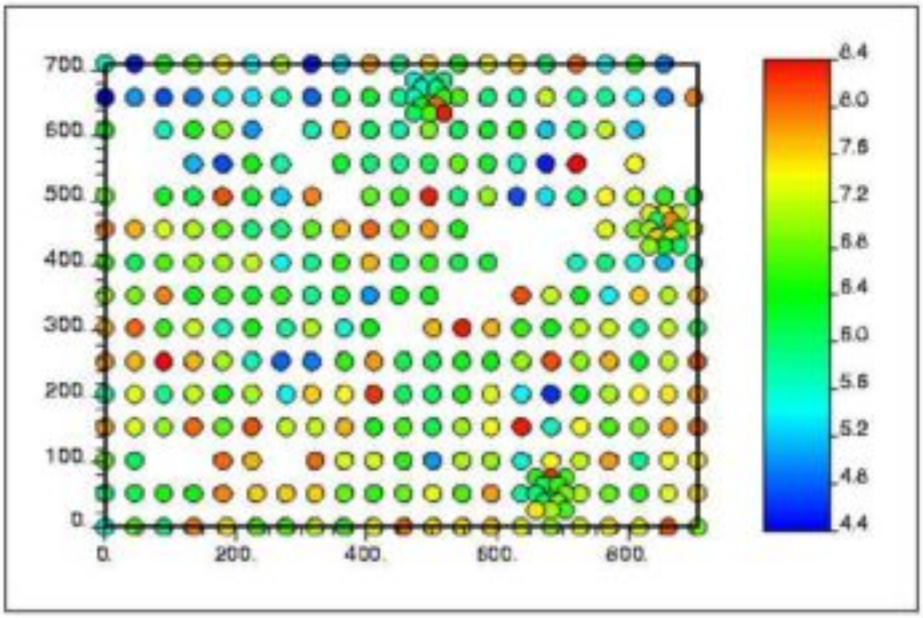


Figure 7.10 : Histogram on map of pH from the weighted averages (0 to 40 cm)

7.4.2 Ordinary Kriging as applied to pH

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 semivariogram was used.

The fitted variogram model is an exponential model with a nugget (C0) of 0.4, sill (C0+C1) of 0.752 and range equal to 258 m (Figure 7.11).

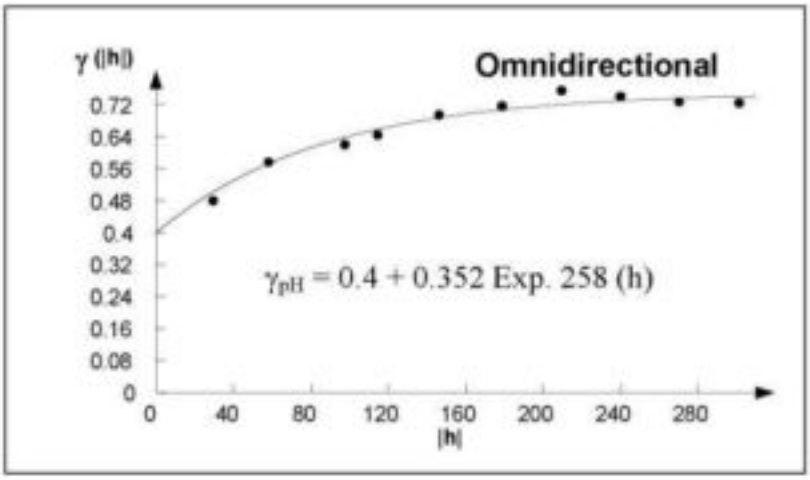


Figure 7.11 : An experimental semivariogram and variogram model of the variable pH for soil depth 0 to 40 cm

The grid for interpolation in block Kriging was 4 m by 4 m. The minimum number of points involved in the interpolation was 2 and the maximum number was 12. The radius of the local window was 200 m, circular and isotropic. The resulting variogram model is given in Figure 7.11.

The pixel plot of the variable pH, after Ordinary Kriging, is given in Figure 7.12.

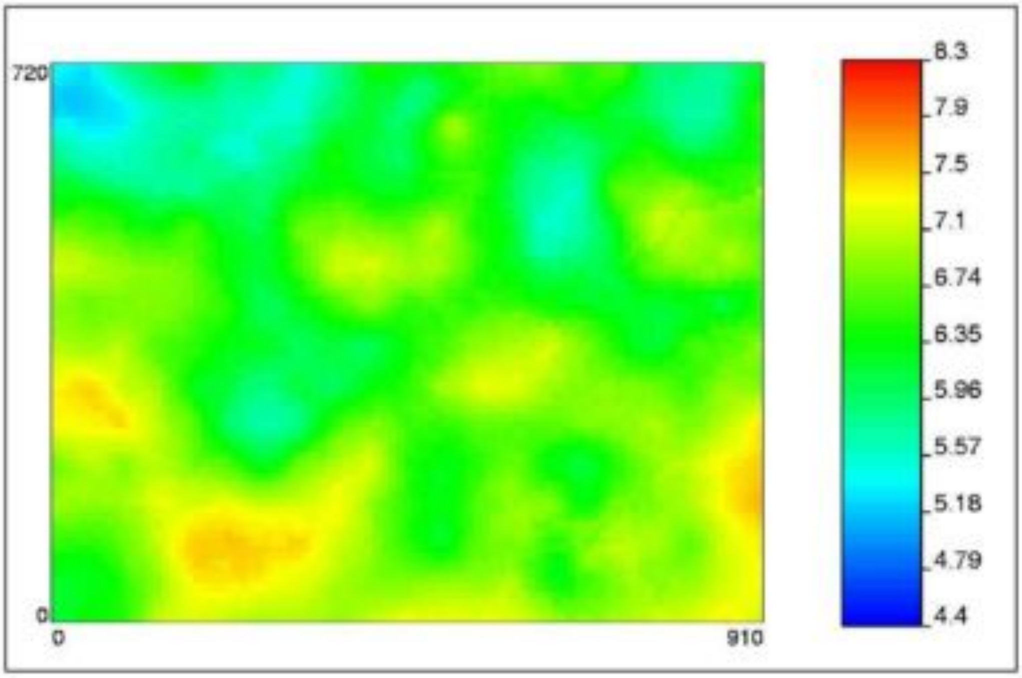


Figure 7.12 : Map of pH measurements generated through Ordinary Kriging

7.4.3 EC_e

In the histogram of EC_e two definite extreme values can be identified that prompted further investigation. The parameters of centrality, spreading, skewness and kurtosis of the EC_e histogram (Figure 7.13) 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.

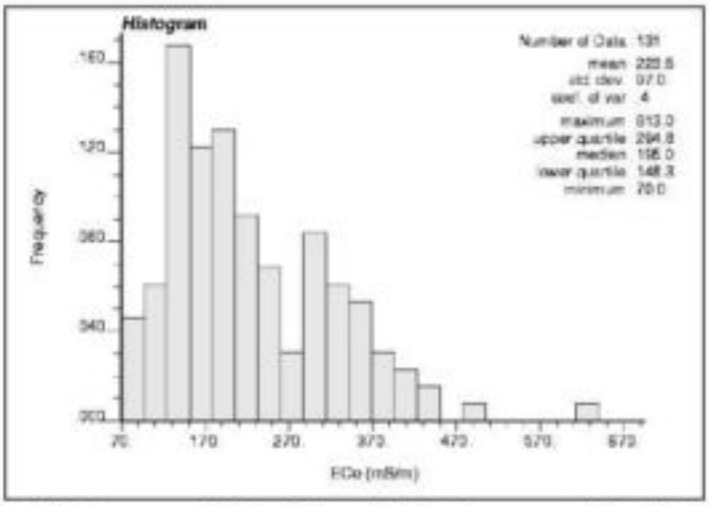


Figure 7.13 : Histogram of EC_e of the weighted average (0 to 40 cm soil depth) with two extreme values

It was found that these values coincided with sites where samples were taken in a heuweltjie. This was confirmed by inspection of a 1:10000 orthophoto-map of the region. This heuweltjie or rather this position in the landscape had much higher EC_e values than the surrounding area. The average and maximum of the EC_e values in this cluster was respectively 330 and 1017 mS m^{-1}. This is much higher than the EC_e values in the surrounding region, where the average and maximum were 170 and 248 mS m^{-1}. The pH in the heuweltjie was also significantly different from that of surrounding soil. After removal of the fourth cluster, the total data set consisted of 612 measurements.

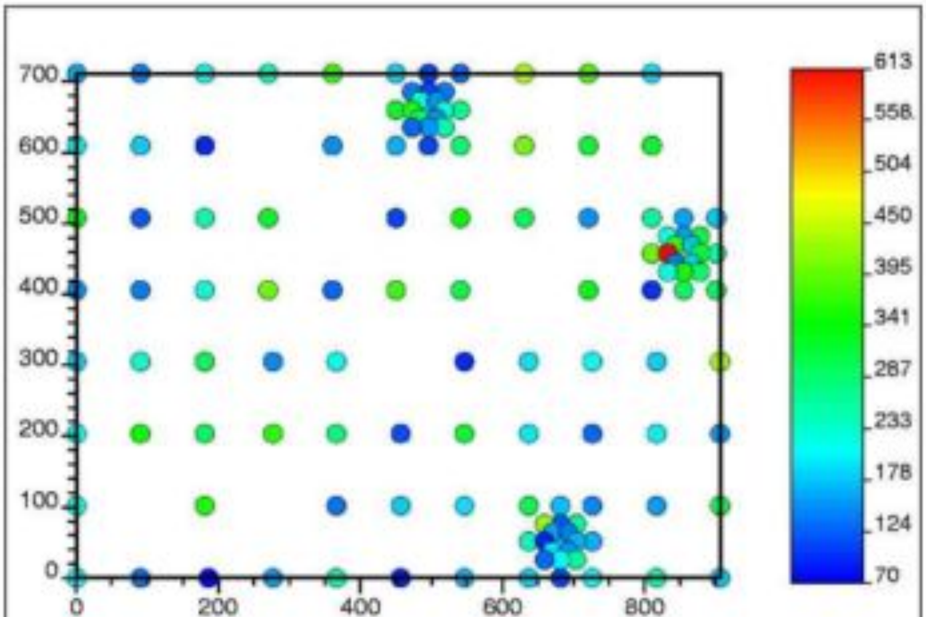


Figure 7.14 : A location map of the weighted averaged EC_e values (0 to 40 cm soil depth)

7.4.4 Ordinary Kriging and Co-kriging applied to EC_e

These two data sets were used to explore the spatial variability of EC_e. To better map this result, co-Kriging was used and the electrical resistance data was included as a second data set, which was much larger, and correlated well with EC_e (R^2 of 72 %).

The maximum lag-distance over which the experimental semivariogram could be calculated was 300 m. As a result of its isotropic nature, the experimental semivariogram is omnidirectional. The fitted variogram model is spherical and is given in Figure 7.15. The fitted variogram model of the electrical resistance is given in Figure 7.16 and the fitted cross semivariogram of the two variables is given in Figure 7.17.

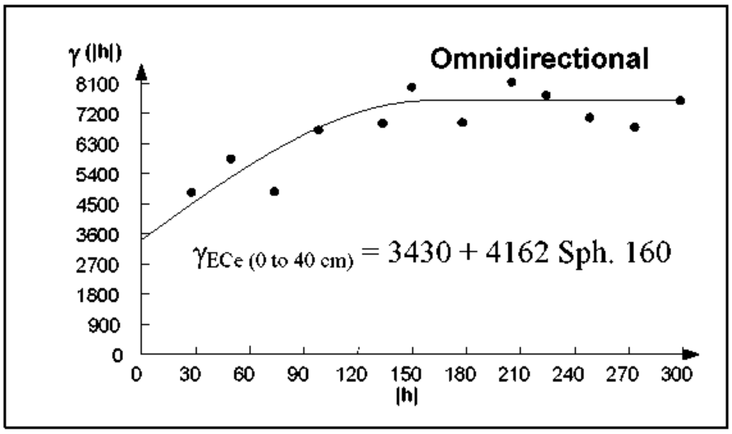


Figure 7.15 : The experimental semivariogram and spherical variogram model of the primary variable EC_e

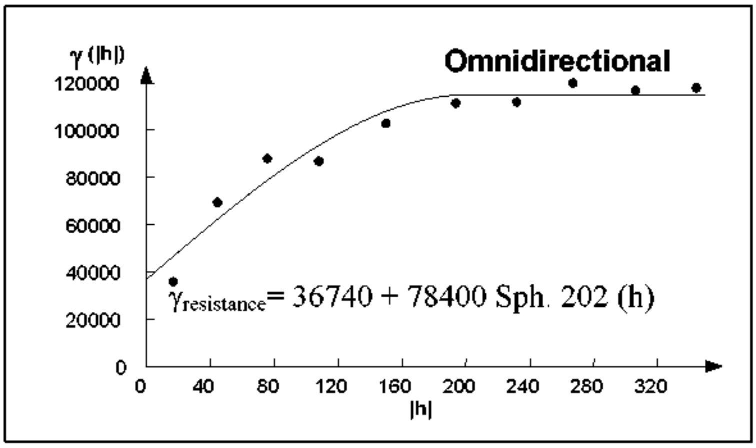


Figure 7.16 : The experimental semivariogram and the spherical variogram model of the second variable, electrical resistance

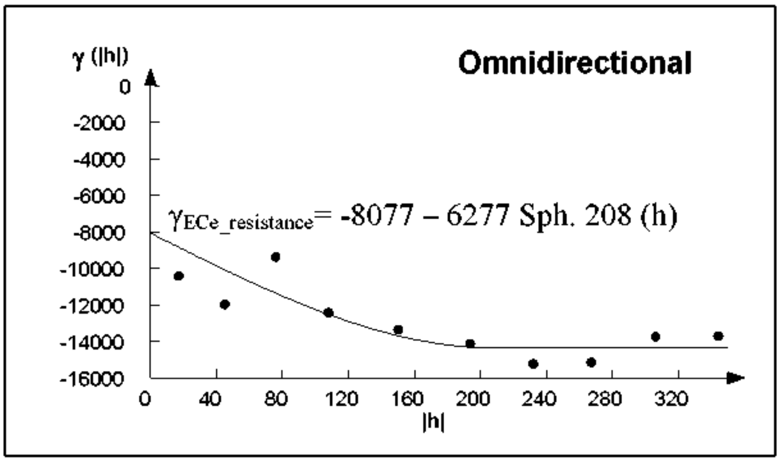


Figure 7.17 : The cross-semivariogram and spherical variogram model of the primary variable EC_e and the secondary variable electrical resistance

The map of the interpolated EC_e-values resulting from these analyses and Ordinary Kriging is given in Figure 7.18. The Co-Kriged result of the Figure 7.17 model is presented in Figure 7.19. It is quite clear from Figures 7.18 and 7.19 that Co-Kriging enhanced the predictability of EC_e in the landscape.

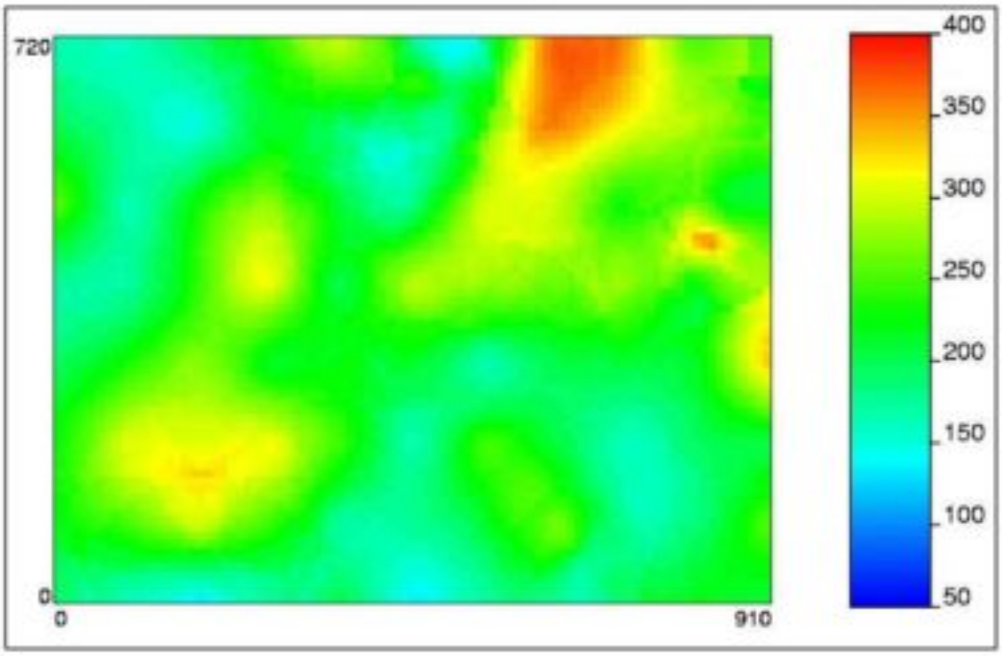


Figure 7.18 : EC_e after application of Ordinary Kriging

The dark blue spots in Figure 7.19 are situated on the ridges, in other words on the highest points in the landscape, while the black belt from the south-western corner to the north-eastern corner is the major drainage path way.

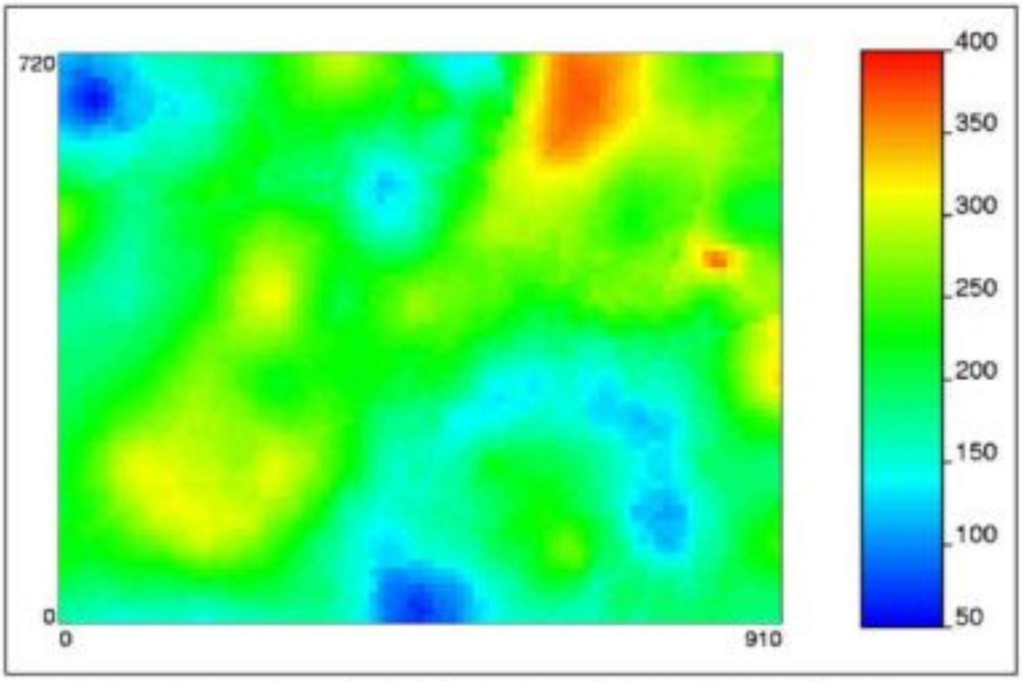


Figure 7.19 : Map of the variable EC_e resulting from Co-Kriging

7.4.5 The spatial variability of vine trunk circumference

Simple Kriging was applied to the residuals of the data set after the annual averages were subtracted from all circumference data. A data set with an average value of zero was generated. An experimental semi-variogram of the residual values was calculated. The isotropic nature of the data led to an omnidirectional semi-variogram model and a spherical model with nugget (C_0) of 1.28, a sill (C_0+C_1) of 3.293 and range of 160 m (Figure 7.20).

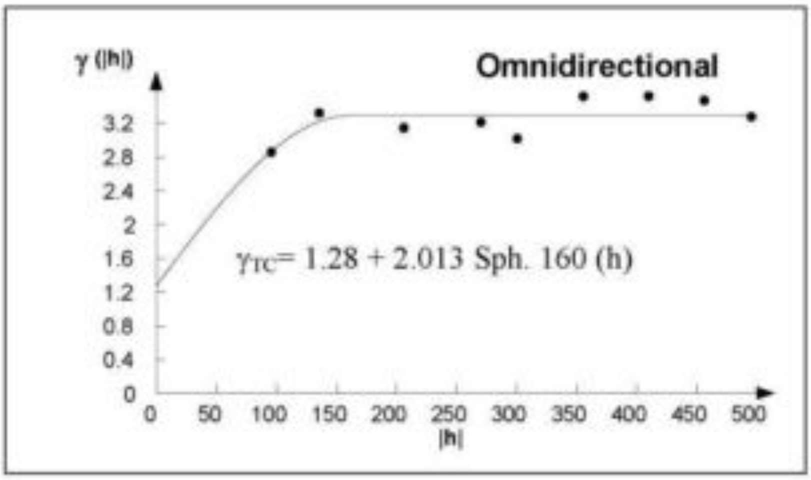


Figure 7.20 : An experimental semivariogram of the variable trunk circumference (TC) fitted to a spherical variogram-model

The minimum and maximum number of points used with interpolation were 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 7.21. Black lines delineate the different vineyards, and also show the areas without any vines such as the roads. Figure 7.21 shows a true year effect.

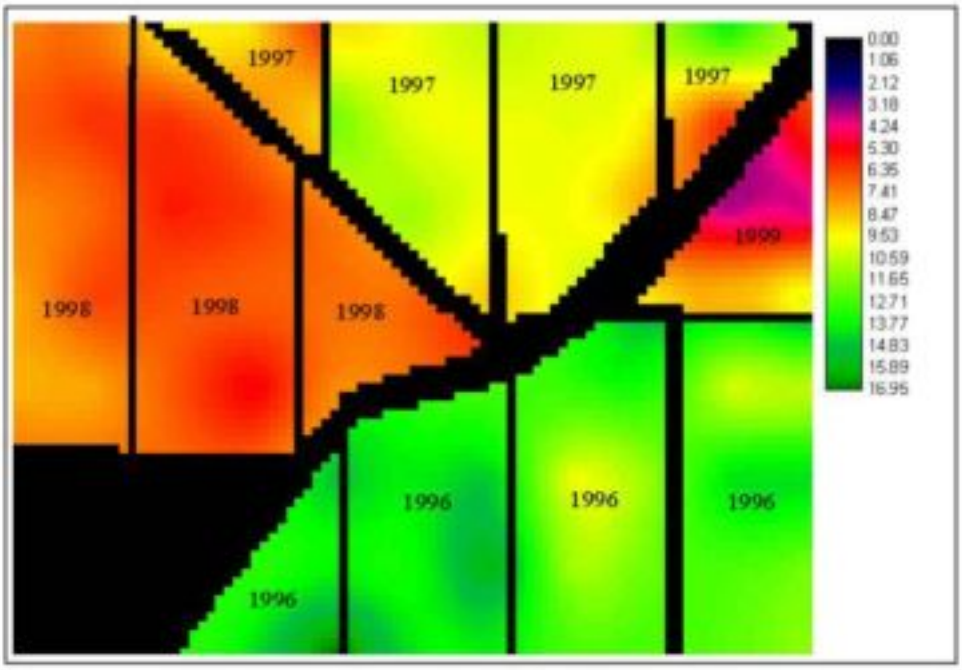


Figure 7.21 : A map of trunk circumference data on the Broodkraal Farm derived from Kriging with an overlay with the field boundaries and an indication of the planting year of each vineyard

7.4.6 The Parameters that Influence TC

The relationship between all the other parameters that were investigated and the trunk circumference was subjected to multiple correlation. The age effect was eliminated to improve the correlation. To accomplish this, the year average was subtracted from the data, leaving the total set with an average of zero. The only significant relationships TC had were with EC_e, the clay percentage and the pH. A positive correlation was found between TC and both clay percentage and pH while the correlation with EC_e was negative. The results are shown in Table 7.6, and Figures 7.22 and 7.23.

Table 7.6 : The calculation of a Pearson Correlation coefficient between [TC-average] (after elimination of the age effect), pH, EC_e and the clay percentage

	*Pearson Correlation	pH	EC_e	%Clay
[TC-average]	Correlation	0.257*	-0.263*	0.288*
	Sig. (2-tailed)	0.037	0.033	0.019
	N	66	66	66
PH	Correlation		-0.179	0.008
	Sig. (2-tailed)		0.112	0.941
	N		80	80
ECe	Correlation			-0.197
	Sig. (2-tailed)			0.080
	N			80

* Correlation is significant at the 0.05 level (2-tailed).

A stepwise-outlier-rejection multiple-regression was used to explore and define the relationships between clay %, age, TC, EC_e and pH. Only factors with significance smaller than 0.06 were included in the model.

The age of the vineyard had the largest influence on the circumference, as would be expected, and 58.6 % of TC was predicted by this variable. However, the inclusion of the other variables in the regression resulted in a prediction of 65.2 % of the values, within the 95% limits. The variable clay was excluded from the equation, as clay percentage did not improve the prediction. The significance of clay percentage (0.165) did not comply with the set acceptance criteria for inclusion in the model. A possible reason for this could be the strong correlation between clay, pH and EC_e causing the added value of clay to become marginal.

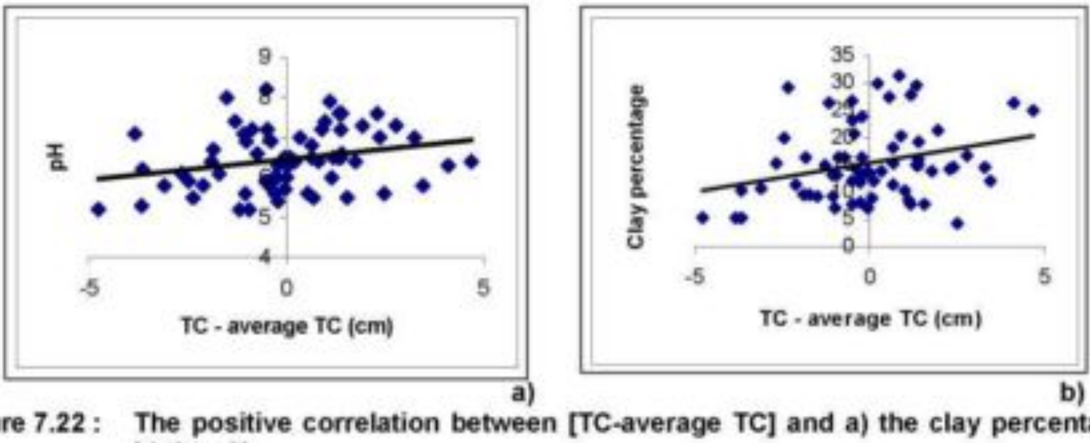


Figure 7.22 : The positive correlation between [TC-average TC] and a) the clay percentage and b) the pH

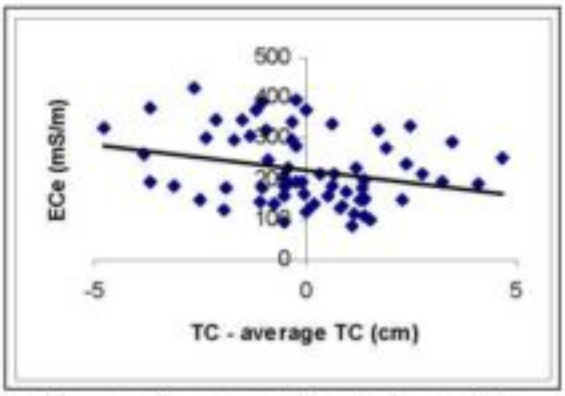


Figure 7.23 : The negative correlation between [TC-averageTC] and the EC_e

Table 7.7 : The multiple regression analysis done by the stepwise outlier-rejection method

Model		Non-standardised coefficients		Standardised coefficients	T	Sig.
		B	Std.Err.	Beta		
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	0.179	2.240	0.029
	EC_e	-5.91E-03	0.003	-0.154	-1.962	0.054

Equation 21 was deduced from the results given in Table 7.7. Equation 10 was then used, together with the overlaid results of Figures 7.12, 7.19 and 7.22, to calculate the result shown in Figure 7.24.

$$TC = 0.518 + 2.046\,Age + 0.808\,pH - 0.005913\,EC_e \qquad 21$$

Figure 7.24 shows the prediction of TC after four years of growth calculated with Equation 21. However, it must be borne in mind that this prediction does not take into account the true ages of different vineyards on the farm. It is simply an equal age prediction, predicting the TC of all vines after four years of growth. In Figure 7.24, A and B are the areas with the most stable growth and yield, while areas B and C have very large variance. Area E, and the similarly coloured section to the left of area E, shows the lowest potential. These results are confirmed by observation on the farm.

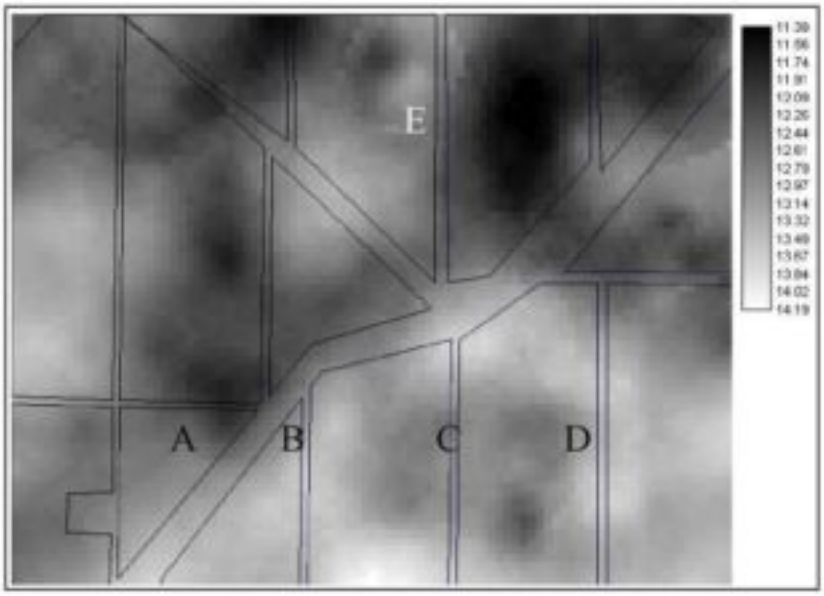


Figure 7.24 : Prediction of TC of the vines after 4 years with the different management blocks projected over the TC prediction

7.4.7 Discussion

The approach used here for mapping soil salinity and related variables must be seen as a trial to investigate the possibility of applying these results on a much larger scale. Soils of the Western Cape are well known for their large variability over short distances and, the advantages of using geostatistical techniques to aid precision farming are clear. The predictable behaviour of EC_e in relation to pH, time and plant vigour has widespread applications for the grape/wine industry of the Western Cape. In particular, soil pH is seen to have the most significant long-term influence on vine-trunk circumference. The techniques used here are the basis for precision farming, and it is therefore most relevant to develop these techniques for managing salinity-related problems.

In the soil preparation process before planting, the soil is homogenised as much as possible by mechanical and chemical means. After a fairly intensive soil sampling procedure, an ameliorant base is developed which will hopefully have long-term effects to ensure stable growth and production, for at least 10 years. However, the application of ameliorants takes place without the use of a database of soil quality variability, in other words, without precision farming techniques. The results of this study show that the optimum results were not achieved, and the economic implications of this are evident.

The EC_e values that were measured in the upper part of the soil in this study must be seen in their context: a region with up to 10 mm evapo-transpiration per day, very little rainfall and a total dependence on irrigation. It can thus be expected that in areas that received over-irrigation, the EC_e will be the lowest. In segments that received irrigation less 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 pH is restricting growth, transpiration is lessened and therefore over-irrigation usually occurs at these sites, resulting in runoff and increased drainage.

From Figure 7.24 it is clear that areas of expected good growth and very bad growth can be predicted prior to planting. Though the information presented in Figure 7.24 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, implies that the vines reacted more to what was happening in the upper part of the soil than the section below that.

The fact that the results in Figure 7.24 resemble a statistical result, with a R^2 value of close to 66 %, indicates that the influence of drought is negligible and that irrigation is, in essence, handled very well on this farm. The fact that production profitability on this farm is just above break-even implies that, had the soil been prepared by using the surveying techniques described in this article, production and profit would surely have been much greater. Apart from that, a measure was created by which the profitability of land in the surrounding area can be evaluated.

Apart from being able to map the different variables as discussed above, the ability to map and investigate individual elements with this approach has very exciting possibilities. In the next section soil sulfate depletion will be mapped to show that geostatistical mapping can also be used to take stock of gypsum in the landscape.

7.5 SO_4 IN THE LANDSCAPE AT BROODKRAAL

Sulphate concentrations are generally fairly high in these soils and generally have a good correlation with EC and ER, with concentrations just lower than that of chloride. However, gypsum is applied as an ameliorant for the initial high salt/sodium content of these soils, before irrigation is introduced. It therefore makes sense to explore sulphate as an indicator of salt transportation and the volumes of irrigation applied in the irrigated soils by mapping sulphate concentration in the upper soil horizons. This will give an indication of the amount of leaching that took place and also the amounts of sulphate added to the river system.

A semi-variogram and variogram model of the spatial variability of sulphate was derived from the soils database at Broodkraal (Figure 7.25). The resulting map is shown in Figure 7.26. The lines on the right side of the map were caused by sparse data.

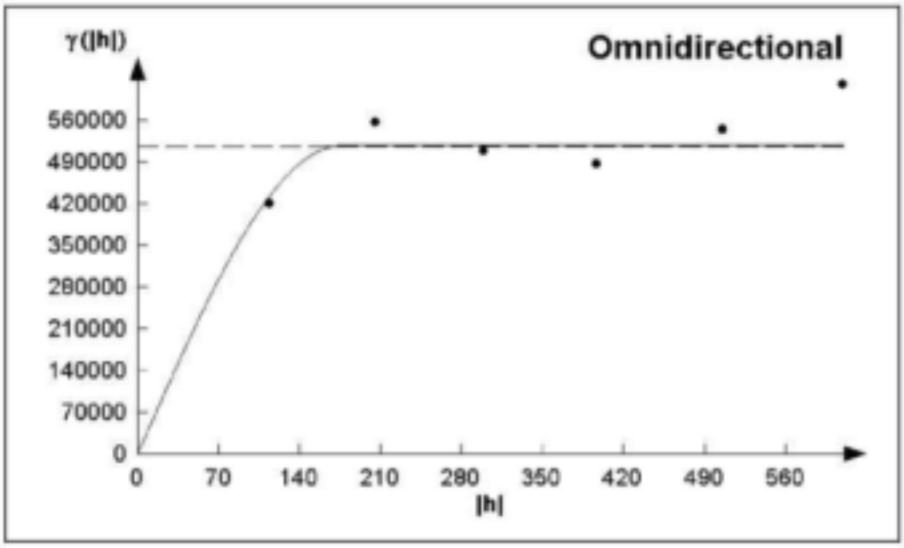


Figure 7.25 : Omnidirectional variogram and variogram model of the variable sulfate on the Broodkraal Farm

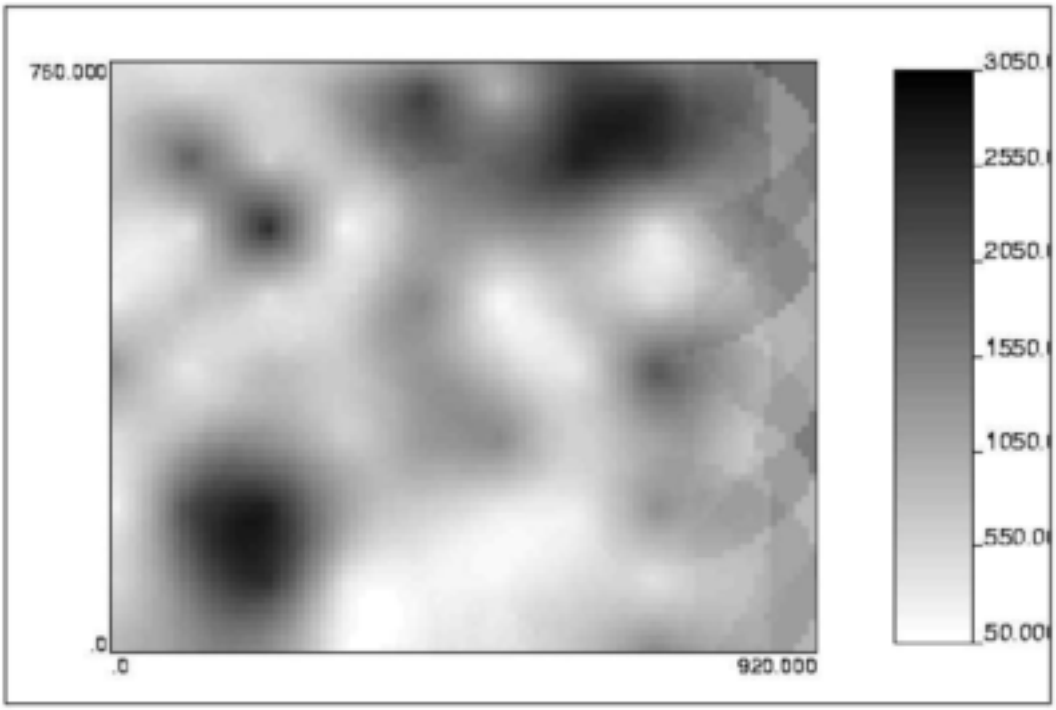


Figure 7.26 : Pixel plot of SO_4 over a 60 ha site at the Broodkraal Farm

The technique used here to map SO_4 on Broodkraal Farm gives an indication of the distribution of SO_4, as well as differences in SO_4 concentration, in the top layers of the soil. The different sections of the farm were subjected to the same gypsum applications when they were first developed for irrigation, but have different ages in terms of their irrigation history. The oldest areas have the lowest SO_4 concentrations (centre south) while the youngest areas have the highest SO_4 levels. From this analysis it is possible to calculate the amount of SO_4 lost from the soils of this area over time, either as a result of dissolution or drainage. This is not possible with the use of standard models that predict on the basis of one or two profiles.

Lastly, it is possible to model SO_4 depletion over time from the mapped result.

7.6 THE BERG RIVER CATCHMENT AND GIS GENERATED MAPS

7.6.1 Defining the Term Salinity Hazard

The term hazard usually generates a lot of confusion. It is therefore necessary to clarify hazard before discussing methods of mapping. The term hazard, may be defined for current purposes as "a condition that might operate against success or safety" and "something risked" (Webster's 3rd new international dictionary).

Salinity hazard has to be seen as a manageable condition. For instance, from a farmer's point of view, it must be realized that salinity hazard can be managed by better irrigation management practices and by varying the crop type (season length and rooting depth). Hazardous soils will therefore be defined as those that have no potential of producing high yields and are salinity prone with a potentially large salt contribution to the river system. Some of these deeper soils that line the lower portions of the catchment, may form a natural salt buffer that contains saline seep and therefore reduces the salinity hazard to the river system during the summer. Irrigation on soils adjacent to these soils can, however, cause a rise of the water table in low-lying areas and a resultant increased seep towards the river. This secondary enrichment of seep from irrigated areas is seen as the main problem that originates from irrigation.

Recognition of highly saline conditions must involve location, terrain form, clay content of the soil, salt reserves of the underlying material and possibly distance from the sea. Usually the slope of the river or any of its tributaries can also give some indication of the degree of salinity hazard.

The salinity hazard map of the BRC was therefore compiled with the aim of categorizing soils according to their average known and inherent salt content and therefore their potential to generate highly saline return-flow over long periods.

7.6.2 Soil surveys and maps

A soil map including most the Berg River catchment was compiled. The method involved intensive travelling and profile investigation over the whole catchment, and frequent sampling and analysis of soil. It also involved consulting all possible soil maps that existed for parts of the BRC. All information, for instance the older soil maps, were field validated and the soil classification updated according to Soil Classification: A Taxonomic system for South Africa. Soil analysis involved EC_e of the profile. Soils were ranked from soils that pose no salinity hazard to soils that pose a high hazard. Soils that pose a high hazard could also be divided into saline and non-saline, basically resulting from the particular location of these soils. For large areas no soil analyses data were available and in such cases inferences were drawn from soil classification and field observations made during the soil survey.

The soils were therefore ranked into 5 groups according to classification and physical character, namely High(H), Medium High(MH), Medium(M), Medium Low(ML), and Low(L). The list and the ranking form part of the soil map legend. Two maps were compiled:

1. The Berg River soils map
2. The Berg River general salinity hazard map.

7.7 SOILS DATABASE

For various reasons it was decided not to development a soil chemical database in the format originally decided upon. The reasons for this include the following:

1. The soil surveys conducted at, for instance Broodkraal, showed that the variability of soil properties over short distances, as little as 10 m, is of such a magnitude that the representativity of a single sample in a 2 ha vineyard is very poor.
2. It was also virtually impossible to locate the exact positions where samples had been taken in the past, as these positions were never accurately logged, and in many instances the property has changed ownership.
3. Variability over short distances in certain soils proved to be more pronounced than the variation with time observed over several years at the same location.
4. Dryland saline seeps also appeared to be influencing the salinity status of the soils of the irrigated lands.

5. Soil salt content varies between seasons, as well as over a number of years, as soils react to climatic and agriculturally induced changes. Such temporally and spatially variable information was difficult to incorporate credibly into one map. The study at the Broodkraal Farm showed that by using variograms, the typical expected variation in the landscape could be defined. It is precisely this type of information that is lacking for the rest of the Berg River catchment.
6. From historical data it was clear that in many instances only composite samples of topsoil were taken while most of the salinity is associated with subsoil horizons.

It was therefore decided to focus on newer information and sites that were known to the authors of this report and the Elsenburg Soil Science Section. This resulted in the narrowing down of the study area to only 10 farms, a number which we hope will increase in the future. The results from these farms are not included in the report, although data from these farms were used in the soil and salinity mapping.

CHAPTER EIGHT
FINAL DISCUSSION AND CONCLUSIONS

A solid information base for modelling irrigation return-flow in the Berg River catchment has been established. The opportunity of using Broodkraal Farm, where soils range in irrigation age from 0 to 6 years, proved to be fruitful. This in a way shortened what would normally be a long-term project to about one or two years of intense sampling.

Mapping of the soils in the Berg River catchment has been achieved. A high quality reconnaissance soil map was completed on a GIS system, which places future planning and development of this area on a sound footing. This information will be easy to access and update in future as the need arises. This map will also play a major role in controlling future irrigation expansion in the Berg River catchment. A derivative map was also produced, presenting useful information regarding soil suitability or hazard for irrigated crops and the general salinity hazard.

In irrigated agriculture, soil salinity may change during and between seasons. The recorded change over one season is normally more dramatic than the general EC drift measured over a number of years. This means that when a single sample is taken once within a year, the likelihood of accurate assessment of salinity is rather poor. Therefore, the large variation in the occurrence of salt in non-irrigated and most importantly in irrigated land prevented us from including historic data in the report. There is no method available of linking data from resampled soils with historic data, especially since the latter were often not properly documented. It was decided to encourage the use of accurate GPS recording with all soil sampling to be done in the catchment. This cannot be expected of private companies and individuals, but where our department and the Department of Agriculture are involved, it certainly is possible.

Soil salinity seemed in many cases a product of the salt content in the parent material and regolith below the root zone. The implication is that soil salinity in the root zone is influenced by that below the root zone and that the latter should be the primary research concern. Though a salinity hazard map was produced, it is no guarantee that when new irrigation is initiated on higher ground (indicated as suitable on the map), lower lying soils (indicated as low risk and situated closer to the river) will not develop salinity problems.

Methods, by which salinity hazard assessment can be carried out, in relation to water management, were also successfully established.

The possibility was recognised of linking the results of geostatistical modelling and mapping of semi-variance to a model such as DISA. Carrying this out for various locations in the BRC would enhance the prediction of salt movement in the catchment.

CHAPTER NINE
RECOMMENDATIONS FOR FUTURE RESEARCH

It is quite important to establish certain measuring points along the Berg River catchment (BRC) where variables for salinity flux models can be measured for inclusion in water management models. It is therefore important that this study must continue. It is also quite important to develop land-use information at the same scale or better than the catchment-scale soil map.

For the first time information regarding the very complex pattern of variation in the occurrence of salinity in this system was generated. It is also the first attempt to show that irrigated agriculture is playing a sub-dominant role to that of the dryland agriculture section, in the salinity/sodicity related problems experienced within this system. The results clearly showed that the dominant source of salinity is the non-irrigated areas (dryland agricultural areas). In many cases, irrigated agriculture suffers as a result of problems generated by dryland salinity. It is thus essential to launch a research initiative to study dryland salinity.

This research is the first step in modelling the very diverse occurrence and variability in soil salinity of the BRC though it is believed that salinity in the soil is merely a product of the high salinity of the regolith and mother material below the root zone. It is therefore not in the interest of the water users in the catchment to stop this research at this very critical stage. The continuation of this project is of high importance, and will be proposed.

Most importantly, this research proposes a systematic identification of points in the BRC and recommends that these points be monitored over long periods to aid return-flow modelling, and to guide planning of dryland agriculture in the BRC.

CHAPTER TEN
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Appendix A

Soil descriptions of the soil and profile at sampling locations

Profile number:	K	Aspect:	North North-east
Map number:	Broodkraal	Water table:	None
Latitude and Longitude:	S32^{0}57'35"/E18^{0}40'34"	Height:	48m
Soil form:	Swartland	Surface stones:	Abundant (40-60%)
Soil family:	Adelaide (2110)	Crop:	Table grapes-Waltham Cross
Terrain unit:	Foot slope	Planting date (Age):	1996 (5)
Gradient:	9%	Underlying material:	Weathering shale to phyllite
Gradient form:	Concave		

Horizon	**Depth (mm)**	Brief description	**Diagnostic horizon/material**
A	0-100	Moist: strong brown colour (7.5 YR 4/6); Coarse sand with 54% clay; Moderate sub angular/fine blocky structure; Dark brown clay cutans, few roots; Disturbed clear transition;	Orthic A (mixed with B-horizon)
B	100-600	Moist: brown colour (7.5 YR 4/4); Coarse clay with 52-63% clay; Moderate to strong sub angular/fine block structure; abundant quartz and shale (weathered) stones present; Yellow, red and brown cutans, common roots; Varying clear transition	Pedocutanic B
C	>600	Shale, partly to well weathered; Signs of wetness for short time of year	Saprolite

Physical properties:

Depth (mm)	**Sand %**	**Clay %**	**Silt %**	**Stone %**	**Texture class**	**Sand Grade**	**Bulk density kg.dm^{-3}**	**Field capacity (%V/V)**
0-150	23	54	23	38	Clay	Coarse sand	1.77	27.5
150-300	16	63	21	34	Clay	Coarse sand	1.77	29.5
300-600	23	52	25	28	Clay	Coarse sand	1.77	27.5
600-900	40	30	29	25	Clay loam	Coarse sand	/	23.2
900-1200	51	16	33	27	Sandy loam	Coarse sand	/	/

Profile number:	J	Aspect:	East North-east
Map number:	Broodkraal	Water table:	None
Latitude and Longitude:	S32^{0}56'82"/E18^{0}40'95"	Height:	22m
Soil form:	Glenrosa	Surface stones:	Abundant (40-60%)
Soil family:	Overberg (2111)	Crop:	Table grapes-Sultana
Terrain unit:	Mid-slope	Planting date (Age):	1997 (4)
Gradient:	15%	Underlying material:	Weathering shale to phyllite
Gradient form:	Convex		

Horizon	**Depth(mm)**	Brief description	**Diagnostic horizon/material**
A	0-100	Moist: strong brown colour (7.5 YR 4/6); Coarse sandy loam with 7% clay; Weak blocky structure; Many large stone fragments lifted up by soil preparation; Disturbed clear transition	Orthic A (mixed with B-horizon)
B	100-700	Moist: strong brown colour (7.5 YR 4/6) and cutans with colours of 10 YR 4/4 en 2.5 YR 4/6; Coarse sandy loam with 7% clay; Weak blocky structure; Abundant shale rocks in different stages of weathering with weathered material in between; Varying clear transition	Lithocutanic B
C	>700	Shale, partly weathered	Saprolite

Physical properties:

Depth (mm)	**Sand %**	**Clay %**	**Silt %**	**Stone %**	**Texture class**	**Sand Grade**	**Bulk density kg.dm^{-3}**	**Field capacity (%V/V)**
0-150	65	7	28	52	Sandy loam	Coarse sand	1.7	18.9
150-300	67	7	26	51	Sandy loam	Coarse sand	1.7	18.9
300-600	66	6	27	53	Sandy loam	Coarse sand	/	12.3

Profile number:	F	Aspect:	North-east
Map number:	Broodkraal	Water table:	None
Latitude and Longitude:	S32^{0}56'95"/E18^{0}40'45"	Height:	0m
Soil form:	Glenrosa	Surface stones:	Abundant (40-60%)
Soil family:	Overberg (2111)	Crop:	Table grapes-Sun red
Terrain unit:	Mid-slope	Planting date (Age):	1996 (5)
Gradient:	15%	Underlying material:	Weathering shale to phyllite
Gradient form:	Straight		

Horizon	Depth (mm)	Brief description	Diagnostic horizon/material
A	0-100	Moist: strong brown colour (7.5 YR 4/6); Coarse sandy loam with clay 8% clay; Weak blocky structure; Many large stone fragments lifted up by soil preparation; Disturbed transition to B-horizon	Orthic A (mixed with B-horizon)
B	100-800	Moist: strong brown colour (7.5 YR 4/6) and cutans with colours of 10 YR 4/4 en 2.5 YR 4/6; Coarse sandy loam with 9% clay; Weak blocky structure; Abundant shale rocks in different stages of weathering with weathered material in between; Varying clear transition	Lithocutanic B
C	>800	Shale, partly weathered	Saprolite

Physical properties:

Depth (mm)	Sand %	Clay %	Silt %	Stone %	Texture class	Sand Grade	Bulk density kg.dm^{-3}	Field capacity (%V/V)
0-150	58	8	24	50	Sandy loam	Coarse sand	1.6	21.4
150-300	57	9.	33	50	Sandy loam	Coarse sand	1.6	21.4
300-600	59	9.	32	49	Sandy loam	Coarse sand	1.7	17.5
600-900	63	8	29	49	Sandy loam	Coarse sand	1.7	15.8

Profile number:	B	Aspect:	East
Map number:	Broodkraal	Water table:	None
Latitude and Longitude:	S32^{0}56'35"/E18^{0}39'97"	Height:	97m
Soil form:	Glenrosa	Surface stones:	Abundant (40-60%)
Soil family:	Overberg (2111)	Crop:	Table grapes
Terrain unit:	Crest (Mid-slope)	Planting date (Age):	1998 (3)
Gradient:	6%	Underlying material:	Weathering shale to phyllite
Gradient form:	Convex		

Horizon	Depth (mm)	Brief description	Diagnostic horizon/material
A	0-150	Moist: strong brown colour (7.5 YR 4/6); Coarse sandy loam with 6% clay; Weak blocky structure; Many and big shale stone fragments lifted up by soil preparation; disturbed clear transition	Orthic A (mixed with B-horizon)
B	150-800	Moist: strong brown colour (7.5 YR 4/6); Coarse sandy loam with 6% clay; Weak blocky structure; Abundant shale rocks in different stages of weathering with weathered material in between; Varying clear transition	Lithocutanic B
C	>800	Shale, partly weathered	Saprolite

Physical properties:

Depth (mm)	Sand %	Clay %	Silt %	Stone %	Texture class	Sand Grade	Bulk density kg.dm^{-3}	Field capacity (%V/V)
0-150	70	6	24	45	Sandy loam	Coarse sand	1.7	/
150-300	71	6	23	41	Sandy loam	Coarse sand	1.6	/
300-600	70	6	24	39	Sandy loam	Coarse sand	1.6	/
600-900	73	5	22	38	Sandy loam	Coarse sand	1.6	/

Profile number:	**H**	Aspect:	North-east
Map number:	Broodkraal	Water table:	None
Latitude and Longitude:	S32^{0}56'67"/E18^{0}39'92"	Height:	88m
Soil form:	Tukulu	Surface stones:	Abundant (40-60%)
Soil family:	Zandvliet (2220)	Crop:	Table grapes
Terrain unit:	Foot slope	Planting date (Age):	1998 (3)
Gradient:	3%	Underlying material:	Transported material (pedisediments)
Gradient form:	Straight		

Horizon	**Depth (mm)**	Brief description	**Diagnostic horizon/material**
A	0-150	Moist: Dark reddish brown colour (2.5 YR 3/4); Coarse clay with 43% clay; Moderate sub angular/fine blocky structure; abundant quartz gravel (30%); Disturbed clear transition	Orthic A (mixed with B-horizon)
B	150-900	Moist: Dark red colour (2.5 YR 3/6) with areas of yellowish red (5 YR 4/6) medium peds in between; Coarse sand with 44-53% clay; Weak sub angular/fine blocky structure, medium peds are moderate blocky; Abundant quartz gravel (30%); Varying gradual transition	Neocutanic B
C	>900	Moist: Dark red colour (2.5 YR 3/6) with yellowish brown mottles (10 YR 5/6); Coarse sandy loam; Pedisedimet (transported) material	Unspecified material with signs of wetness

Physical properties:

Depth (mm)	**Sand %**	**Clay %**	**Silt %**	**Stone %**	**Texture class**	**Sand Grade**	**Bulk density kg.dm^{-3}**	**Field capacity (%V/V)**
0-150	37	43	20	38	Clay	Coarse sand	1.6	/
150-300	35	46	19	34	Clay	Coarse sand	1.6	/
300-600	29	53	18	26	Clay	Coarse sand	1.7	/
600-900	34	44	22	20	Clay	Coarse sand	1.7	/
900-1200	52	18	30	18	Sandy loam	Coarse sand	/	/

Profile number:	**M**	Aspect:	North-west
Map number:	Rooihoogte	Water table:	None
Latitude and Longitude:	S33°04'15"/E18°50'48"	Height:	70m
Soil form:	Swartland	Surface stones:	Common (20-40%)
Soil family:	Bonnievale (2221)	Crop:	Table grapes
Terrain unit:	Foot slope	Planting date (Age):	1992
Gradient:	6%	Underlying material:	Weathering shale to phyllite
Gradient form:	Concave		

Horizon	**Depth (mm)**	Brief description	**Diagnostic horizon/material**
A	0-200	Moist: dark yellowish brown colour (10 YR 4/6); Coarse sandy loam with 25% clay; Medium/coarse weak blocky structure; Disturbed clear transition	Orthic A (mixed with B-horizon)
B	200-400/500	Moist: red colour (2.5 YR 4/6) ; Coarse sandy loam with 24-27% clay; Medium/coarse moderate angular blocky structure with areas of weaker structure in between; Common shale and quartz stones; Varying clear transition	Pedocutanic B
C	>400/500	Shale, partly weathered	Saprolite

Physical properties:

Depth (mm)	**Sand %**	**Clay %**	**Silt %**	**Stone %**	**Texture class**	**Sand Grade**	**Bulk density kg.dm^{-3}**	**Field capacity (%V/V)**
0-150	46	25	29	40	Loam	Coarse sand	1.8	/
150-300	44	27	29	40	Loam	Coarse sand	1.7	/
300-600	47	23	30	43	Loam	Coarse sand	1.7	/
600-900	51	22	27	44	Sandy clay loam	Coarse sand	/	/
900-1200	53	18	29	41	Sandy loam	Coarse sand	/	/

Profile number:	**N**	Aspect:	North-west
Map number:	Rooihoogte	Water table:	None
Latitude and Longitude:	S33^{0}04'21"/E18^{0}50'55"	Height:	79m
Soil form:	Tukulu	Surface stones:	Common (20-40)
Soil family:	Zandvliet (2220)	Crop:	Table grapes
Terrain unit:	Mid-slope	Planting date (Age):	1992
Gradient:	6%	Underlying material:	Transported material (pedisediments)
Gradient form:	Convex		

Horizon	**Depth (mm)**	Brief description	**Diagnostic horizon/material**
A	0-200/300	Moist: brown colour (7.5 YR 4/4); Coarse sandy loam with 9-15% clay; Weak blocky structure; Abundant quartz gravel (40%); Disturbed clear transition	Orthic A (mixed with B-horizon)
B	200/300-700/800	Moist: red colour (10R 4/8) with red-orange mottles (2.5 YR 4/8); Coarse sandy loam with 34% clay; Weak fine blocky structure; Abundant quartz gravel (40%); Varying gradual transition	Neocutanic B
C	>700/800	Moist: red colour (10R 4/8) with yellowish brown mottles (10 YR 5/6); Coarse sand with 74% clay; Common quartz gravel (20-40%; Transported material (pedisediments)	Unspecified material with signs of wetness

Physical properties:

Depth (mm)	**Sand %**	**Clay %**	**Silt %**	**Stone %**	**Texture class**	**Sand Grade**	**Bulk density kg.dm^{-3}**	**Field capacity (%V/V)**
0-150	62	9	29	37	Sandy loam	Coarse sand	1.8	/
150-300	57	15	28	38	Sandy loam	Coarse sand	1.8	/
300-600	42	34	24	32	Clay loam	Coarse sand	1.6	/
600-900	13	76	11	25	Clay	Coarse sand	1.6	/

Appendix B

Soil maps

An interactive Adobe Acrobat presentation was included and can be viewed from the accompanying CD-rom. It can be viewed directly from the CD or the whole directory can be copied to any directory on a hard drive and the program can run from there. Any version of Adobe Acrobat must however be installed on the computer first. If these files have to be viewed frequently, it will be best to install a shortcut from the file, BRCmaps.pdf, to your desktop. The maps and photographs in this system are high-resolution pictures. By pressing the ESC button, the normal Acrobat heading appears and the relevant tools can be used to zoom in or out. Press the BACK, NEXT or EXIT onscreen buttons to proceed.

To view the Berg River Catchment soils map only, find file BRCsoils.pdf.

To view the Berg River salinity hazard map only, find file BRChazard.pdf.

To view the Berg River soils and hazard map legends only, find file BRClegend.pdf.

Appendix C

Archiving of the data

Al data is available from:

Department of Soil Science

Stellenbosch University

P/bag X1

Matieland

7602

Tel 021-8084794

Fax 021-8084791

Email: water@sun.ac.za, wpdc@sun.ac.za

Appendix D

Publications and technology transfer that emanated from this research

Transfer actions.

De Clercq, W.P. 2001. Dealing with salinity in irrigated agriculture. Farmers day at the Rooihoogte farm, 28 October 2001

Engelbrecht, E. 2001. The spatial and depth distribution of salt in the irrigation landscape. Farmers day at the Rooihoogte farm, 28 October 2001

Ellis, F. 2001. Salinity associated with heuweltjies in the Berg River catchment. Farmers day at the Rooihoogte farm, 28 September 2001

Articles

De Clercq, W.P., Ellis, F. 2002. Irrigation return flow or saline seep. Meeting with DWAF, DA Elsenburg on Broodkraal farm,21 Janury 2001.

De Clercq, W.P., Van Meirvenne, M.,. De Smet, G. 2001. Mapping soil salinisation in an irrigated vineyard in South Africa. Chapter in "Land degradation and management". Submitted October 2001.

Ellis, F. 2001. Land degradation on old land surfaces affected by termite activity in arid and semi-arid regions of South Africa. Chapter in "Land degradation and management". Submitted October 2001.

Papers presented at workshops and congresses:

De Clercq, W.P., Van Meirvenne, M., De Smet, G. 2001. Mapping soil salinisation in an irrigated vineyard in South Africa. Bilateral SA/Flemish Workshop on Land Degradation:24-25 Sept 2001, Gent, Belgium.

Ellis, F. 2001. Land degradation on old land surfaces affected by termite activity in arid and semi-arid regions of South Africa. Abstract prepared for the Bilateral SA/Flemish Workshop on Land Degradation:24-25 Sept 2001, Gent, Belgium.

Ellis, F. 2001. Contribution of termites to the formation of hardpans in soils of arid and semi-arid regions of South Africa. Abstract for paper to be delivered at the 17th World Congress of Soil Science, Bangkok, Thailand, August 2002.

Ellis, F., De Clercq, W.P. and Engelbrecht, H. 2001. Soils associated with micro relief features ("heuweltjies") occurring on an ancient land surface in the lower Berg River Valley Soil Sci. Soc. South Africa Congress, Pretoria.

Dissertations:

De Smet, G. 2001. Mapping soil salinity in South Africa. Land and Forest management, Ghent University, Belgium. (Ing)

Engelbrecht, H. 2002. Modelling soil salinity in the Berg River Catchment. In progress, Dept Soil Science, University Stellenbosch. (MSc, in progress)

De Clercq, W.P. 2002. Defining & mapping soil salinity hazard in irrigated vineyards of S.A., Dept soil management, Ghent University, Belgium. (PhD, In progress).