ON-FARM WATER AND SALT MANAGEMENT GUIDELINES FOR IRRIGATED CROPS: LEVEL THREE DECISION SUPPORT

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On-Farm Water and Salt Management Guidelines for Irrigated Crops: Level Three Decision Support

Report to the
Water Research Commission

by

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The publication of this report emanates from a project entitled *Management guidelines for technology transfer to reduce salinisation of irrigated land with precision agriculture* (WRC Project No. K5/2499//4) and forms part of a series of three reports, namely:

1. On-farm water and salt management guidelines for irrigated crops: Level one decision support. (WRC Report No TT 847/1/21)
2. On-farm water and salt management guidelines for irrigated crops: Level two decision support. (WRC Report No TT 847/2/21)
3. On-farm water and salt management guidelines for irrigated crops: Level three decision support. (WRC Report No TT 847/3/21)

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EXECUTIVE SUMMARY

Soil salinity and sodicity in agricultural is a well-established and well-researched discipline in agronomy, both globally and locally. Despite the large investment in research and development in other regions in the world and South Africa, the size of affected areas has intensified and even increased over time. Some researchers pose the question whether irrigation could be sustained for long periods in any region. The question is also applicable to the 1.5 million ha of irrigation land in South Africa. Our approach is that irrigation is sustainable on the condition that the industry is committed to apply water and salt-management guidelines derived from scientific theory and best-management practices. The aim of this project was to compile guidelines on water and salt management and to conduct research on site-specific management (precision agriculture) of water and salt in irrigated fields. In Addition, lessons learned from the site-specific management should also be incorporated into guidelines. Thus, except for this report (Volume 3) two other reports, i.e. Volume 1 (Van Rensburg et al. 2020a) and Volume 2 (Van Rensburg et al. 2020b), were compiled on water and salt management.

1. Volume 1

Research objectives were specifically designed so that the research is directed to a level that agricultural extension officers, i.e. Behaviour Change Officers (BCOs), can utilise, and apply the information to guide their farmers. The guidelines cater for all types of farmers, regardless of their scale of operation, whether they be producing food for their families, or for the country, or for international communities. Four objectives were set and discussed as individual content chapters:

i. to summarise the main findings from the socio-economic survey on knowledge about salt management of irrigators from the commercial sector in the Breede River, Vaalharts and Douglas irrigation schemes, and the northern KwaZulu-Natal district;
ii. to extract from literature the art and science of irrigation scheduling, and the packaging of information as a guideline, using two best scheduling practices as examples, viz. crop coefficients and continuous measuring probe technology;
iii. to distil from literature the fundamental principles required for salt management of crop fields and to package the information as a salt management guide;
iv. to compile a solution-management guideline on the treatment of root-zone salts in a proactive and active manner.

The first content chapter provided context to the theme of knowing your farmers. This information was distilled from research published in the Volume 3 report, as part of the objective of compiling guidelines from site-specific research conducted with field crops, vineyard and sugarcane farmers. The second content chapter focused on fundamentals of irrigation water management as a guideline for BCOs. This information was distilled from mainly Water Research Commission (WRC) reports as well as international literature. The third content chapter summarised the fundamentals of salt management as a guide for BCOs, which was also extracted from WRC reports and international publications. The last content chapter provided a guide for BCOs with the theme: solutions for salt related problems. However, it is important to note that BCOs still have to re-pack the information for their clients for on-farm application. The training of BCOs fell outside the scope of this project, but is an important part in the successful dissemination of information to resource-deficient farmers.

2. Volume 2

There is a shift in land use from field crops toward perennial crops in the major irrigation schemes of South Africa. Perennial crops require high initial investments, but they are also seen as high-value crops. With higher incomes, farmers can also invest in their fields to protect them against water and salt accumulation. This guideline is designed to encourage and support those farmers who want to change towards site-specific management, i.e. precision management of water and salts. Two objectives were designed for the scaling out of electromagnetic induction technology (EMI) to farmers, namely:

i. to illustrate a logical framework, using EMI derived soil properties, for supporting scientifically sound decisions regarding the site-specific assessment of soil salts in the rootzone. The specific objectives of the framework were a) to show where the salts are in the crop field, b) how it impacts the hydro-physical properties, such as bulk density, saturated hydraulic conductivity and water storage in the profile, and c) to couple site-specific procedures to rectify problematic areas. A case study on a vineyard was used to establish the concept;
ii. to create case studies on site-specific assessment of water and salts in perennial crops to broaden the base and support for out scaling of EMI technology. Crops used as case studies, were lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries.

These objectives were discussed in separate content chapters. Firstly, the development and application of a logical framework for assessing water and salts in the root zone of perennial crops. The latest technology in site-specific management involves EMI surveys and ground truthing of soil properties related to soil salts. Experienced gained in the application of EMI in crop fields during and prior to the WRC project, helped us in the development of the logical framework for assessing water and salts in crop fields. The second content chapter focuses on the scaling out of EMI technology. It is envisaged that the eight case studies with different perennial crops will be of great value for information dissemination via their crop-specific associations. Again, BCOs will play an important role in the process of scaling out of the EMI technology, but they need training. Training of BCOs is beyond the scope of the project.

3. Volume 3

The third volume on salinity management reflects on EMI research (upscaling) conducted on selected irrigation farms in the Northern Cape, Free State, Eastern Cape and KwaZulu-Natal. This is to achieve a deeper understanding of salt-related problems and their medium to long-term management. This type of decision support is on a research level and is aimed at serving the science community, although mega-farmers, corporations, and companies can also benefit from it in the medium to long-term. In this case, salinity models like SWAMP (Soil Water Management Program) were used to make medium to long-term estimates of salts on land productivity. Volume 3 consists of five content chapters with specific objectives.

3.1. Chapter 2: Socio economic study

The main reasons for adoption success and/or failure, generally, are well documented in the literature, but little is published on the adoption of salinity management practices. It seems that there are virtually no case studies found that benchmark the actual knowledge levels, perceptions and attitudes of farmers with respect to farm practices which address salinity in South Africa. The scale of the problem, therefore, extends beyond the classification and mapping of areas with salinity problems. Farmers' knowledge levels, perceptions, attitudes and capability to deal with salinity is known even less. Several research questions were defined and based on these questions; the following hypotheses were tested:

i. Farmers do not perceive salinity as a threat to the future of irrigation farming (H1);
ii. Farmers do not understand causes of salinity (H2);
iii. Farmers do not have knowledge of preventative and corrective measures (H3);

iv. The benefits of preventative and corrective measures do not outweigh the costs (H4);
v. The benefits of preventative and corrective measures do not outweigh the implementation effort (H5).

A questionnaire was designed to test the above-mentioned null hypothesises. Three areas were surveyed, *viz.* Vaalharts and Douglas as a unit that represents field crops (42 respondents). The Breede River in the Western Cape for the grape area (40 respondents) and northern KwaZulu-Natal for the irrigated sugarcane growing area (34 respondents). Surveys were conducted by the project team members and post-graduate students. Data were analysed in Excel, using pivot tables and chi-square tests to evaluate differences among groups. Based on the results, the null hypothesis for H1 was rejected because more than half the indicators for all three regions suggested that the respondents recognise the danger that soil salinity poses a threat. Similar results were obtained for the null hypothesis H2-H4. The null hypothesis of H5 was accepted, because only the Breede River area agreed that it would be easy to adjust irrigation scheduling as a management practice.

Overall, it can be concluded that the acceptability of farmers' knowledge (or lack thereof) about the salt status of their soils, irrigation water and diagnostic parameters is debatable. Farmers suggest that they have advisory consultants to help, therefore there is less need for them to be knowledgeable on the specifics of the subject. For this reason, the benefit of growing knowledge levels only is uncertain. In alignment with the literature, the hypotheses' results also suggest that more than just information sharing is required. Behaviour change initiatives need to engage at the level of implementation. Implementation at the farm or field level in a case study context is required to reassure/convince farmers of the economic viability, the practical realities linking to the disruptive or non-disruptive nature of salt management practices and/or the skill and effort required to implement salt management practices. On-farm testing, demonstration plots, hands-on training interventions or allowing farmers to learn from fellow farmers via farm visits and technical tours are higher leverage pathways to stimulate uptake and adoption. Purposeful and deliberate effort is also required to establish examples of implementation and to gather and make the relevant economic and practical information accessible to larger farmer groups.

3.2. Chapter 3: Sugarcane case studies on soil salt distribution and yields

Historically, two areas in the sugar industry are renowned for the occurrence of alkali (sodic) and saline soils derived from the Beaufort Group, located at Heatonville and Nkwaleni. Today the occurrence of salt-affected soils is much more common in the industry, and probably covers about 21000 ha, i.e. about 20% of the total irrigated area. In the previous chapter it was mentioned that poor adoption of irrigation scheduling in the region is a concern, especially in the light that sugarcane is regarded as moderately tolerant to salinity, but less tolerant to sodicity. The degree of sensitivity varies between varieties and even from crop to crop. The objective of this chapter is to provide guidelines on water and salinity management of sugarcane, derived from literature and two case studies.

The case studies were selected from data obtained from routine measurements at the Fertiliser Advisory Service laboratory at South African Sugarcane Research Institute (SASRI), showing the presence of saline-sodic and sodic soil conditions. Case study 1 was in the Mkhuze district in the northern parts of KwaZulu-Natal (KZN) at an altitude between 180 and 211 masl. The site has a slope of 11% and consists mainly of soils from the Bonheim Form. The average clay content of the topsoil is 58%. Only 45 ha of the 60 ha centre pivot could be used in the study as the sugarcane on the rest of the site was to be harvested in a different season. Case study 2 was near Empangeni in the Heatonville irrigation scheme at an altitude between 70 and 95 masl. The site stretched over two half circle centre pivots covering areas of 54 ha and 68 ha of which the 63 ha was used in this study. The clayey soils consist of Katspruit, Tukulu, Swartland and

Willowbrook forms. EMI and topographical surveys were conducted during July 2016 and June 2017 (Case study 1) and during October 2016 and 2017 (Case study 2). Soil samples were collected from the geo-referenced grid points (1 sampling point per ha) and the samples were used to analyse clay and organic carbon. An additional 12 profiles were sampled using the EC_a-directed (apparent soil electrical conductivity) sampling procedure (Chapter 4) with depth intervals of 0.3 m over the profile of 1.5 m. These soils were analysed for pH (H_2O), electrical conductivity of a saturated soil sample (EC_e), cations to determine sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP). EC_a data from the 12 sampling points were regressed with the individual soil properties, establishing regression models to convert bulk EC_a data to soil-property maps. Biomass yields were measured at the 12 EC_a-sampling points. Irrigation and rainwater were also analysed for pH, EC (electrical conductivity), K, Ca, Mg, Na and HCO_3 and used to calculate SAR, adapted SAR and effective EC.

The literature study provided guidelines on the effect of salinity and sodicity on sugarcane yield from several local experiments. These studies confirmed that yield losses can be expected at a rate of 5.9 tonnes of sugarcane per 100 mS m^{-1} increase in EC_e above the threshold of 170 mS m^{-1}. In general, sugarcane yield decreases linearly at a rate of 1.5 to 2.4 t ha^{-1} for every 1% increase of ESP and no yield was obtained at ESP > 60%. The literature study suggested further that the EC and SAR values in the irrigation water should be adjusted to accommodate the diluting effect of local rainfall and irrigation on EC and the effect of Ca, Mg and carbonates on SAR. A pH value of 8.3 or greater is a signal to analyse the water sample for carbonates.

Far-reaching results were obtained from the two case studies, and these may be used to create awareness amongst farmers to improve their water and salt management. The EC_e maps indicated that salinity is not a problem in both the sites. The real problem is the high Na levels that generally increase with depth and vary over the field. Large areas in both sites were above the threshold ESP value of 7% which resulted in significant stalk yield losses; 10.2 t ha^{-1} for every 1% increase in ESP at Case study 1 and 1.9 t ha^{-1} per unit in Case study 2. The accumulation of Na in the subsoil is attributed to the poor drainage of the sites due to the high clay content and dispersion, and inherent high Na content of the parent material, Na content of irrigation and rainwater as well as the inherent natrophobic property of sugarcane. Natrophobe is a phenomenon found by certain plants that have limited or no ability to absorb Na from soil solution, spending substantial amounts of energy in preventing Na from entering the plant, and being translocated to the stalks. Workshops are recommended to create awareness of water and salt management, which includes monitoring of irrigation water quality, monitoring and identification of salt affected areas within fields, promoting the installation of artificial drains and leaching of salts.

3.3. Chapter 4: Literature synopsis

The literature study was conducted against the background of the general aim of the WRC-project, i.e. to compile guidelines for technology exchange to manage the salt load associated with irrigation at farm- and field level with precision agriculture and specific aims to:

i. compile water and salt management guidelines and elicit the acceptability thereof from stakeholders;
ii. evaluate on a case-study basis the methods/procedures employed by advisors for delineating site-specific-water and salt-management units;
iii. develop a software-based decision support system for recommendations to improve site-specific water and salt management.

Thus, the chapter focuses on three important aspects. Firstly, best on-farm water and salt management practices distilled from international and regional literature. Principles for proactive management of water and salt were derived from the research contributions, viz. i) to minimise salt mobilisation and additions through irrigation water, ii) to prevent decreases in crop yield due to excessive dissolvable salt accumulation in the root zone, iii) to prevent degradation of soil permeability due to excessive sodium concentrations and iv) to minimise irrigation-induced drainage and leaching. Guidelines to achieve this will not only address on-site problems, but also off-site issues of water conservation and degradation of groundwater and river water sources, as well as leaching of essential nutrients. In practice, salt sources and control factors should be considered, inter alia i) suitability of the soils for irrigation, ii) residual salt content of the soils, iii) irrigation water quality, iv) topography and its effect on subsurface drainage, v) type of system and amount of irrigation, vi) climatic conditions and reliability of the irrigation water supply, vii) environmental impact of drainage water and viii) interception and possible re-use of drainage water. Fortunately, the WRC funded, for over four decades, numerous projects that fit into the domain of water and salt management and from which the above-mentioned principles and practices could be embedded into tailor-fit guidelines for South African conditions. These guidelines were described and used in Volume 1 and Volume 2 of this project.

The second aspect of the literature review focuses on precision farming principles and practices. With the ever-increasing availability and affordability of technology to support decisions within a field, the need also exists for spatial water and salt management. The literature synopsis provided a discussion on how to accomplish this. This discussion is based on the published general framework for precision agriculture or rather site-specific-crop management, namely i) spatial *in situ* direct or indirect soil, crop and terrain measurements and monitoring ii) mapping of these attributes iii) decision support and iv) deferential action. Each of these components were briefly discussed in a general site-specific-crop-management context and how it relates to spatial salinity management. From this discussion, it was evident that the spatial measurement of EC_a through EMI has and continues to play a significant role in characterising soil properties relevant to salinity management. As with site-specific-crop management, mapping these soil properties through deterministic or stochastic interpolation methods needs special intention when adopting site-specific-salinity management. Again, some of these procedures were used to survey several sites over South Africa to characterise salt distribution over crop fields as discussed in Volume 2 of the project reports. Water and salt management solutions derived from the Volume 1 report were also used to address problematic areas encountered in these fields.

The last aspect of the literature revolved around decision support, which is of utmost importance for solving complex problems associated with water and salt management. In terms of decision support for salinity management, differences in the approaches adopted by popular transient state soil-crop-water salinity models were briefly highlighted. The aim of this section was not to provide a comprehensive review of all transient-state models, but rather to discuss some of the general approaches adopted by popular models and highlight differences between them. Against this background, approaches in soil-water flow, crop growth and yield, potential evaporation and transpiration, actual transpiration and root water uptake and salt transport are briefly discussed.

3.4. Chapter 5: Wheat and maize case studies: Spatial characterisation of soil properties related to water and salt management

Spatial soil measurements and monitoring are needed as a first step in adopting precision agriculture to manage the salt load associated with irrigation at field level. Relevant soil properties include soil salinity, sodicity, water content, soil particle size distribution, bulk density and saturated hydraulic conductivity. To spatially characterise these soil properties, EC_a readings obtained through EMI gained in popularity over the last few decades. Unfortunately, EC_a surveys aimed at spatially characterising these soil properties, have and continue to produce dubious results due to the complex nature of the measurement and incorrect interpretations. The objective of this chapter is to spatially characterise soil properties of crop fields under wheat and maize production using EMI technology and the ESAP-95 Version 2.01R (Electrical conductivity Sampling Assessment and Prediction) software package. Soil properties of interest were soil salinity, water content, clay content and bulk density. These properties were investigated across centre-pivot irrigated fields, located in three provinces, to highlight two important aspects, namely: the feasibility and effectiveness of EC_a surveys done on irrigated soils to map all four these properties. Data sets of the seven crop fields were organised per soil layer with a thickness of 0.3 m depth intervals up to 1.5 m where possible.

Two data sets were used, *viz:* a set of data obtained from samples collected on a grid basis of about 1 site per hectare and another set of data obtained from soil samples collected from 12 EC_a-directed soil sampling sites per field. All seven sites were scanned with an EM38-MK2 instrument (Geonics Limited, Mississauga, Ontario, Canada) at a transect width of about 10 m. Measurements were geo-referenced with a Trimble R4 RTK GNSS surveying system. The mean EC_a readings per hectare amounted to 354 with a coefficient of variation of 25%. Where possible, fields were scanned at the beginning of the experiment near planting, then after harvest or after planting of the next crop and after harvesting of the second crop, depending on the farmers' management programme. Twelve sampling sites per field were chosen from the first EC_a survey by selecting the spatial response surface sampling algorithm (SRS) option within ESAP-RSSD (ESAP-Response Surface Sampling Design). Soils were sampled and EC_e, (mS m^{-1}), clay content (%), θ_g (%, gravimetric soil water content) and BD (kg cm^{-3}, bulk density) were measured. Dataset 1 was first used in ESAP-Calibrate through a DPPC (Dual Pathway Parallel Conductance) correlation analysis to evaluate the feasibility of performing EC_a surveys to spatially characterise EC_e, clay content, θ_g and BD at the various fields. For data set 2, the same DPPC correlation analysis was used as an objective technique to judge the validity of EC_a readings and measured soil property data.

The DPPC correlation analysis of dataset 1 revealed the following main findings from the calculated EC_a results (EC_{ac}) over the seven crop fields: i) for sandy to sandy loam soils of the central irrigation areas of South Africa, EC_e values below $\pm$ 150 mS m^{-1} tend to dominate EC_{ac} readings. This was also true for the sandy clay loam soils with low EC_e values (< 100 mS m^{-1}) or high ($\pm$ 250 mS m^{-1}). ii) As expected, an increasing clay content has an increasing influence on bulk soil conductance, provided that the range in spatial variability is within the $\pm$ 20% clay content limit. iii) In this study it seems that water content did not influence the EC_{ac}. Only one field showed a reasonable correlation (r = 0.59) between EC_e and θ_v.

Data set 2 revealed the following main findings: i) it appears that shallow EC_a-readings (apparent soil electrical conductivity for 0.5 m coil separation) and not so much the deep readings ((apparent soil electrical conductivity for 1 m coil separation) of the EM38-MK2 instrument are influenced by ambient temperature during the day. Hence, care should be taken when interpreting shallow EC_a readings; ii) in some fields, $EC_{a\ deep}$ readings and soil property data correlated well and others not. Hence, further research is needed as we are not sure whether the DPPC model is applicable to soils found in semi-arid parts of South Africa. iii) For sandy to sandy loam soils, uniform in depth, and spatially across the field in terms of clay content, low EC_e values (< 150 mS m^{-1}) significantly influenced low $EC_{a\ deep}$ readings (± 50 mS m^{-1}). This was according to the spatial multiple linear regression (MLR) models that were developed with data from the June 2016 survey. However, it seems that wetter soil conditions dominated the $EC_{a\ deep}$ readings in the same fields. iii) Only one field showed evidence that clay content significantly influenced $EC_{a\ deep}$ readings.

According to the spatial MLR models, none of the fields with clay soils EC_e significantly influenced $EC_{a\ deep}$ readings.

During the survey period, only one field showed the potential to reduce maize yields and wheat due to buildup of salts in the soil. It was assumed that the EC_e thresholds of maize, a moderate salt tolerant crop, and wheat, a salt tolerant crop, were 170 and 600 mS m^{-1}, respectively. However, the results suggested that the bean yield, a salt sensitive crop with a threshold of 100 mS m^{-1}, would be negatively affected in several of the fields surveyed.

3.5. Chapter 6: Decision support with the soil water management program, SWAMP

For a given irrigation system, the decision on when to open the tap to irrigate a crop and when to close the tap is critical in the bigger picture of sustainability. Farmers are using and constantly testing water-management support systems to facilitate irrigation scheduling decisions. A popular decision support system is the soil-water sensor technology, comprising continuous measuring probes, telemetry and web-based irrigation software, also termed e-agronomy. The software programmes are advanced and support farmers daily in scheduling decisions. A common water management strategy is to deplete the profile to a pre-determined level, and then refill the profile to the drained upper limit. One of the draw backs of the technology is that most of the commercial soil-water probes do not measure osmotic potential of soils. In practice it implies that salt management is somewhat in the background and not integrated with soil-water management.

Water management models, like SWB and SWAMP, are important decisions support systems to analyse water management decisions or to show gaps in knowledge. Concerning the development of SWAMP, in 2015 subroutines were added to the model and some algorithms adapted to allow for salt accumulation and distribution within a soil profile and the subsequent osmotic effect on water uptake and crop yield. Recently, the source code of SWAMP was adapted and translated to the Visual Basic for Applications (VBA) programming language. This mean that in one simulation (run or loop) of multiple years predefined crop-rotations, with predefined multiple different soils per rotation at varying depths per soil can be simulated daily. The VBA code now provides the user with an option to use SWAMP for temporal and spatial support regarding soil, crop and water and salt related decisions in irrigated and rain-fed crop production systems. More important is the fact that SWAMP can now be integrated with an economic model and/or various optimisation algorithms, which significantly enhance the model's capabilities.

The objectives of the chapter are: (i) to briefly describe the newly developed source code of SWAMP to simulate the soil water and salt balance and consequent matric and osmotic stress effects on water uptake and field crop yield; (ii) to apply the model in assessing the importance of integrating water and salt management and (iii) assess the potential to apply the optimised irrigation schedule in precision farming as a future decision support option.

Using the soil, crop and atmospheric data of one of the case studies of the project, a 40 ha sandy loam field in the Orange-Riet Irrigation Scheme, three irrigation strategies were selected. Strategy 1 allows a 50% depletion before irrigating a net irrigation amount of 14 mm. Strategy 2 depletes the soil water with 30% before applying a net irrigation of 14 mm and strategy 3-optimal irrigation schedule. The Differential Evolution (DE) algorithm that is developed as part of the WRC project on the "Economic management of water and salt stress for irrigated agriculture: a precision agriculture case study" was adjusted and combined with the VBA SWAMP source code to determine an optimal irrigation schedule. Initial conditions were soil water-content of 0.176 mm mm^{-1} and EC_e of 250 mS m^{-1} and EC of irrigation water was a constant value (120 mS m^{-1}) over the three-year simulation period, representing a worst-case salinity scenario. The simulation was run daily over three years, for a consecutive wheat-maize crop rotation.

The results showed that SWAMP can simulate the impact of management decisions on changes in matric and osmotic potentials that are highly dynamic. Furthermore, the results showed that irrigation strategy choice has a significant influence on these potentials as well as the resulting crop yields. Care should therefore be taken to apply steady-state concepts to provide decision support regarding salinity management. The optimal irrigation strategy clearly showed the importance of taking a longer-term view when managing salinity because decisions made in one season have an impact on the feasibility of crop production in the following season. Applying the optimal irrigation strategy for the worst-case scenario to lesser worse case scenarios showed that management principles applied to the worst case will be applicable to lesser worse case scenarios. The optimal irrigation strategy assumes complete knowledge of production conditions over the season, which should be challenged. The potential of using the optimisation algorithm to devise management zones for applying precision irrigation is vast.

4. Recommendations

It is important for national food security that areas in crop fields subjected to waterlogging and salinity be addressed. Our own situation reveals that, conservatively estimated, about 90 000 ha of South Africa's irrigation soil is salt affected, and it impacts negatively on the livelihoods of farmers across all scales. The EMI-technology in conjunction with remote sensing technology provide solutions to identify these areas and to make site-specific recommendations. The following recommendations were made:

i) Training of BCOs

Application of guidelines in Volume 1: One of the pre-requisites for using the guidelines summarised in Volume 1 is that potential users should have a basic knowledge of irrigation sciences related to climate, soil, and crop sciences. Thus, there is a need to train or retrain extension officers and advisors in the technical aspects (BCOs) of water and salt management. Application of guidelines in Volume 2: The scaling out of the EMI-technology to farmers is a problem. Here it is recommended that training should be provided to BCOs. The motivation is that BCOs play a decisive role in dissemination of information. Relationships between scientists on the one side, farmers on the other side (applicator) and behaviour change officers (BCO) at the base side, forming an equilateral triangle, are imperative to forward the initiative.

ii) Organising of crop-specific workshops on the out scaling of EMI technology

The main problem, however, is the scaling out of the EMI-technology to leading farmers, which is often recognised as an essential platform to introduce new technology to co-farmers. Nine case studies on site-specific assessment of water and salts in perennial crops were conducted, viz, grapes, lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries. These case studies provide the opportunity for out-scaling of EMI application through crop-specific workshops. Without exception, the case studies were successful in (a) showing where the salts are in the crop field, (b) how these impacts on the hydro-physical properties, such as bulk density and water storage in the profile, and (c) applying site-specific procedures to rectify problematic areas.

iii) Demonstration of salt removal experiments

The socio-economic survey revealed that the benefits of salinity management outweighs the costs. However, farmers are also of opinion that the effort to implement salt-management interventions can hinder or reduce the benefit gained. Clever work is required to bridge the mindset of applicators and to package EMI-information. It is recommended that demonstration trials on land reclamation with artificial drainage be conducted at leading farmers' fields. A good example is the macadamia case study where the farmer insisted that demonstration trials be conducted in some of the affected areas to show the efficiency of the latest subsurface drain technology.

iv) On-farm water and salt management policies

The opportunity is there to develop policies that will guide landowners/users of irrigation land towards a higher level of responsibility and accountability in protecting natural resources against water and salt accumulation. EMI-technology provides the means to monitor such impacts as demonstrated in the case studies. It is recommended that EMI should be used to monitor and assess water and salt management at least once in 10 years, preferably once every 5 years. In the case of small-scale farmers, it is recommended that Government should subsidise the monitoring of salt-affected soils.

v) Developing and testing of underground drainage/irrigation system

Shallow groundwater table soils are high in demand amongst dryland farmers and are regarded as a Class 1 dryland soil. A problem with the soils is the potential build-up of salts via long-term use of fertilisers and the mobilisation of salt from parent material. Another problem affecting these soils is that during high-rainfall periods, which we experienced this year, there is a danger that the water table can rise uncontrollably, causing waterlogging that results in severe crop losses. A potential solution to the two problems is the installation of an underground system that can be used to control the water table heights through drainage and irrigation. Thus, it is important that the water table heights and salinity levels be monitored. EMI technology can be used to identify such soils. It is recommended that research should be conducted on the development and testing of a dual underground drainage/irrigation system together with sensors that can monitor water-table heights cost effectively.

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11. Ms M Lovisa for valuable inputs in proofreading of this report.

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LIST OF ABBREVIATIONS

ASAR	:	adjusted sodium adsorption ratio
BCO	:	behaviour change officer
BD	:	bulk density
CEC	:	cation exchange capacity
DPPC	:	dual pathway parallel conductance
DSS	:	decision support system
DUL	:	drained upper limit
EC	:	electrical conductivity
EC_a	:	apparent electrical conductivity
EC_{ac}	:	calculated apparent electrical conductivity
$EC_{a\ prd}$	:	predicted apparent soil electrical conductivity correlation structure
EC_d	:	electrical conductivity of drainage water
EC_e	:	electrical conductivity of saturated paste extract
EC_i	:	electrical conductivity of irrigation water
EEC	:	effective electrical conductivity
EMI	:	electromagnetic induction
ESAP	:	electrical conductivity sampling assessment and prediction (software package)
ESP	:	exchangeable sodium percentage
ET	:	evapotranspiration
ET_0	:	reference evapotranspiration
FAS	:	fertiliser advisory service
FC	:	filter cake
IQR	:	interquartile range
K_{sat}	:	saturated hydraulic conductivity
LL	:	lower limit (of plant available water)
MIR	:	mid-infrared (spectroscopy)
MLR	:	multiple linear regression
NIR	:	near infrared (spectroscopy)
PAWC	:	plant available water capacity
RMSE	:	root mean square error
RSSD	:	response surface sampling design
SAR	:	sodium adsorption ratio
SASRI	:	South African Sugarcane Research Institute
SP	:	saturation percentage

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CHAPTER 1. INTRODUCTION

1.1 Contextualisation

The aim of this project is to compile guidelines on water and salt management and conduct research on site-specific management (precision agriculture) of water and salt across irrigated fields. Lessons learned from the site-specific management should also be incorporated into guidelines. Thus, except for this report, two other reports (i.e. Volume 1 and Volume 2) were compiled on water and salt management.

In Volume 1 (Van Rensburg et al. 2020a), entitled "On-farm water and salt management guidelines for irrigated crops", four objectives were addressed, namely:

i. to summarise main findings from a socio-economic survey on knowledge about salt management of irrigators from the commercial sector in the Breede River, Vaalharts and Douglas irrigation schemes, and the northern KwaZulu-Natal district;
ii. to extract from literature the art and science of irrigation scheduling, and the packaging of information as a guideline using two best scheduling practices as examples, viz. crop coefficients and continuous measuring probe technology;
iii. to distil from literature the fundamental principles required for salt management of crop fields and package the information as a salt management guide;
iv. to compile a solution-management guideline on the treatment of root zone salts in a proactive and active manner.

The objectives were specifically designed so that the research is directed at a level that agricultural extension officers and advisors, i.e. Behaviour Change Officers (BCOs), can utilise and apply the information provided to guide their farmers. The guidelines cater for all types of farmers, regardless of their scale of operation-, whether they are producing food for their families or for the country or for the international communities. The report is structured in 4 content chapters: The first content chapter provides context to the theme of "knowing your farmers". This information was distilled from research published in Volume 3, as part of the objective to compile guidelines from site-specific research conducted with field crops, vineyard and sugarcane farmers. The second content chapter focused on "Fundamentals of irrigation water management" as a guideline for BCOs. This information was distilled mainly from Water Research Commission (WRC) reports as well as international literature. The third content chapter summarises the theme "The fundamentals of salt management" as a guide for BCOs, also extracted from WRC reports and international publications. The last content chapter provides a guide for BCOs with the theme: Solutions for salt-related problems. However, it is important to note that BCOs still have to re-pack the information for their clients for on-farm application. The training of BCOs fell outside the scope of this project but is an important part in the successful dissemination of information to resource-deficient farmers.

In Volume 2 (Van Rensburg et al. 2020b), entitled "On-farm water and salt management guidelines for irrigated crops", two objectives were formulated for the scaling out of electromagnetic induction (EMI) technology to farmers, namely:

i. to illustrate a logical framework, using EMI derived soil properties, for supporting scientific sound decisions regarding the site-specific assessment of soil salts in the rootzone. The specific objectives with the framework were a) to show where the salts are in the crop field, b) how it impacts the hydro-physical properties, such as bulk density, saturated hydraulic conductivity, water storage in the profile and c) to couple site-specific procedures to rectify problematic areas. A case study on a vineyard was used to establish the concept;

ii. to create case studies on site-specific assessment of water and salts in perennial crops to broaden the base and support for out-scaling of EMI technology. Crops used as case studies were lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries.

The guideline is aimed at farmers who cultivate perennial crops as part of the process learning and adopting water and salt management practices. There is a shift in land use from field crops to perennial crops in the major irrigation schemes of South Africa. This is what our country needs for sustaining our irrigation schemes. Perennial crops require high initial investments but are also seen as high-value crops. With higher incomes, farmers can also invest in their fields to protect them against water and salt accumulation. This guideline is designed to encourage and support those farmers who want to change towards site-specific management, i.e. precision management of water and salts. The guideline has two themes linked to the objectives, and expressed in two content chapters. Firstly, the development and application of a "Logical Framework" for assessing water and salts in the rootzone of perennial crops. The latest technology in site-specific management involves EMI surveys and ground truthing of soil properties related to soil salts. Experience gained in the application of EMI in crop fields during and prior to the WRC project, helped us in developing the logical framework for assessing water and salts in crop fields. The second content chapter focused on the scaling out of EMI technology. It is envisaged that the eight case studies with different perennial crops will be of great value for information dissemination via their crop-specific associations. Again, BCOs will play an important role in the process of scaling out of the EMI technology, but they need training. Training of BCOs is beyond the scope of the project.

1.2 Problem, motivation and objectives of Volume 3

The third volume reflects on EMI research (upscaling) conducted on selected irrigation farms in the Northern Cape, Free State, Eastern Cape and KwaZulu-Natal. This is to achieve a deeper understanding of salt-related problems and their medium-to-long-term management. This type of decision support is on a research level and is aimed to serve the science community, although mega-farmers, corporations, and companies can also benefit from it in the medium to long-term. Volume 3 is structured in stand-alone chapters wherein the problem, motivation and objectives are presented in each of the 5 content chapters.

- Chapter 2 focuses on the socio-economic survey conducted amongst irrigation farmers to capture their understanding of water and salt management.
- Chapter 3 reveals research on sugarcane case studies with regard to what the real scenarios are in relation to salinity and sodicity. The objective of this chapter was to provide guidelines on water and salinity management of sugarcane, derived from literature and two case studies.
- Chapter 4 was allocated to a literature synopsis on three aspects: Firstly, best on-farm water and salt management practices distilled from international and regional literature. Secondly, precision farming principles and practices, and thirdly, decision support systems, especially the application of SWAMP model.
- Chapter 5 was structured to research the application of apparent soil electrical conductivity readings (EC_a), as measured through EMI, to characterise the spatial variability of soil properties. Based on the theoretical background, an analysis was performed on EC_a surveys and the application of the software package, ESAP-95 Version 2.01R (Electrical conductivity Sampling Assessment and Prediction, Lesch et al., 2000) software package to characterise spatial variability of soil salinity and other soil physical properties in the above mentioned case studies. This was done to highlight two important aspects, namely the feasibility and effectiveness of EC_a surveys done on irrigated South African soils to map all four these properties.

- Chapter 6 elaborates on decision support research with the following objectives in mind: i) to briefly describe the newly developed source code of SWAMP to simulate the soil water and salt balance and consequent matric and osmotic stress effects on water uptake and field crop yields; ii) to apply the model in assessing the importance of integrating water and salt management; iii) assess the potential to apply the optimised irrigation schedule in precision farming as a future decision support option.

CHAPTER 2. SOCIO-ECONOMIC STUDY: ACCEPTANCE OF SALINITY MANAGEMENT PRACTICES BY FARMERS

2.1 Introduction

The main reasons for adoption success and/or failure, generally, are well documented in literature (Kuehne et al., 2017). Causal factors include the characteristics of the innovation/practice (Rogers, 2003; Hochman and Carberry, 2011; Kuehne et al., 2017), personality traits of the farmer (Rogers, 2003; Vanclay, 2004), as well as economic, social and environmental factors (Sunding and Zilberman, 2001; Leeuwis, 2004; Everingham et al., 2006; Stirzaker et al., 2010; Baumgart-Getz et al., 2012). Regarding the characteristics of the innovation, Kuehne et al. (2017) reported that the relative advantage offered by an innovation was the best predictor of the peak adoption level (i.e. how many individuals will adopt), while complexity or ease of use was the best predictor of the time lag to achieve peak adoption. Rogers (2003) reported that compatibility with value systems and existing operations, the ability to trial on a small scale and observable results were other important characteristics of the innovation which influenced adoption. Rogers (2003) also reported that early adopters were typically younger farmers, with higher levels of education, direct access to primary information and higher income or larger scales of operation. As a result, early adopters have a better capacity to take on and cope with risk and uncertainty. In contrast, late adopters are typically resource poor and generally need to be assured that a new innovation will not fail before they can adopt. For this reason, late adopters usually require a large percentage of the population to adopt and prove the innovation to be low risk before they adopt.

Hence, literature provides a strong basis for designing processes and interventions to encourage uptake and implementation of better farm management practices (Kuehne et al., 2017). Abadi Ghadim and Pannell (1999), Pannell (1999). Marra et al. (2003) and Pannell et al. (2006) presented a series of ideas which highlighted the dynamic, central role of “information acquisition” and “learning by doing” in the context of perceptions, attitudes and the adoption decision making process. Pannell et al. (2006) asserted that “adoption is based on subjective perceptions or expectations rather than on objective truth”. Beliefs and assumptions can override facts when influencing behaviour.

Soil salinity and sodicity in the agricultural context is a well-established and well-researched discipline both globally (Van Schilfgaarde, 1990; Letey, 1994; Rhoades, 1997; Hillel, 2000; Oster and Wichelns, 2003; Hillel and Vlek, 2005; Kijne, 2006) and in South Africa (Cass, 1986; Nel, 1988; Greef, 1990; Moolman, 1993; Herold and Bailey, 1996; Herald, 1999; Moolman et al., 1999; Du Preez et al., 2000; De Clercq et al., 2001a; De Clercq et al., 2001b; Ellington et al., 2004; Ehlers et al., 2007; Van Rensburg et al., 2012). Despite the large investment and success in research and development in South Africa, Hillel and Vlek (2005) report that salinity was widespread, pervasive and inherent enough to question whether irrigation could be sustained for long periods in any region in South Africa. Very little is published with respect to the adoption of salinity management practices. In addition, there are virtually no case studies benchmarking the actual knowledge levels, perceptions and attitudes of farmers with respect to farm practices to address salinity in South Africa. The scale of the problem, therefore, extends to beyond the classification and mapping of areas with salinity problems. Farmers’ knowledge levels, perceptions, attitudes and capability to deal with salinity is even less known. Therefore, a socio-economic survey was conducted at the start of the project to benchmark these variables in order to guide the development of content and processes to improve adoption and uptake of salt management practices.

The question addressed in the study is: why do some farmers apply salinity and waterlogging preventative and corrective measures and other farmers not? Is this a matter of socio-economic background, knowledge, experience and/or perceptions?

The specific research questions addressed in this study are:

- Q1: What are farmers' current control and management strategies concerning salinity?
- Q2: How do farmers perceive salinity on irrigation lands?
- Q2: Do farmers perceive salinity as a threat to their continued existence?
- Q3: Do farmers understand the causes of salinity?
- Q4: Do farmers know how to prevent and/or manage salinity?
- Q5: Do farmers perceive that the benefits of corrective and management practices outweigh the cost thereof?
- Q6: Do farmers perceive that the benefits of corrective and management practices outweigh the efforts to implement such measures?

These questions was tested against a set of defined hypotheses:

- H1: Farmers do not perceive salinity as a threat to the future of irrigation farming.
- H2: Farmers do not understand causes of salinity.
- H3: Farmers do not have knowledge of preventative and corrective measures.
- H4: The benefits of preventative and corrective measures do not outweigh the costs.
- H5: Benefits of preventative and corrective measures do not outweigh the implementation effort.

2.2 Methodology

A questionnaire aiming to provide the information required to test the hypotheses, was designed to determine farmer's knowledge, experience, perceptions and practices regarding irrigation on saline soils. Three areas were identified for surveying: Vaalharts and Douglas as a unit, The Breede River in the Western Cape and the irrigated sugarcane growing areas of northern KwaZulu-Natal. Douglas and Vaalharts were handled as a unit, even though they are about 200 km apart, because the farmers irrigate similar soils and the areas are situated in the same Köppen climate region (Bsk: dry, cold, summer rainfall).

Organisations[1] serving farmers in the target areas were asked to give address lists of clients and from these non-alphabetic lists, 48 farmers were selected per survey area for interviewing by starting at the top of the list and moving down until the required number were selected. The surveys were conducted by project team members and students who visited the sampled farmers. Farmers were asked to complete the questionnaire without referring to soil analyses because the aim was to find out what the farmer knows to identify the nature of his own experience. Travel time and time required to complete the surveys was about 2 hours per survey point.

In general, respondents were willing to cooperate. Some respondents were not available at the time of the survey. In that case, a neighbouring farmer was visited and asked to complete the questionnaire. Alternatively, the questionnaire was left at the farmers' office and the farmer was asked to complete the questionnaire at a later stage and to mail it to the researchers.

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[1] Douglas irrigation area: GWK, Douglas and Orange-Vaal Water Users Association; Vaalharts: Vaalharts Farmer's Association; Breede River: Breede River Irrigation Board; Kwazulu-Natal: SASRI extension service.

The survey data were analysed in Excel, using pivot tables and chi-square tests to evaluate differences among groups. The confidence level in statistical analyses was set at 0.05. Hypotheses testing was based on perceptions of the recipients regarding facets of irrigation on saline soils through illustrative statistics. Illustrative statistics using graphs are used to summarise data. The illustrative statistics facilitate the statistical judgement (University of Bedfordshire, 2012).

- Each hypothesis was tested based on several elements that together reflect the perception of the respondents regarding the specific hypothesis. The statistical approach for hypothesis testing may be described as follow: Test respondents' perceptions on each of the elements on a five-point Likert-type scale. Agreement reflects the correct approach to the element being tested.
- No comparable research results were found, therefore, boundaries for acceptance or rejection of hypotheses had to be defined (Prof R Schall, Mathematical Statistics, Actuarial Science, and Applied Statistics, UFS, personal communication, 7 November 2016).
- Boundaries of acceptance to determine true/false level of responses for testing hypotheses:
    - It was assumed that the result of the responders to a question follows a normal distribution curve.
    - It was also assumed that a response of agree or partially agree to a statement represents a true situation.
    - The cut-off boundary, illustrated in Figure 2.1, was defined as the mean value plus one times the standard deviation, which was equal to 84 %. Hence, if 84% of responders to a specific statement indicate true or partially true, the statement is accepted as representing the perception of the population represented by the respondents
- If most indicators used to test a null hypothesis disagree with the null hypothesis, the null hypothesis was rejected
- Equal weights were given to all elements that test a hypothesis.

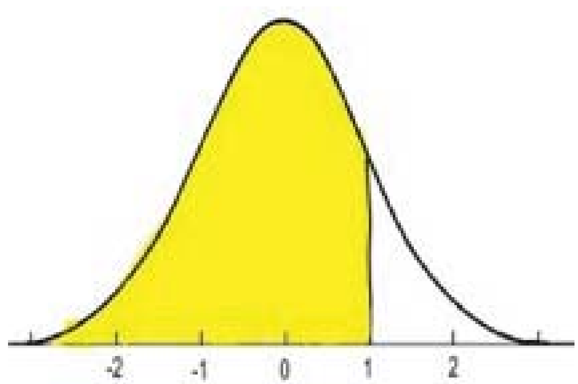


Figure 2.1 Normal curve with -2, -1, 0, +1 and +2 standard deviations indicated with acceptance as true level beyond +1 standard deviation

2.3 Results

Table 2.1 Distribution and sample size of farmers interviewed

Area	Number of farmers (n)	Area farmed (ha)
Breede River	40	5 605
Central (Vaalharts & Douglas)	42	19 784
KZN North	34	24 185
Total	116	49 574

2.3.1 Socio-economic

Age: All three target areas show an age distribution typical of a South African farming community, with most of the farmers in the three areas aged between 31 and 50 years with different ratios between the age groups, resulting in a significant difference between the areas (χ^2 (10, N=116), P = 0.047) (Figure 2.2). In all three areas, the median age is in the 41 to 50 years' group. Exceptions include no respondents under 31 years in the KwaZulu-Natal sample and the 13% of respondents in the 71 years and older group in the Breede River sample. Ages of farmers in the United States of America (USA) show a similar distribution, although the average age in the USA (59 years) is higher (United States Department of Agriculture, 2012).

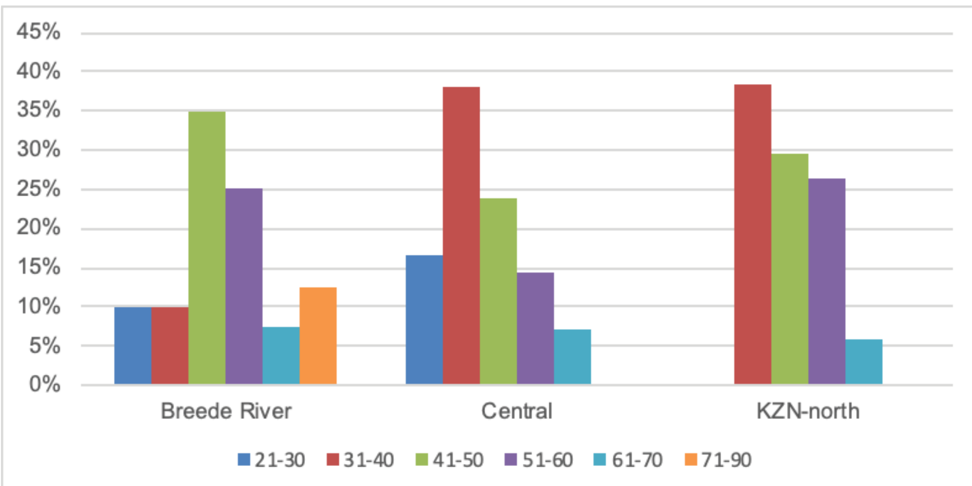


Figure 2.2 Age distribution of respondents in the Breede River, central South Africa and KwaZulu-Natal north irrigation areas (χ^2 (10, N=116), P = 0.047)

Training: There is a significant difference among the three groups regarding their levels of training (χ^2 (14, N=116), P = 0.004) (Figure 2.3). Most respondents in the KwaZulu-Natal sample have a diploma (53%), while most respondents from the central parts of South Africa have B-degrees (29%). In the Central region, while a further 17% of the respondents have diplomas, 21% and 17% of the remaining respondents had only a matric qualification or less, respectively. Most respondents in the Breede River have B-degrees and diplomas (38% of each).

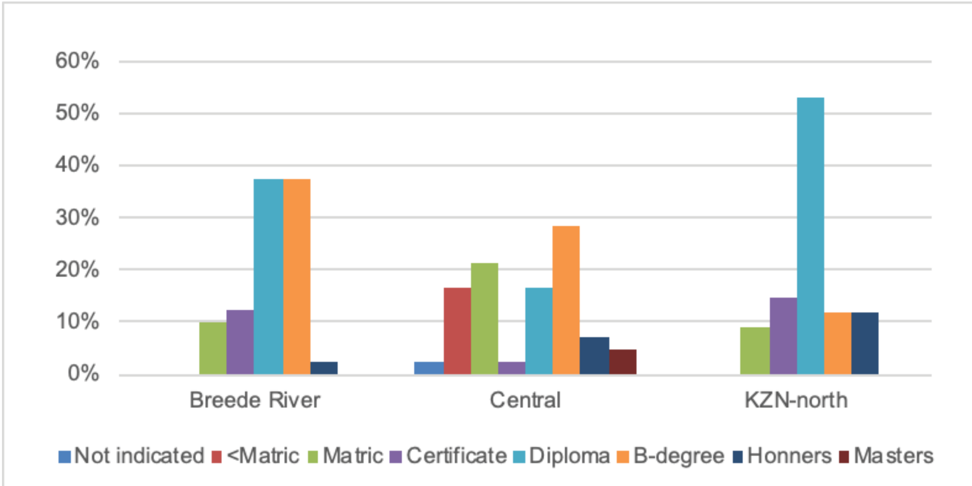


Figure 2.3 Training level distribution of respondents in the Breede River, central South Africa and KwaZulu-Natal north irrigation areas (χ^2 (14, N=116), P = 0.004)

Experience in irrigation farming: Most of the Breede River respondents (35%) have 21 to 30 years of experience in farming. In the central irrigation areas, 52% have from 11 to 20 years of experience and in the KwaZulu-Natal area 44% also have from 11 to 20 years' experience. The pattern of experience found among the respondents of the different areas, differs significantly from one other (χ^2 (14, N=116), P = 0.018) (Figure 2.4).

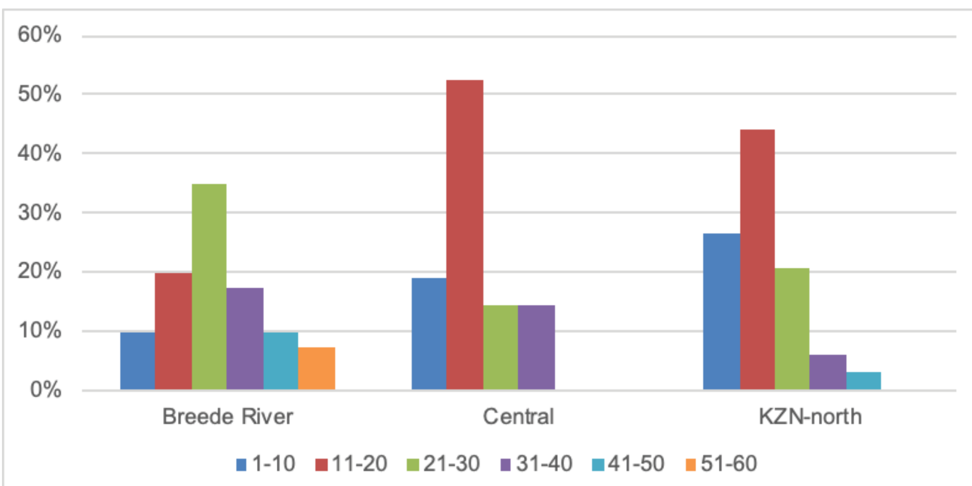


Figure 2.4 Distribution in experience in irrigation farming of respondents in the three target regions of South Africa (χ^2 (14, N=116), P = 0.018)

Cropped area under irrigation: The area annually irrigated per farmer differed significantly between the three regions (χ^2 (16, N=116), P = 0.009) (Figure 2.5). In the Breede River area, 86% of the respondents irrigate between 50.1 and 500 ha. In the central regions of the country, 67% own more than 200 ha, while in KwaZulu-Natal 86% own more than 100 ha. Median values for the three areas are between 101 and 200 ha for the Breede River and between 201 and 500 ha for both the central regions and for KwaZulu-Natal.

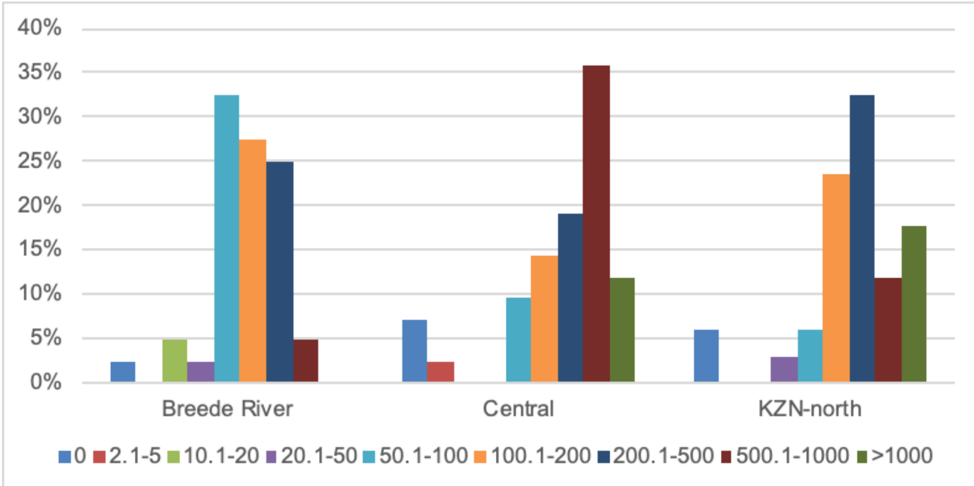


Figure 2.5 Distribution of irrigated area on land owned by respondents in the Breede River, central South Africa and KwaZulu-Natal north irrigation areas (χ^2 (16, N=116), P = 0.009)

Few respondents rent irrigated land. In the Breede River area only 7% of respondents are tenant farmers. In the central area this value increases to 31% and is 29% for the KwaZulu-Natal area. The pattern of rented irrigation land does not differ significantly across the three regions (χ^2 (16, N=116), P = 0.689) (Figure 2.6).

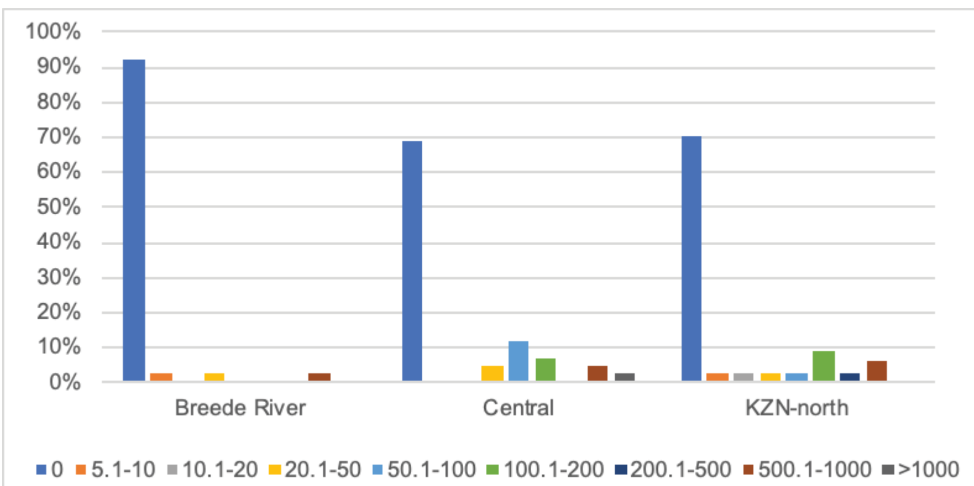


Figure 2.6 Distribution of irrigated area on rented land in the Breede River, central South Africa and KwaZulu-Natal north irrigation areas (χ^2 (16, N=116), P = 0.689).

Knowledge of soil form: The respondents were asked to indicate if they knew the soil forms on their farms. The results, present in Figure 2.7, indicate that knowledge about soil form significantly differed for the 3 target areas (χ^2 (2, N=116), P = 0.0003). In the Breede River, Central and northern KwaZulu-Natal regions, 85%, 52% and 41% of the respondents did not know the soil forms which were present on their farms.

In the Breede River area, a regional soil classification system was encountered. This was apparently the result of information transfer by extension personnel who served that area before the binomial soil classification system (Soil Classification Working Group, 1991) became fully implemented. This system was based on a combination of soil colour, texture and geographic position or origin. Terms such as “red karoo”, “soft karoo”, calcareous karoo”, “sandy red karoo” were commonly found. The sense in this local naming system is that the irrigation farmers of the Breede River could talk “soil” amongst themselves and understand the meaning, although the outsider might not exactly understand the meaning of these terms.

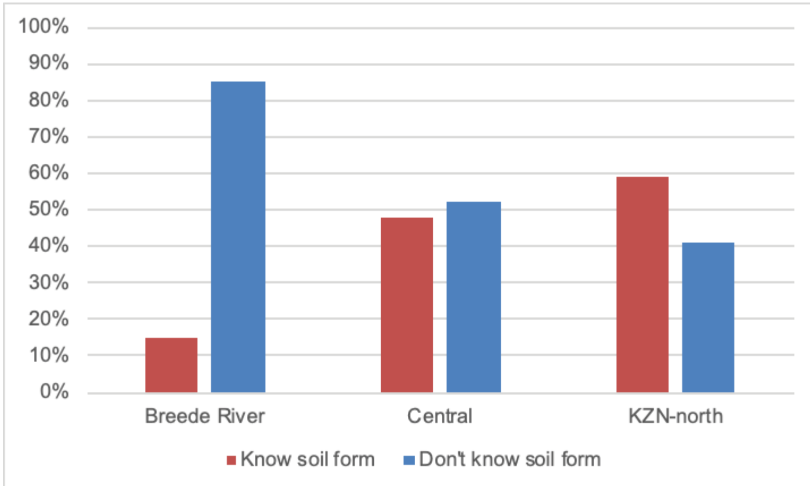


Figure 2.7 Distribution of respondents who know or don't know the soil form in the 3 target areas (χ^2 (2, N=116), P = 0.0003).

Effective depth of soil: The perceived effective depth of irrigated soil in the three areas varies from less than 0.7 m to more than 2 m, with most of the Breede River area (60%) indicated as between 1.1 and 2 m. Similarly, 48% of the respondents in the central irrigation areas perceived a depth of between 1.1 and 2 m. Contrastingly, 47% of the KwaZulu-Natal respondents indicated an effective soil depth of 0.1 to 0.6 m (Figure 2.8), resulting in a significant difference in the perceived soil depths of the three regions (χ^2 (6, N=116), P < 0.001). Most of the irrigators in all three regions could indicate the soil texture classes of the soils they irrigate.

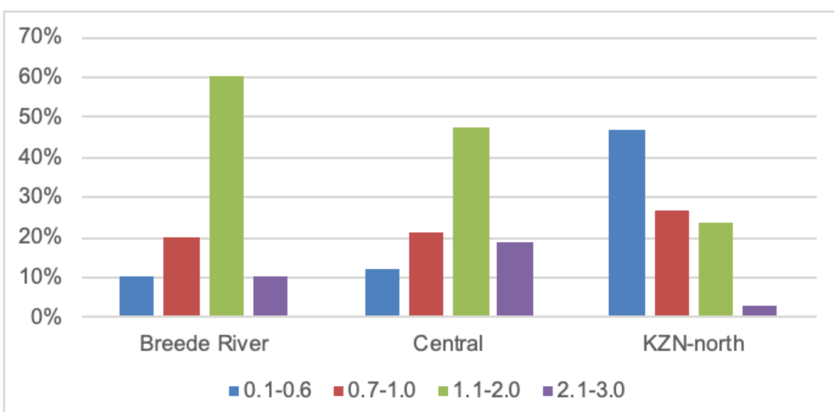


Figure 2.8 Distribution of effective soil depth in the Breede River, central South Africa and KwaZulu-Natal north irrigation areas (χ^2 (6, N=116), P < 0.001).

Soil salinity status (pH, electrical conductivity and sodium adsorption ratio): In order to test knowledge levels about their own farms, respondents were asked to indicate the values of the parameters used to evaluate soil salinity status for their respective farms, or to indicate if they did not know. As depicted in Figure 2.9, a large portion of the respondents did not know the pH, Electrical Conductivity (EC) or Sodium Adsorption Ratio (SAR) values for the soils on their farms. The results were not significantly different for each region (χ^2 (4, N=285), P = 0.743).

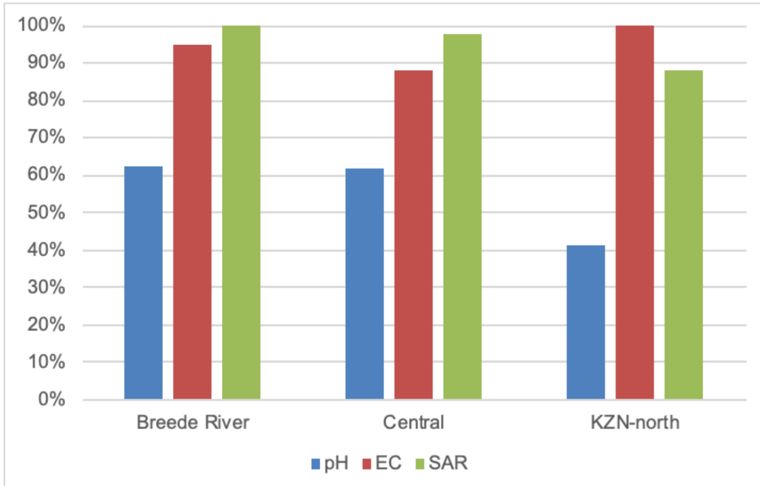


Figure 2.9 Distribution of knowledge gaps relating to soil salinity status (% who did not know) in the Breede River, central South Africa and KwaZulu-Natal north irrigation areas (χ^2 (4, N=285), P = 0.743).

Knowledge of threshold values of salt diagnostic parameters: Respondents' knowledge on the critical threshold values of parameters, normally used to diagnose salinity were also evaluated. These parameters are typically reported on soil analysis reports from soil laboratories and include calcium (Ca), magnesium (Mg), sodium (Na), sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP). Figure 2.10 illustrates that most of the respondents did not know the critical threshold values for each of the above-mentioned parameters. There was significant homogeneity across the regions (χ^2 (10, N=511), P = 1).

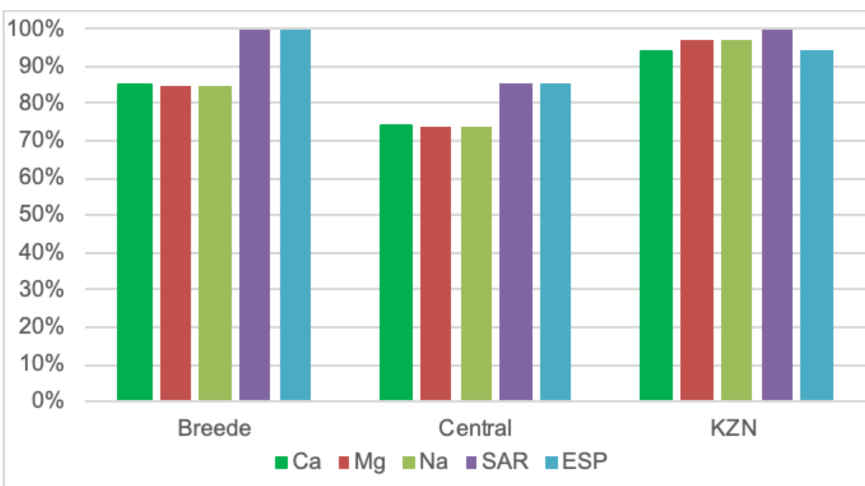


Figure 2.10 Distribution of knowledge gaps relating to threshold values for salinity diagnosing parameters (% who did not know) in the Breede River, central South Africa and KwaZulu-Natal north irrigation areas (χ^2 (10, N=511), P = 1).

Presence of a water table and of salinity: Respondents were asked to indicate if there were visible signs of a shallow water table or salinity on their farms. Respondents were also asked to indicate if there was some form of drainage (surface or subsurface) on their respective farms. The results for each of the target areas are presented in Table 2.2. In all 3 regions, 50% or more of the respondents indicated that there were visible signs of salinity on the farms (79% in KwaZulu-Natal). Large portions of the farms were also drained, and despite the presence of drainage, these areas still appear to have higher levels of salinity compared to areas not drained, irrespective of whether there were signs of a shallow water table or not.

Table 2.2 Prevalence of water table and soil salinity

Area	Water table	Drained	Water table drained combinations (%)	Has salinity (%)	No salinity (%)
Breede River	Has water table	Drained	22.5	20	2.5
		Not drained	0	0	0
	No water table	Drained	70	35	35
		Not drained	7.5	5	2.5
Total				60	40
Central	Has water table	Drained	19	12	7
		Not drained	0	0	0
	No water table	Drained	55	33	21
		Not drained	26	5	21
Total				50	50
KZN-north	Has water table	Drained	53	47	6
		Not drained	3	3	0
	No water table	Drained	41	26	15
		Not drained	3	3	0
Total				79	21

Irrigation water supply: Four questions were posed relating to irrigation water supply.

- Is the water supply permanent?
- Is the water allocation adequate for crop requirement alone?
- Is the water supply adequate for crop requirement and leaching requirement?
- Is irrigation water monitored for salinity?

The results show that 90%, 95% and 94% of the respondents in the Breede River, Central areas and northern KwaZulu-Natal state that their water supply is permanent (Figure 2.11). This simplifies planning of production systems, and by extension financial planning. Homogeneity regarding the permanence of water supply is significant amongst the three areas (χ^2 (4, N=116), P = 0.531). Most respondents in all three regions indicated that irrigation water was enough to satisfy crop demand with few differences across the three regions (χ^2 (4, N=116), P = 0.665) (Figure 2.12).

Similarly, most respondents say they get enough irrigation water to satisfy crop-water requirements as well as leaching demands, but the number of respondents who agree with this is fewer than the number who agreed that enough water is supplied to satisfy crop requirements only (Figure 2.13). Homogeneity between the three regions is significant (χ^2 (4, N=116), P = 0.430).

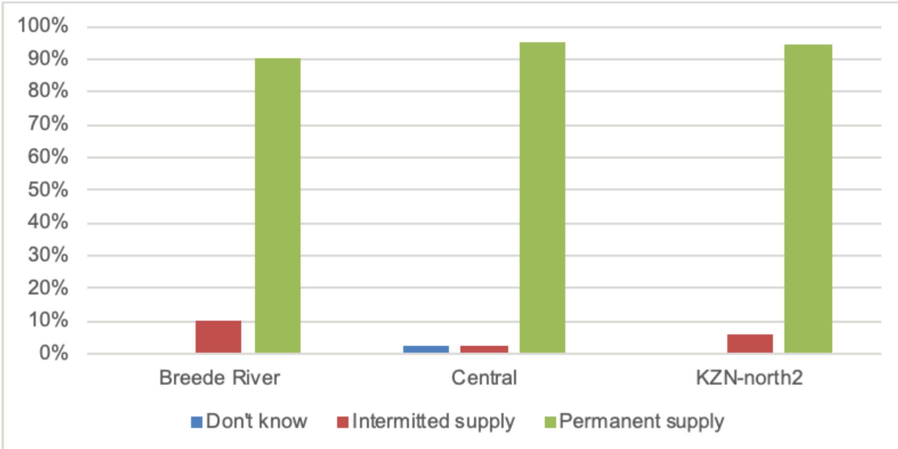


Figure 2.11 Distribution of permanency of irrigation water supply to respondents in the three target regions of South Africa (χ^2 (4, N=116), P = 0.531).

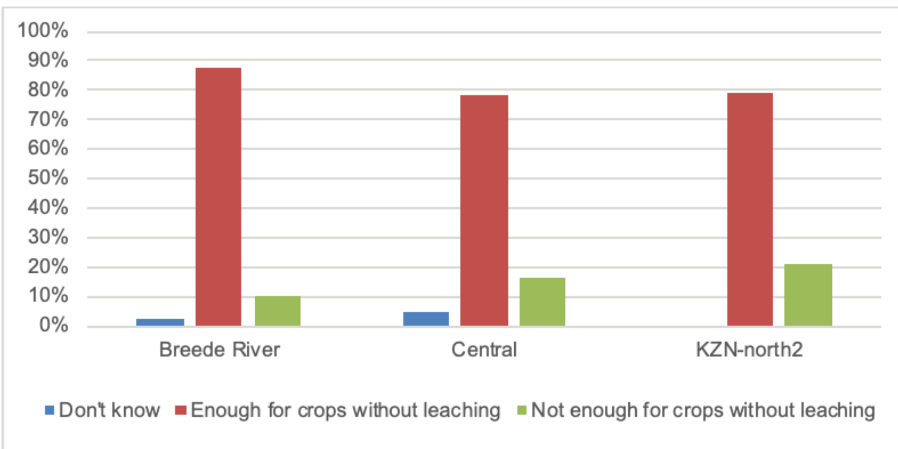


Figure 2.12 Distribution of adequacy for crops without leaching of irrigation water supply to respondents in the three target regions of South Africa (χ^2 (4, N=116), P = 0.665).

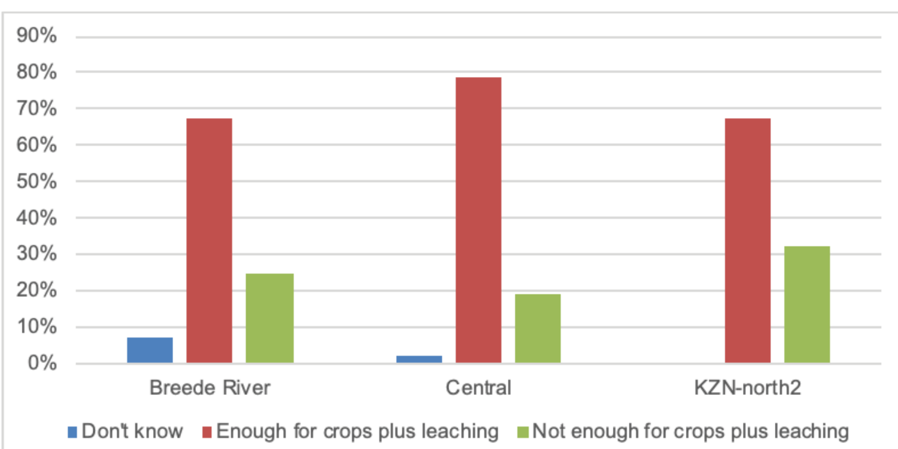


Figure 2.13 Distribution of adequacy for crops plus leaching of irrigation water supply to respondents in the three target regions of South Africa (χ^2 (4, N=116), P = 0.430).

Most respondents in the Breede River and the central parts of South Africa agree that irrigation water is monitored for salinity. Less than half of the northern KwaZulu-Natal respondents agreed that water quality was being monitored (Figure 2.14). Differences between regions were not significant. The monitoring of salinity levels in the irrigation water is usually a responsibility of the water management authority and not that of the irrigation farmer. Hence, most farmers in KwaZulu-Natal could not report any EC value or quality class, despite indicating that water quality was monitored.

Irrigation systems: The distribution of irrigation systems in the three areas, based on hectares per system, is shown in Figure 2.15. The irrigation systems differ significantly across the three areas. The type of irrigation systems is likely to reflect the relative importance of different crops and perennials. In the central parts where farming is mainly with field crops, such as maize, wheat, lucerne and cotton, centre pivot systems dominate (87% of area). In the Breede River area, mainly with grape and fruit production, drip irrigation dominates (58%) and in the KwaZulu-Natal sugar growing areas, centre pivot (36%), draglines (21%) and drip systems (24%) are most commonly found.

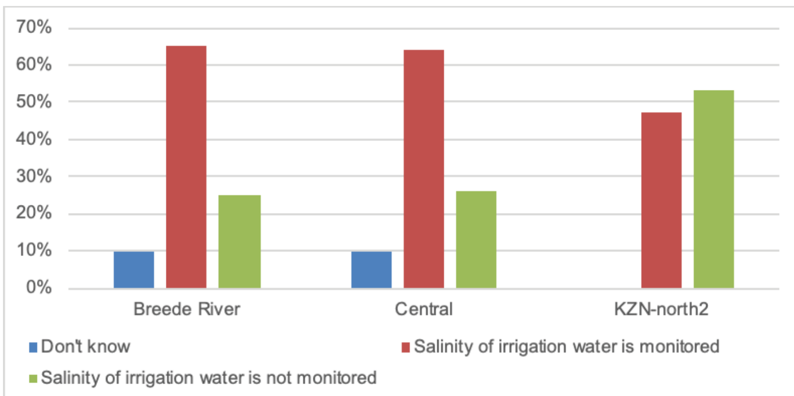


Figure 2.14 Distribution of irrigation water monitoring by respondents in the three target regions of South Africa (χ^2 (4, N=116), P = 0.108).

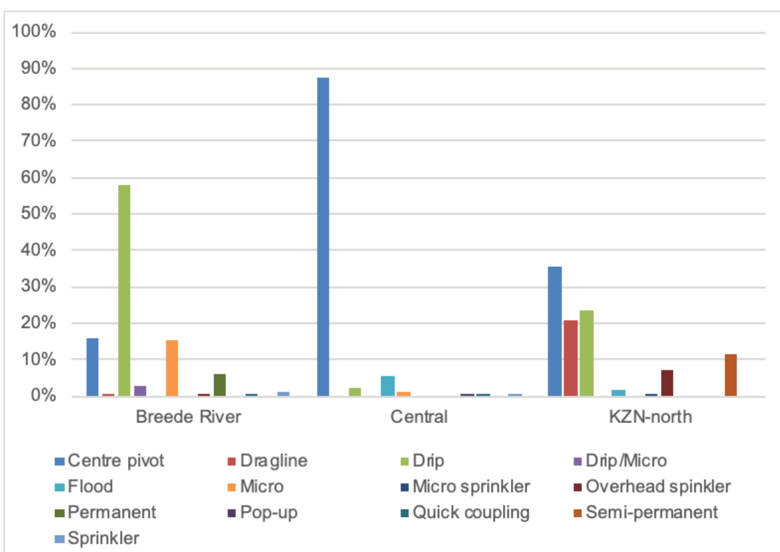


Figure 2.15 Distribution of irrigation systems based on area irrigated in the Breede River, Central and northern KZN areas (χ^2 (26, N=116), P < 0.001).

Irrigation scheduling: Respondents use various approaches for scheduling their irrigations (Figure 2.16). Values add up to more than 100% per region because respondents could indicate any number of approaches used for a farming enterprise. Scheduling based on crop requirements and soil-water balance dominate, although a noticeable proportion of the respondents use experience as the only criterion. In KwaZulu-Natal, 21% of the respondents also indicated that they don't make use of any method to schedule irrigation. Scheduling service seems to dominate the central parts. Responses significantly differed between regions (χ^2 (14, N=390), P < 0.001).

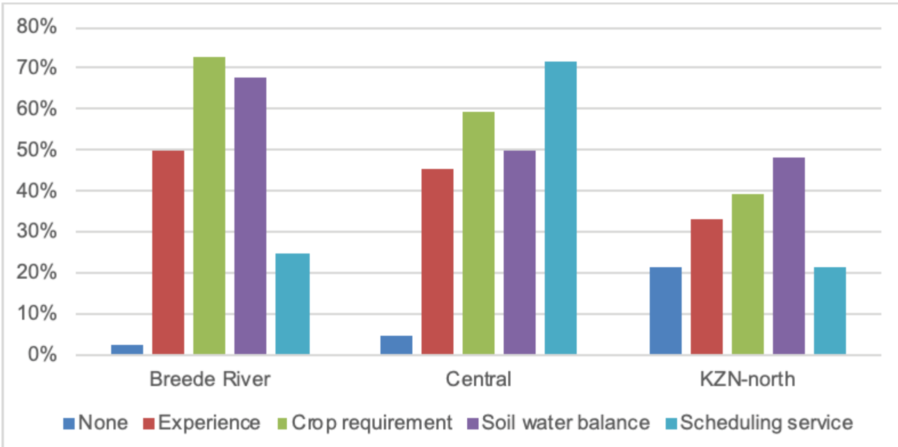


Figure 2.16 Irrigation scheduling approaches by respondents in the three target irrigation areas.

Application of leaching as a salinity management practice: Figure 2.17 depicts the percentage of respondents who were applying leaching as a salt management practice. The results were significantly different for the 3 regions (χ^2 (4, N=116), P = 0.006). In the Breeder River, Central and northern KwaZulu-Natal regions, 58%, 43% and 88% of the respondents indicated that they did not apply a leaching fraction to wash salts out of the crop root zone.

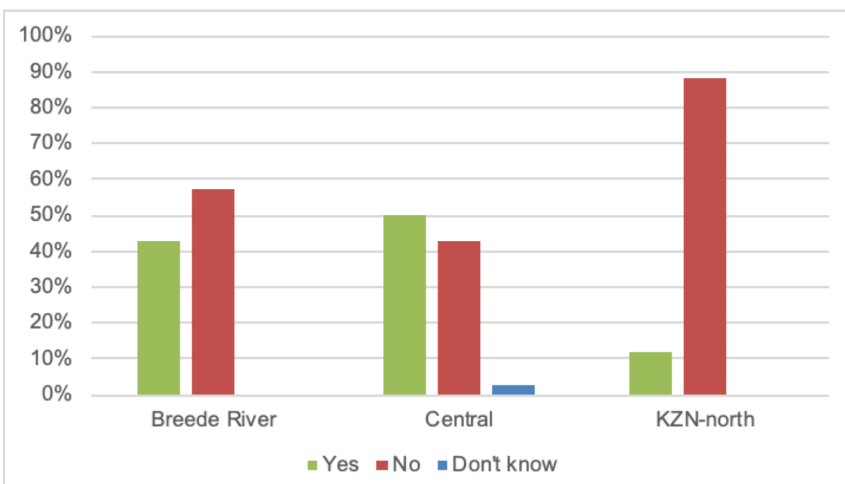


Figure 2.17 Application of leaching by the respondednts in the 3 target areas (χ^2 (4, N=116), P = 0.006).

As a follow-up question, respondents were asked if they thought leaching was a good practice. The results, shown in Figure 2.18, differed significantly for each region (χ^2 (4, N=116), P = 0.006). More growers indicated that they did not know the answer to this question for all 3 regions, compared to those who said no or yes.

Using partial wetting as part of irrigation strategy: On average, 78% of respondents do not apply partial wetting and 11% do not know of the practice. This is perhaps not surprising, as the application of partial wetting is a technique usually applied in orchards and vineyards. The latter notwithstanding very few people in the Breede River apply this technique.

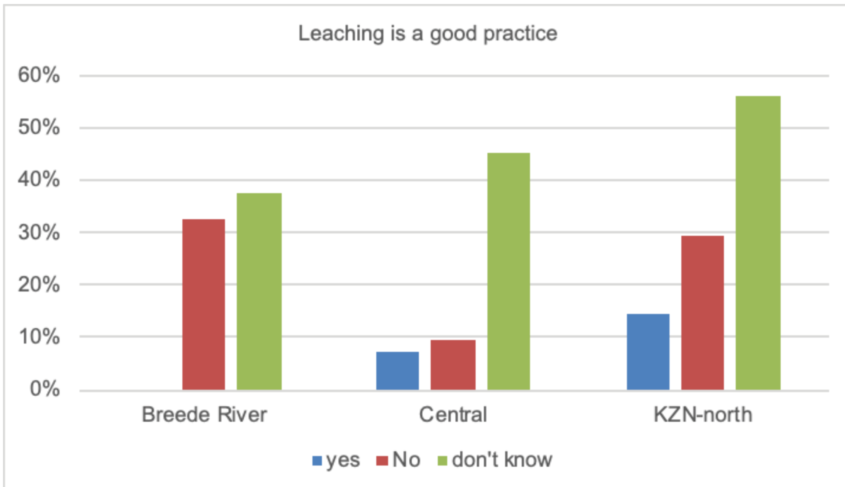


Figure 2.18 Distribution of responses in the 3 target areas to the question "is leaching a good practice" (χ^2 (4, N=116), P = 0.006).

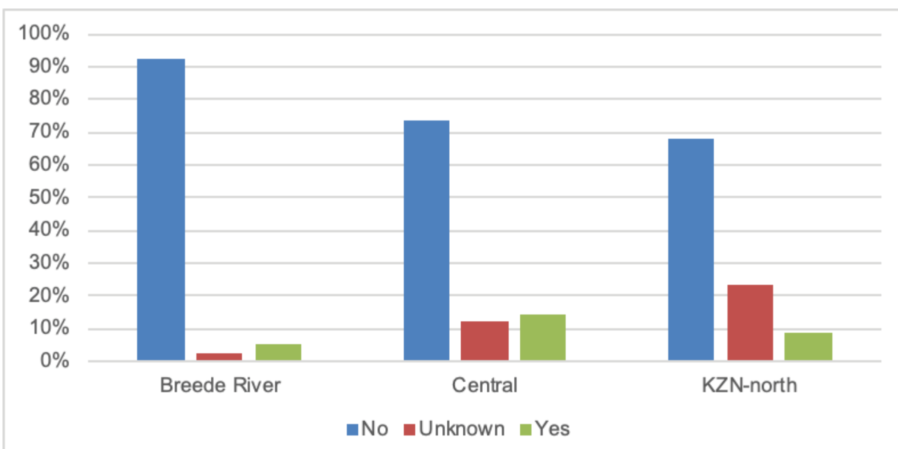


Figure 2.19 Application of partial wetting by respondents in the three target irrigation areas.

Crops grown: The crops grown, and average crop yield are shown in Table 2.3.

Sources of information: Respondents were provided with a list of information sources and asked to indicate how regularly they used each source and what degree of importance they attributed to each option. Figure 2.20 shows the distribution in terms of percentage of respondents who indicated that they use the source of information on a regular basis. Percentages exceed 100% per area because respondents could list more than one source of information. The three groups of respondents are not homogeneous in the sources they use and regions differ significantly in their responses (χ^2 (20, N=565), P = 0.004). Seed company personnel appears as an important source only in the central region, where the planting of seasonal crops is common practice. Fertiliser company personnel (86%) and agricultural advisors (83%), however, were the top two most regular sources of information for farmers in the Central region. In the Breede River area, agricultural advisors (70%), soil laboratories (65%) and fertiliser company personnel (60%) were the top three most regular sources of information. In KwaZulu-Natal, soil laboratories (88%) and agricultural advisors (85%) were the top two, with research stations, farmer days and media also featuring as regular sources of information (70 % each). It is also clear that scientific journals and conferences were not a regular source of information for farmers in all the regions.

Table 2.3 Most important crops grown, based on ha per crop, and their average fresh yields, in the Breede River, central South Africa and northern KwaZulu-Natal irrigation areas

Breede River			Central			KZN-north		
Crop (Sensitivity to salinity*)	**Crop importance (%)**	**t ha^{-1}**	**Crop**	**Crop importance (%)**	**t ha^{-1}**	**Crop**	**Crop importance (%)**	**t ha^{-1}**
Grapes (MS)	64	22.1	Maize (MS)	34	13.4	Sugarcane (MS)	89	86.8
Lucerne (MS)	6	16.4	Wheat (T)	28	7.5	Macadamia (MS)	3	1.7
Maize silage (MS)	5	53.8	Lucerne (MS)	17	20.9	Sunn hemp	2	
Pasture (MT)	5		Barley (T)	7	7.5	Oats (MT)	1	
Peaches (S)	5	38.4	Pecan (S)	4	2.2	Maize (MS)	1	8.0
Grass-clover pasture (MS)	2		Cotton (T)	4	5.8	Beans soy (MT)	1	3.0
Kikuyu (MT)	2		Groundnuts (MS)	3	3.2			
Pears (S)	2	40.0						
Prunes (S)	2	25.3						

*S = sensitive; MS = moderately sensitive; MT = moderately tolerant; T = tolerant (Van Heerden and Walker, 2016)

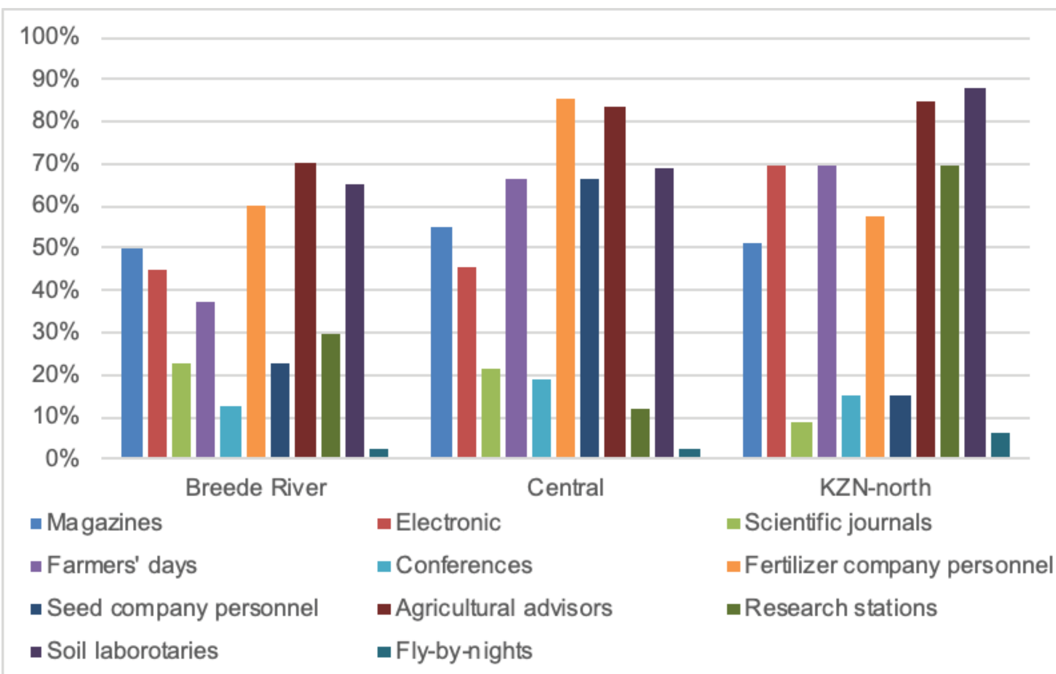


Figure 2.20 Sources of information regularly used by respondents of the Breede River, Central and northern KZN irrigation areas (χ^2 (20, N=565), P = 0.004).

The importance of information sources (Figure 2.21) differs from the frequency of use (Figure 2.20). However, similar to the frequency of use, the three regions also differed significantly in the degree of importance attributed to the sources of information ($\chi 2$ (20, N=467), P = 0.003).

The most important sources of information for the Breede River Valley were agricultural advisors (55%). For the central regions, agricultural advisors (67%), fertiliser company personnel (62%), farmers' days (50%) and soil laboratories (50%) were the most important, while soil laboratories (97%), agricultural advisors (91%), research stations (85%), farmers' days (73%) and electronic media (70%) were the most important for the northern KwaZulu-Natal region.

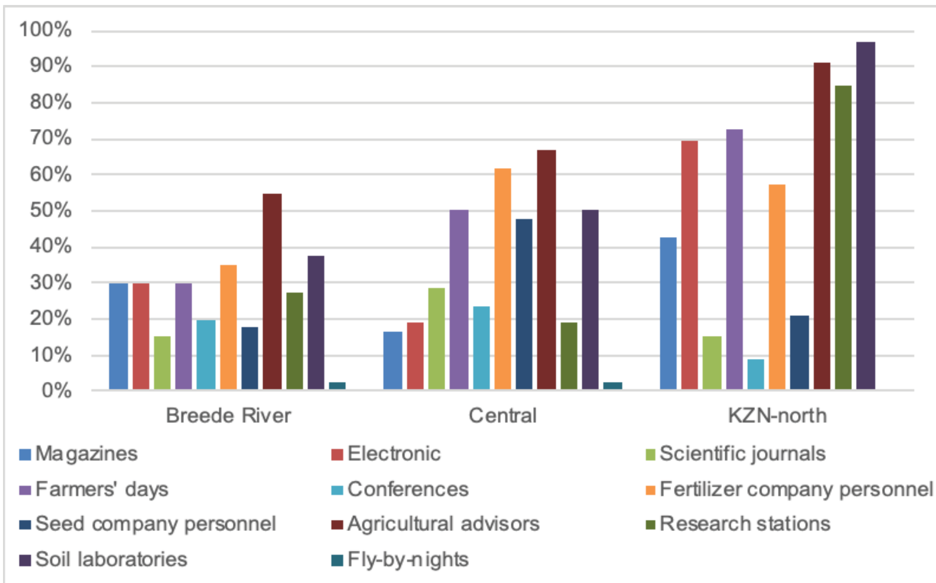


Figure 2.21 Importance of information sources regularly used by respondents of the Breede River, Central and northern KZN irrigation areas (χ^2 (20, N=467), P = 0.003).

2.3.2 Hypothesis 1: Farmers do not perceive soil salinity as a threat

The elements used to test this hypothesis are given in Table 2.4, with the boundary of acceptance level ($\mu + 1\sigma$) at 84%. In all these cases, as depicted in the following tables, agree and partially agree are treated as positive. For more than half the indicators for all three regions, respondents recognise the danger that soil salinity poses, and the hypothesis is therefore rejected. Discussion of the individual elements follows.

Table 2.4 Percentage of respondents who perceive soil salinity as a threat (boundary of acceptance = 84%)

Indicator	Breede River	Central	KZN-north
Slower infiltration	83%	74%	74%
Less water available for the crop	93%	88%	88%
Reduced germination	100%	95%	94%
Reduced uptake of plant nutrients	95%	93%	94%
Increased uptake of some nutrients	25%	50%	24%
Reduced production of natural veld	80%	90%	85%
Variation of natural veld plants is less on saline soils	95%	88%	88%

Infiltration of water into sodic soils: The respondents' perceptions of the slower infiltration of water into sodic soils is depicted in Figure 2.22. The answers from the regions did not significantly differ from each other. On average 77% of respondents agree that water infiltration rate is slower on sodic soils than on non-sodic soils. However, this result did not exceed the boundary of acceptance level of 84%.

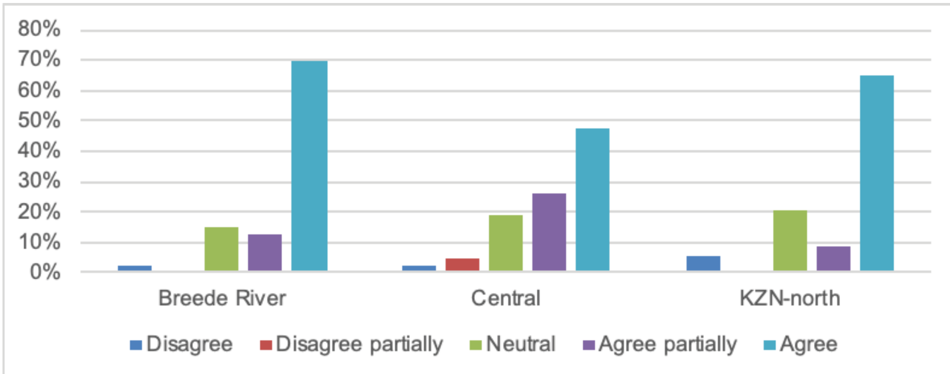


Figure 2.22 Comparison of perception regarding the statement that infiltration is slower on a sodic soil for the three target areas (χ^2 (8, N=116), P = 0.318).

Availability of water to plants: Most respondents (90% on average) agreed with the statement that less water is available to the crop on a saline soil (Figure 2.23). Differences amongst the three regions are not significant (χ^2 (8, N=116), P = 0.928).

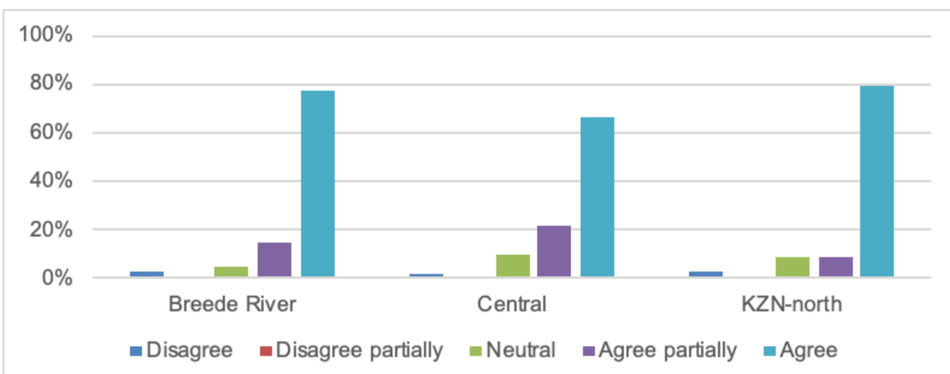


Figure 2.23 Comparison of perception that less water is available for crops on a saline soil for the three target areas (χ^2 (8, N=116), P = 0.928).

Reduced germination on saline soils: Most respondents of the three regions agreed that germination of crops on saline soils is reduced (Figure 2.24) (χ^2 (8, N=116), P = 0.109).

Reduced uptake of plant nutrients on saline soils: More than 92% of the respondents agreed that saline soils suppress the uptake of plant nutrients (Figure 2.25) with little differences between the three regions (χ^2 (8, N=116), P = 0.995).

Increased uptake of some minerals: On the matter of the increased uptake of some minerals on saline soils, the respondents seem largely unsure, with more disagreement than agreement with the statement (Figure 2.26). Differences in responses across the three regions were not significant (χ^2 (8, N=116), P = 0.079).

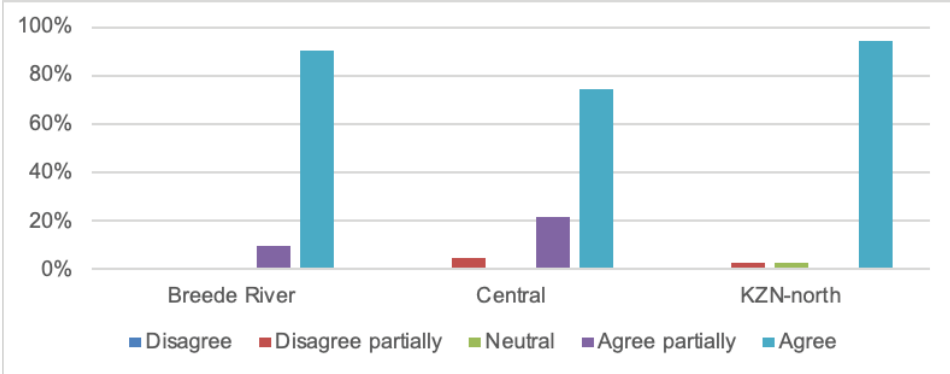


Figure 2.24 Comparison of perception regarding reduced germination of crops on a saline soil for the three target areas (χ^2 (8, N=116), P = 0.109).

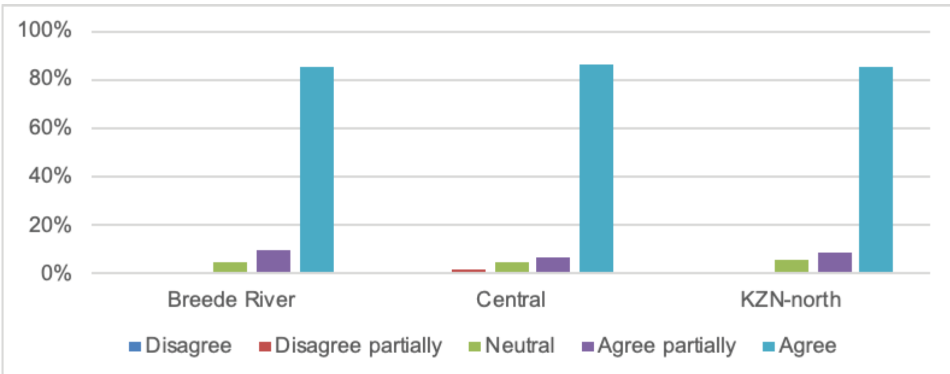


Figure 2.25 Comparison of perception regarding the reduced uptake of plant nutrients on a saline soil for the three target areas (χ^2 (8, N=116), P = 0.995).

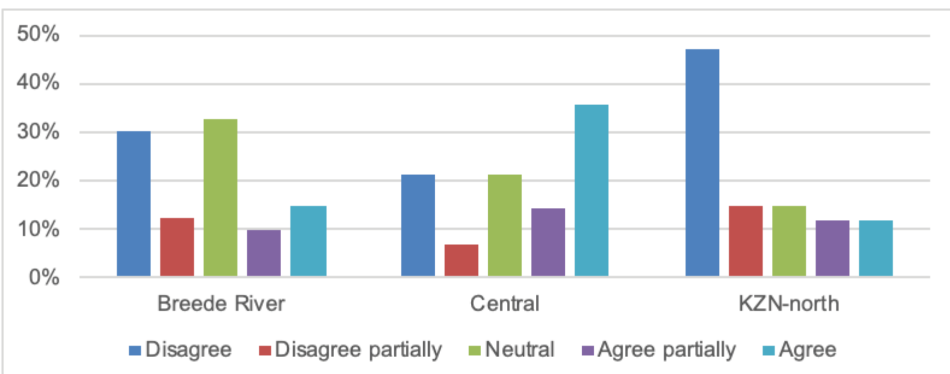


Figure 2.26 Comparison of perception regarding the increased uptake of some plant nutrients on a saline soil for the three target areas (χ^2 (8, N=116), P = 0.079).

Reduced production of natural vegetation: Most of the respondents of the three regions agree that veld production is reduced on saline soils (Figure 2.27), (χ^2 (8, N=116), P = 0.154).

Variety of natural vegetation: Most of the respondents of the three regions agree that the variation in plants of natural veld is reduced on saline soils (Figure 2.28), (χ^2 (8, N=116), P = 0.902).

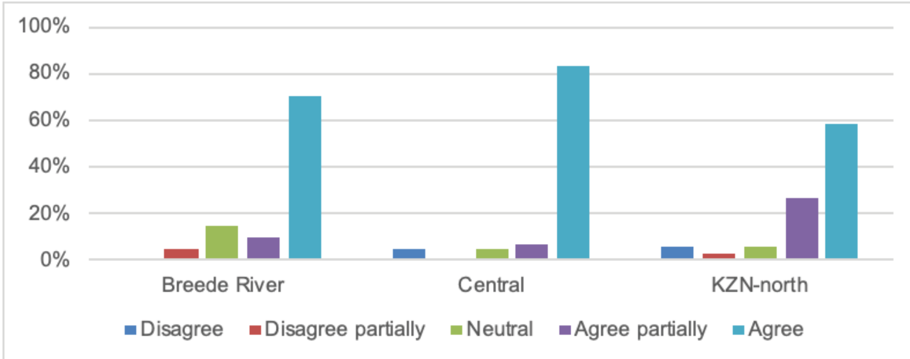


Figure 2.27 Comparison of perception regarding the reduced production of natural veld on a saline soil for the three target areas (χ^2 (8, N=116), P = 0.154).

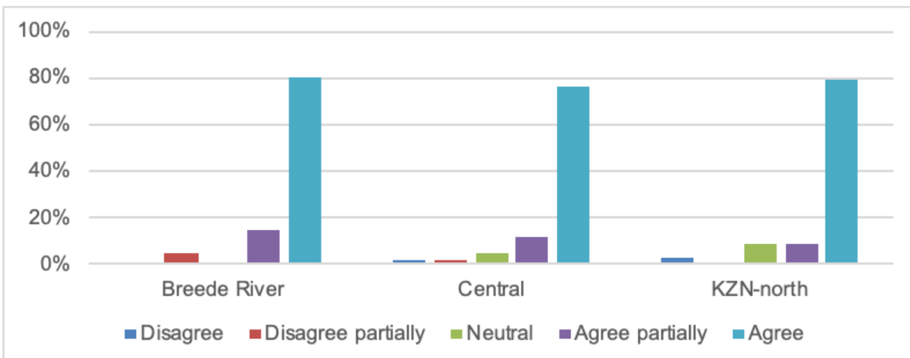


Figure 2.28 Comparison of perception regarding the reduced plant variation of natural veld on a saline soil for the three target areas (χ^2 (8, N=116), P = 0.902).

2.3.3 Hypothesis 2: Farmers do not understand the causes of salinity

The state of the indicators used to test this hypothesis are given in Table 4.5. For all indicators, respondents recognise the causes of soil salinisation and, therefore, hypothesis 2 is rejected. Discussion of the individual elements follow.

Table 2.5 Percentage of respondents understanding causes of soil salinity (boundary of acceptance = 84%)

Indicator	Breede River	Central	KZN-north
Irrigation with poor quality water can enhance salinisation	98%	90%	100%
Poor irrigation management can enhance salinisation	100%	98%	100%
Mineral salts are a natural constituent of soil	95%	92%	91%
Soil surface evaporation can lead to an increase in the salt in the upper soil layer	93%	81%	89%

Perceptions regarding irrigation with poor quality water: Most respondents from the three regions agree that irrigating with poor quality water can enhance salinisation of irrigation soil (Figure 2.29) (χ^2 (8, N=116), P = 0.779).

Reduced production of natural vegetation: Most of the respondents of the three regions agree that veld production is reduced on saline soils (Figure 2.27) (χ^2 (8, N=116), P = 0.154).

Mineral salts are a natural constituent of soil and can lead to salinity problems: Most respondents agreed with this statement (Figure 2.31) (χ^2 (8, N=116), P = 0.047).

Soil surface evaporation lead to an increase in salt content in the upper soil layer: Most respondents agreed that soil surface evaporation could lead to salinity (Figure 2.32) (χ^2 (8, N=116), P = 0.418).

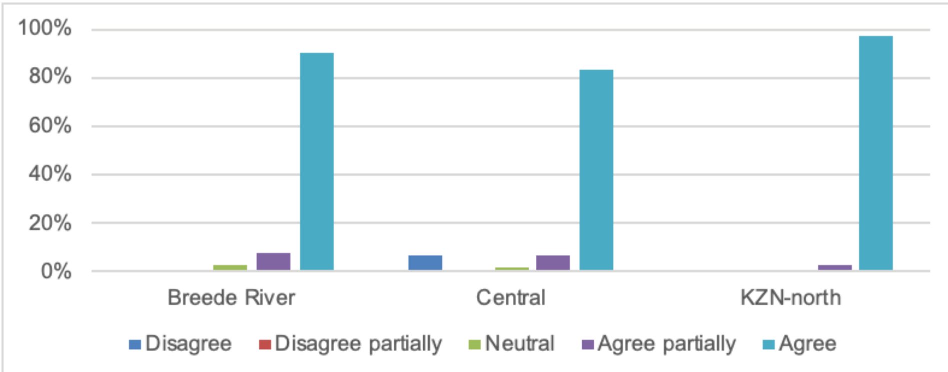


Figure 2.29 Comparison of perception regarding the increased uptake of some plant nutrients on a saline soil for the three target areas (χ^2 (8, N=116), P = 0.079).

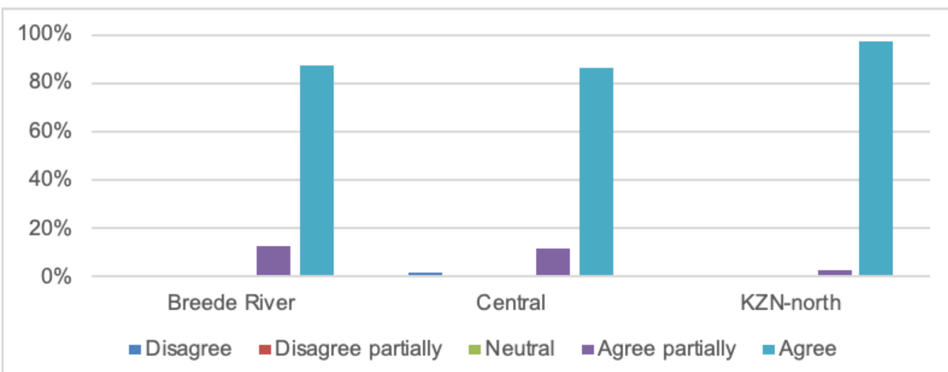


Figure 2.30 Comparison of perceptions regarding the reduced production of natural veld on a saline soil for the three target areas (χ^2 (8, N=116), P = 0.154).

2.3.4 Hypothesis 3: Farmers are not aware of preventative and corrective management practices that can be applied to saline soils

The indicators used to test this hypothesis are given in Table 2.6. Only in the central region do all indicators exceed the threshold value of mean plus 1 multiplied by the standard deviation. The test shows that in all three regions, the respondents know preventative and management actions that can be applied to saline soils, and the null hypothesis is rejected. It needs to be borne in mind that only three elements were used to test this hypothesis and that the inclusion of more elements could have given a different result.

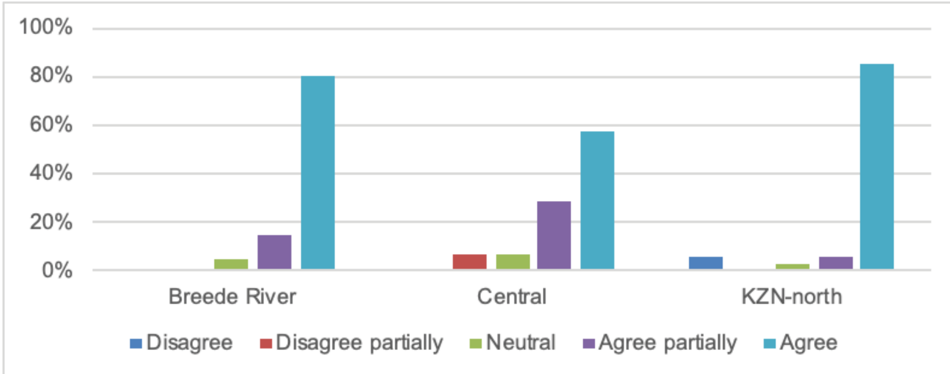


Figure 2.31 Comparison of perception that mineral salts are a natural constituent of soil and can enhance salinisation for the three target areas (χ^2 (8, N=116), P = 0.047).

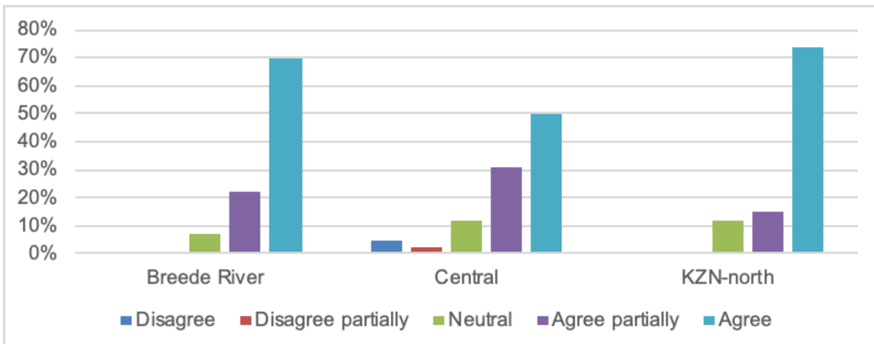


Figure 2.32 Comparison of perception that soil surface evaporation can lead to an increase in the salt content of the upper soil layer for the three target areas (χ^2 (8, N=116), P = 0.418).

Table 2.6 Percentage of respondents who know preventative and corrective management practices for soil salinity (boundary of acceptance = 84%)

Indicator	Breede River	Central	KZN-north
Soil salinisation can be prevented by applying correct irrigation scheduling	91%	88%	89%
Planting salt tolerant crops can be considered	93%	91%	82%
Installation of an artificial drainage system can enhance leaching	98%	98%	100%

Applying correct irrigation scheduling: Most respondents in all three regions agree that salinisation of irrigation soil can be prevented, or even turned around, by good irrigation management (Figure 2.33) (χ^2 (8, N=116), P = 0.938).

Planting salt tolerant crops: Most respondents in all three regions agree that the planting of salt tolerant crops is a management approach that is well worth considering for saline soils (Figure 2.34) (χ^2 (8, N=116), P = 0.202).

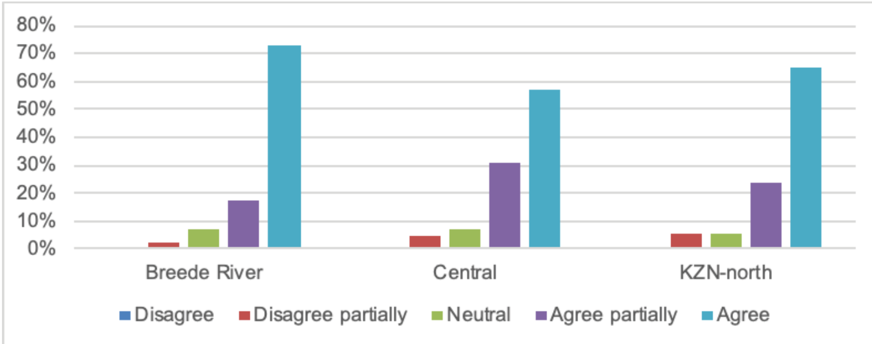


Figure 2.33 Comparison of perception that salinisation can be prevented or improved upon by applying correct irrigation scheduling for the three target areas (χ^2 (8, N=116), P = 0.938)

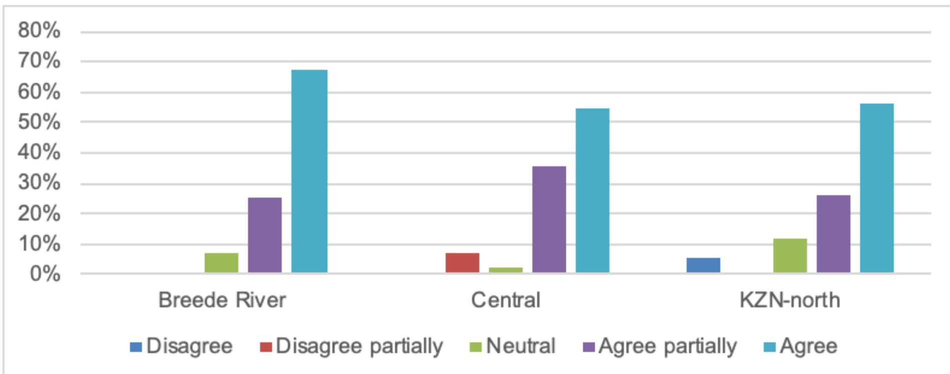


Figure 2.34 Comparison of perception that planting salt tolerant crops can be considered for the three target areas (χ^2 (8, N=116), P = 0.202).

Leaching: All three regions agreed with the statement that artificial drains could enhance leaching (Figure 2.35). No significant differences amongst the three regions were found (χ^2 (8, N=116), P = 0.936).

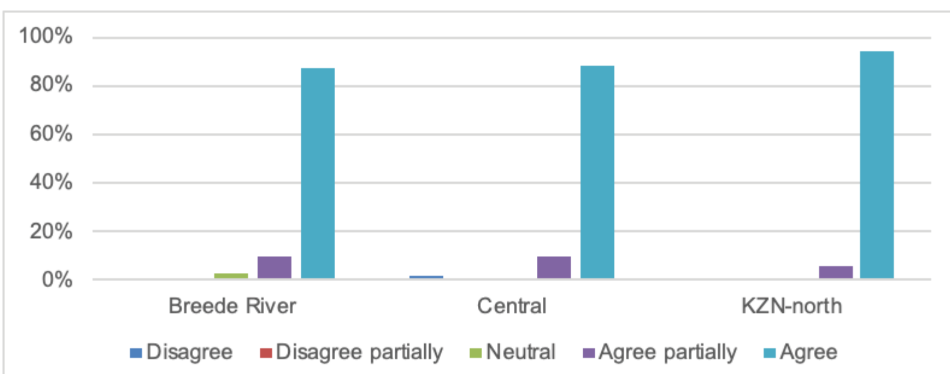


Figure 2.35 Comparison of perception that installation of an artificial drainage system can enhance leaching for the three target areas (χ^2 (8, N=116), P = 0.936).

2.3.5 Hypothesis 4: The benefits of preventative and corrective measures do not outweigh the cost of implementation

Respondents' perceptions regarding the elements relating to the relative cost of preventative and corrective management practices that can be taken on saline soils were measured (Table 2.7). The test shows that the percentage of respondents agreeing with the statement exceeded the threshold of mean plus 1 multiplied by the standard deviation. Two out of three statements indicated agreement, and the null hypotheses is therefore rejected. Only three elements were used to test for the rejection or non-rejection of this hypotheses, and the inclusion of more test elements could have given a different result.

Table 2.7 Percentage of respondents who perceive that the results of preventative and corrective measures outweigh the cost of implementation (boundary of acceptance = 84%)

Indicator	Breede River	Central	KZN-north
Application of salinity preventative measures is relatively cheap provided that drainage is not included	73%	57%	68%
Applying salinity management practices will be to my advantage because of an increase in crop production	95%	98%	100%
Adapting my irrigation system to manage the effects of shallow water table is worth it	85%	91%	97%

Salinity preventative measures are relatively cheap: In all three regions, the respondents agreed that salinity preventative measures are cheap, if the installation of drainage systems is unnecessary. However, the agreement is less than the threshold level of mean plus 1 multiplied by the standard deviation (Figure 2.36). The level of disagreement and neutrality or non-decisiveness indicates that some uncertainty surrounds this statement. Future messages to the communities should include case study calculations of cost-advantage and/or partial enterprise budgets to alleviate the present level of uncertainty.

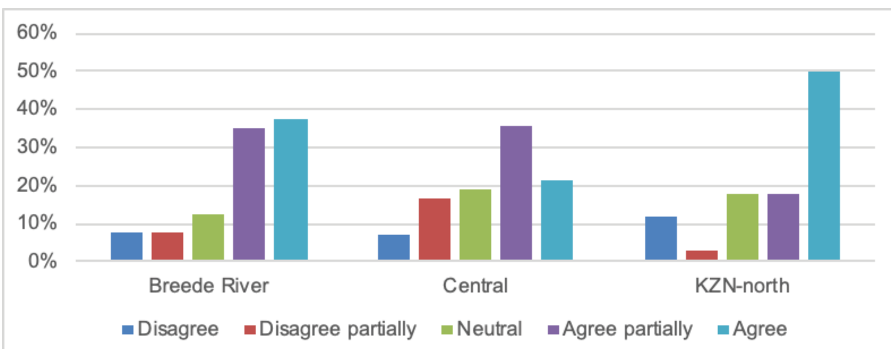


Figure 2.36 Comparison of perception that application of salinity preventative measures is relatively cheap if drainage is not included for the three target areas (χ^2 (8, N=116), P = 0.142).

Salinity management practices will be to my advantage because of an increase in crop production: The respondents of the three regions agreed that salinity management practices will lead to an increase in crop production (χ^2 (8, N=116), P = 0.705) (Figure 2.37). The agreement is greater than the threshold level of mean plus 1 multiplied by the standard deviation.

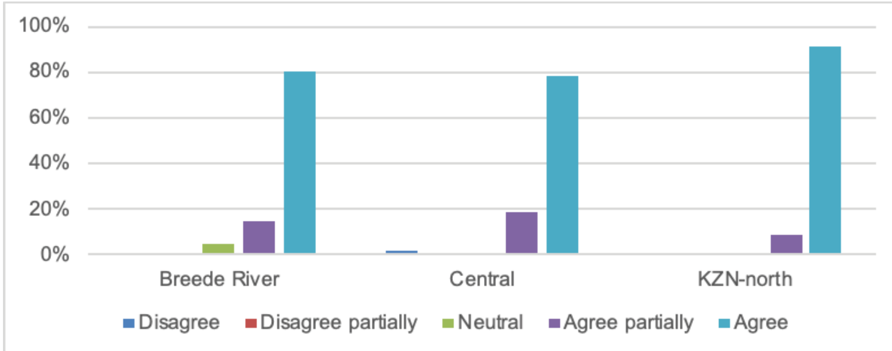


Figure 2.37 Comparison of perception that applying salinity management practices will be to my advantage because of an increase in crop production for the three target areas (χ^2 (8, N=116), P = 0.705).

Adapting my irrigation system to manage the effects of shallow water table is worth doing: Respondents of the three regions agreed that adapting their irrigation system to manage the effects of shallow water table is worth doing, although the level of agreement differed across regions (χ^2 (8, N=116), P = 0.004) (Figure 2.38). Agreement with the statement is beyond the threshold level mean plus 1 multiplied by the standard deviation.

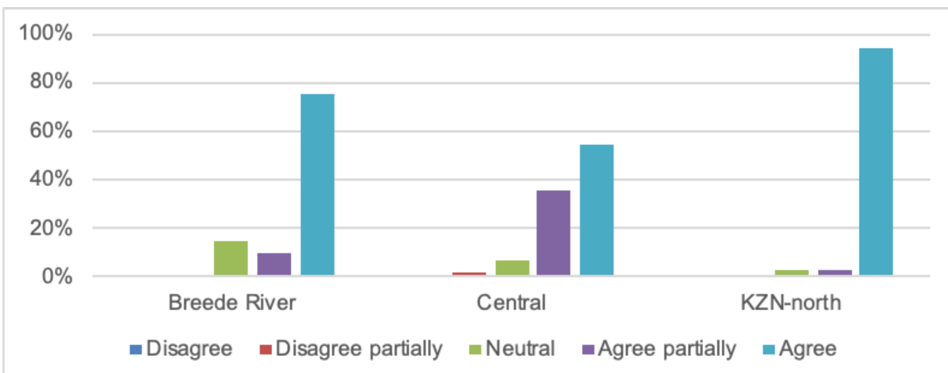


Figure 2.38 Comparison of perception that adapting my irrigation system to manage the effects of shallow water table is worth it for the three target areas (χ^2 (8, N=116), P = 0.004.

2.3.6 Hypothesis 5: The benefits of preventative and corrective measures do not outweigh the implementation effort

Respondents' perceptions regarding the indicators relating to the effort to implement preventative and corrective management practices on saline soils was measured (Table 2.8). The test shows that in one of these elements – corrective measures for salinity can be tested on a small scale – only one region agreed at mean plus 1 multiplied by the standard deviation level. Similarly, only the Breede region agreed that it would be easy to adjust irrigation scheduling as a management practice. Generally speaking, the respondents did not agree, and therefore null hypothesis 5 is not rejected.

Discussion of the individual elements follows.

Corrective measures for salinity can be tested on small scale: The respondents from the three regions agreed that salinity preventative and management practices can be tested on a small scale before full implementation (χ^2 (8, N=116), P = 0.884) (Figure 2.39). The possibility of testing on a smaller than full application scale is useful, because the farmer can then observe the effects of the application of salinity management practices before deciding on full application (Rogers, 2003).

Table 2.8 The percentage of respondents who perceive that the results of preventative and corrective measures outweigh the effort of implementation (boundary of acceptance = 84%)

Indicator	Breede River	Central	KZN-north
Corrective measures for salinity can be tested on small scale	85%	83%	97%
Application of salinity corrective practices will not disrupt farming activities	76%	69%	68%
Salinity corrective management practices are easy to apply	48%	43%	58%
I can manage salinity corrective practices	78%	71%	71%
Adjusting irrigation scheduling for salinity management is easy	88%	69%	76%

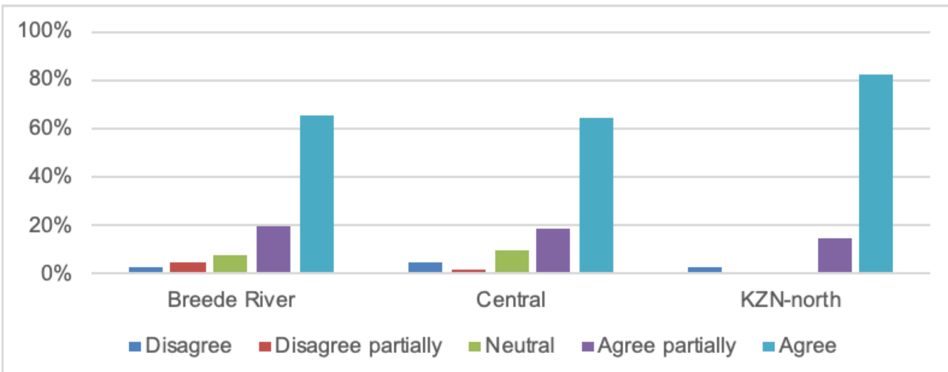


Figure 2.39 Corrective measures for salinity can be tested on small scale (χ^2 (8, N=116), P = 0.884).

Application of salinity corrective practices will not disrupt farming activities: Not all respondents of the three regions are convinced that the application of salinity preventative and management practices will not disrupt their farming activities, with answers somewhat differing between regions (χ^2 (8, N=116), P = 0.085) (Figure 2.40). The installation of drainage systems could be disruptive, depending on the intensity of installation of drainage systems. However, if that is not necessary, and management practices are limited to changes in irrigation scheduling, the selection of saline-tolerant crops, and the application of ameliorants, will result in a minimal disruption of farming activities.

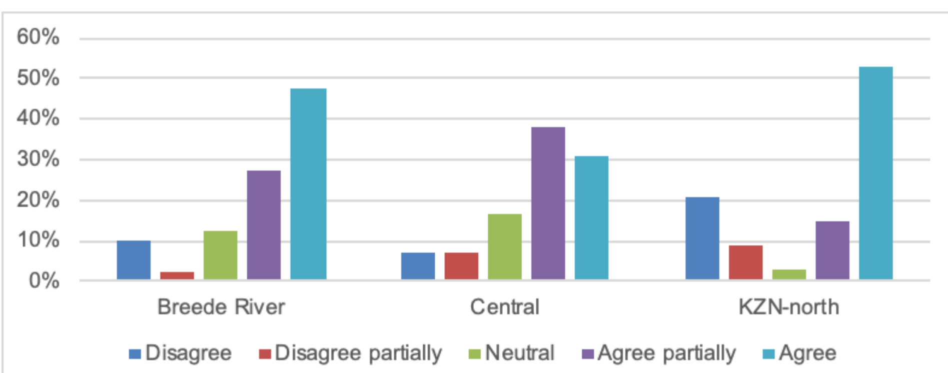


Figure 2.40 Application of salinity corrective practices will not disrupt farming activities (χ^2 (8, N=116), P = 0.085).

Salinity corrective management practices are easy to apply: The respondents' reaction to this statement that salinity corrective and management practices are easy to apply, are less than the threshold value of 84% which would indicate acceptance of the application of such practices. The range of responses from agreement to disagreement indicate a measure of uncertainty, probably the result of insufficient knowledge and lack of experience (χ^2 (8, N=116), P = 0.638) (Figure 2.41).

I can manage salinity corrective practices myself: Most of the respondents of the three regions agree that they can manage salinity problems (Figure 2.42), but the numbers that agreed do not reach the threshold value of 84% to indicate community agreement. This indicates some uncertainty amongst the respondents about their own ability to manage salinity corrective and management practices on their own. This is a problem that could be relieved by extension programmes aimed at increasing the knowledge of the actions required to handle this situation.

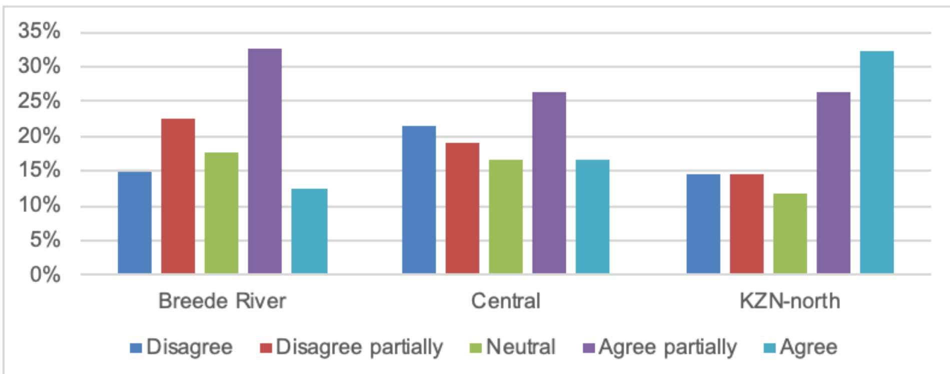


Figure 2.41 Salinity corrective management practices are easy to apply (χ^2 (8, N=116), P = 0.638).

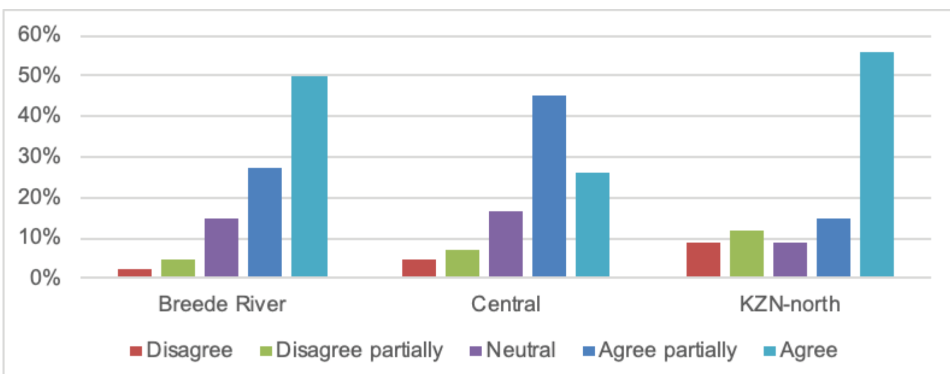


Figure 2.42 I can manage salinity corrective practices myself (χ^2 (8, N=116), P = 0.079).

Adjusting irrigation scheduling for salinity management is easy: Most respondents of the Breede River and Central areas agree they can adjust their irrigation scheduling to manage salinity problems, while the KwaZulu-Natal north group agreed to a lesser extent. The survey did not cover the reasons for such a difference could be found amongst respondents of the different areas (Figure 2.43).

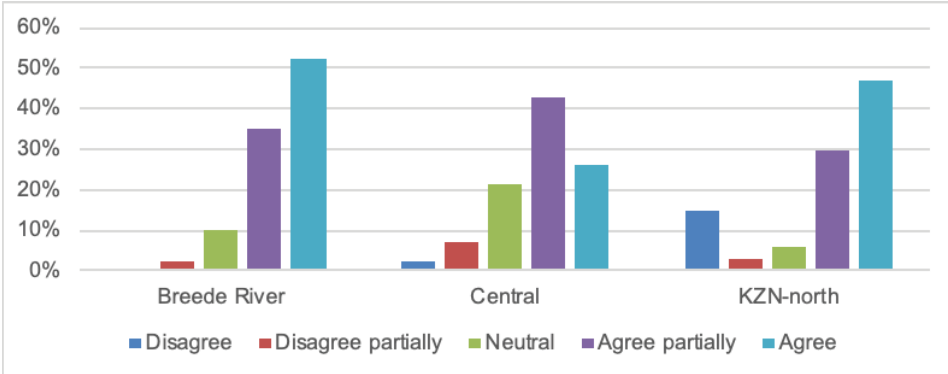


Figure 2.43 Adjusting irrigation scheduling for salinity management is easy (χ^2 (8, N=116), P = 0.033.

2.4 Discussion

2.4.1 Socio-economic

Literature suggests that farmers who adopt innovations at an early stage tend to be younger, more educated, have higher incomes, have larger farm operations and are more reliant on primary sources of information (Rogers, 2003). The relatively young age (31 to 50 years), high training levels (mainly diploma and B-degree) and number of years' experience (mostly 11 to 30 years) found amongst the three groups could be the reason why these respondents appear to be successful farmers. These characteristics of the respondents also predict that an agricultural expert could successfully introduce innovations into such communities.

Land tenure and scale of farming operations tend to also inform willingness and capability to invest or investigate innovations. The irrigated area per owner has increased over time under pressure of the need to increase enterprise size to remain profitable – referred to as advantage of scale (Olsen et al., 2006) – which gives the bigger farmers a greater bargaining power for accessing expert advice and for funding. An example of such consolidation is found in the Vaalharts Irrigation Scheme where the original irrigation farms were 25 morgen (21.4 ha) per owner (Van Vuuren, 2010), and which has increased to the present size of 201 to 500 ha per owner for most farmers. Most of the irrigated land is owned by the farmers. The spread of land ownership size is non-homogeneous amongst the three areas, with a tendency towards smaller irrigated fields or farms in the Breede River and larger fields in the central and northern KwaZulu-Natal areas.

Based on the results above, the majority of the farmers surveyed in the sample should be relatively well positioned to receive Level 1 information, and to adopt better salt management practices. Younger farmers, with higher levels of education and higher income or larger farm operations, are good indicators of where Level 2 interventions could possibly be appropriate.

2.4.2 Knowledge levels and current practices relating to salinity

The study revealed several knowledge gaps. A large portion of respondents did not know the soil form (as per binomial classification), soil salinity status, or the quality of irrigation water used on their respective farms. There was also a fair amount of uncertainty when reporting the effective depth of irrigated soils. The threshold values of the parameters used to diagnose salinity and sodicity were also not known by almost all of the respondents.

Knowledge about the soil forms and the perceived effective soil depth was significantly different amongst the 3 target areas. For soil form, the difference in knowledge levels was attributed to a localised soil classification system encountered in the Breede River, alluding to the importance of indigenous knowledge when providing advisory services or conducting knowledge exchange interventions in this specific area. Similarly, in northern KwaZulu-Natal, the respondents perceived a higher proportion of shallower soil depth (47% at 0.1-0.6 m and 26% at 0.7-1 m) relative to the other areas. While acknowledging that this data represents respondents' perceptions (which may or may not be a reflection of the actual soil depth), it does highlight that shallow soils indicate a higher susceptibility/risk to damage from salts and a need for more skilful management of irrigation. Choice of irrigation systems and strategies will also be more important on shallow soils, such as those perceived by the farmers in northern KwaZulu-Natal. Hence, identification of high-risk farms that are inherently susceptible or already being impacted by salinity can help to direct where behaviour change efforts are needed the most, especially when the situation is compounded by low levels of knowledge about the soil and its inherent susceptibility and/or need for more skilful management.

In terms of knowledge relating to soil salinity status and the threshold values for diagnostic parameters, there were no significant differences across the regions, indicating a consistency in the knowledge gap. Considering that a larger proportion of respondents indicated visible signs of salts on their farms (60, 50 and 79% in the Breede River, Central and northern KwaZulu-Natal regions, respectively), this knowledge gap should be a concern. If salinity were a viable problem, one can expect farmers to be more knowledgeable on the topic. Many farmers, however, indicated that they did not need to know the exact numerical values or the critical threshold values of salt indicator/diagnostic parameters. Respondents indicated that the soil laboratory report will highlight the problems for them, or agricultural advisors and consultants were often appointed to assist with interpretation of soil test results and recommendations.

Over and above knowledge levels, the study also provided insight into irrigation practices related to salinity management. While the larger proportion of respondents made use of scientific methods to schedule irrigation, a sizeable percentage depended on their own experience only, to guide scheduling decisions. Similarly, substantial portions indicated that they do not practice leaching of salts with irrigation (58% – Breede River, 43% – Central region and 88% – northern KwaZulu-Natal) and that they were unsure if leaching were a good practice (38% – Breede River, 45% – Central region and 56% – northern KwaZulu-Natal). The results for not practising leaching and not knowing if leaching were a good practice were significantly different across the regions with northern KwaZulu-Natal having higher levels relative to the other areas. The farmers in KwaZulu-Natal suggested that summer rainfall was often adequate to leach unwanted salts away from the root zone.

2.4.3 Information sources / technology transfer

Behaviour and choice of action in the context of farming practices can be strongly influenced by the information made available to farmers. In addition, low levels of knowledge (which can easily occur in isolated rural areas), can lead to inefficient, harmful and misguided farming practices (Leeuwis; 2004; Adendorff et al., 2016). Understanding the preferred sources through which farmers obtain information is therefore key. Table 2.9 depicts the ranking of information sources, both in terms of frequency of use and importance to the respondents. Agricultural advisors were ranked as both the most used and most important source. Compared to these, magazines, while a well-used source, are not considered to be very important. Planners of technology transfer strategies should take note of the preferred information sources in Table 2.9 and should preferably make use of combinations of these to communicate with farmers. There are various role players in the agricultural advisory field and the aim should be that these different advisors disseminate the same messages. One possibility of coordination would be to establish working groups consisting of different role players for a specific area. These working groups could plan and execute coordinated advisory strategies.

Table 2.9 Proportion of respondents (%) who indicated that the information source is used regularly and ranked as important (based on results shown in Figure 2.20 and Figure 2.21)

Source	Regular information source			Importance of source		
	Breede River	**Central**	**KwaZulu-Natal**	**Breede River**	**Central**	**KwaZulu-Natal**
Agricultural advisors	70	83	85	55	67	91
Soil laboratories	65	69	88	38	50	97
Fertiliser company personnel	60	86	58	35	62	58
Farmers' days	38	67	70	30	50	73
Electronic media	45	45	70	30	19	70
Magazines	50	55	52	30	17	42

2.4.4 Hypotheses

Hypothesis 1: Farmers do not perceive soil salinity as a threat

The results show that most respondents see soil salinity as a threat to their continued existence. They agreed that salinity leads to:

- Less water available for crops on saline soils;
- Reduced germination;
- Reduced uptake of plant nutrients;
- Reduced uptake of water; and;
- Variation of veld plants is less on saline soils.

All these result in a reduction in plant production, which could reduce the viability of their farming enterprises, and this hypothesis was thus rejected.

There were some elements, of which the respondents seemed less sure:

- Slower infiltration;
- Increased uptake of some nutrients;
- Reduced production of natural veld.

Since respondents were less sure that these elements need attention and should be included when planning technology transfer interventions:

- The differences in infiltration rate between saline and sodic soils because of the dispersion of soil particles usually associated with sodic soils.
- The uptake of some nutrients associated with high pH soils to toxicity levels. This problem is perhaps limited in scope because boron which is the only nutrient that could become toxic is not crucial, except for irrigation farmers that are situated in a boron-problem area.
- The effect that saline soils have on natural vegetation, both in production and in limiting the variety of plants. While this does not affect the irrigator directly, it is a good indicator of the chemical status of soils where new irrigation development is being considered.

Hypothesis 2: Farmers do not understand the causes of salinity

Most of the respondents seem to understand the causes of salinity, therefore this hypothesis was rejected. Elements tested are:

- Irrigation with poor quality water can enhance salinisation;

- Poor irrigation management can enhance salinisation;
- Mineral salts are a natural constituent of soil;
- Soil surface evaporation can lead to an increase in the salt in the upper soil layer.

While it appears that the respondents understand the causes of salinity and there is less need for communication on this topic, we recommend that the causes of salinity are regularly included in communications to prevent the farmers from forgetting these factors.

Hypothesis 3: Farmers do not know preventative and corrective management practices that can be taken on saline soils

The respondents in all three groups were sure about the following elements:

- Soil salinisation can be prevented by applying correct irrigation scheduling.
- Installation of an artificial drainage system can enhance leaching.

Farmers were uncertain about:

- Planting of salt tolerant crops.

This hypothesis was rejected; farmers indicated that they are aware of the preventative and corrective management practices that can be taken on saline soils. However, it is worth noting that while the respondents claim to have the knowledge, earlier questions suggest that a substantial portion of the respondents were still not scheduling irrigation scientifically or tracking the quality of irrigation water or applying leaching. Knowledge of preventative and corrective practices were not necessarily accompanied by implementation. Furthermore, due to the uncertainty amongst respondents, there is a need for special attention in the transfer of technology concerning salt tolerant crops:

- The planting of alternative salt tolerant crops as a strategy to manage/reclaim saline soils can be included in communication interventions. Content can include information on which crops are salt tolerant and enterprise budget comparison to compare profitability of different crops to help farmers better decide what to cultivate under their circumstances.

Hypothesis 4: Benefits of preventative and corrective measures do not outweigh the cost of implementation

Most respondents indicated that it was worth the cost to apply corrective and management practices for salinity, therefore this hypothesis was rejected. The elements that the respondents are sure of, include:

- Applying salinity management practices will be to my advantage because of an increase in crop production;
- Adapting my irrigation system to manage the effects of shallow water table is worth the cost.

The one element that respondents were less sure of:

- Application of salinity preventative measures is relatively cheap if drainage is not included.

This element is key and highlights the cost of drainage as a barrier to adoption. Technology transfer interventions should include comparative cost-estimates for salinity management when drainage systems are not required or already in place.

Hypothesis 5: Benefits of preventative and corrective measures do not outweigh the implementation effort

Most of the respondents showed uncertainty, therefore this hypothesis is accepted. Elements on which there is less agreement are:

- Corrective measures for salinity can be tested on a small scale;
- Application of salinity corrective practices will not disrupt farming activities;

- Salinity corrective management practices are easy to apply;
- I can manage salinity corrective practices myself;
- Adjusting irrigation scheduling for salinity management is easy.

Respondents were not sure and agreed to a lesser extent that salt management practices were easy to apply or that practices will not disrupt farming activities. In other words, the participant farmers were not convinced, or unsure, whether the effort to implement salinity preventative and corrective measures was worth it. This suggests a lack of confidence rather than a lack of knowledge. If farmers doubt whether the benefit will outweigh the implementation effort, then there is a need to allow farmers to gain practical experience with the specific practice, so that it can be fairly judged against realised benefits. During technology transfer activities, the uncertainty shown above needs to be addressed by:

- Discussion, possibly with case study examples and practical insight, on the amount of disruption or non-disruption that can be expected when applying different levels of salinity management practices.
- Demonstration of the relative advantage and ease of application of salinity management practices, possibly with case study examples on local farms.
- Practical training interventions on the salinity management practices that can be applied by the farmer and who the farmer could contact for management advice and support.
- Encouraging and supporting experimental testing of salinity management practices on smaller scales, at lower risk.

2.5 Conclusions

The acceptability of farmers' knowledge (or lack thereof) about the salt status of their soils, irrigation water and diagnostic parameters is debatable. Farmers suggest that they have advisory consultants to help, therefore there is less need for them to be knowledgeable on the specifics of the subject. For this reason, the benefit of growing knowledge levels only is uncertain. In past research, Ghadim and Pannell (1999), Pannell (1999), Marra et al. (2003) and Pannell et al. (2006) described adoption as a multi-stage learning and decision process involving "information acquisition" and "learning by doing" in order to systematically reduce perceptions of risk and uncertainty. This idea is corroborated by Annandale et al. (2011) who proposed that experiential learning initiatives, amongst others, were required to improve adoption of better management practices.

Therefore, in alignment with the literature, the hypotheses' results also suggest that more than just information sharing is required. Behaviour change initiatives need to engage at the level of implementation. Implementation at the farm or field level in a case study context is required to reassure/convince farmers of the economic viability, the practical realities linking to the disruptive or non-disruptive nature of salt management practices and/or the skill and effort required to implement salt management practices. On-farm testing, demonstration plots, hands-on training interventions or allowing farmers to learn from fellow farmers via farm visits and technical tours are higher leverage pathways to stimulate uptake and adoption. Purposeful and deliberate effort is also required to establish examples of implementation and to gather and make accessible the relevant economic and practical information to larger farmer groups.

CHAPTER 3. SUGARCANE CASE STUDIES ON SOIL SALT DISTRIBUTION AND YIELDS

3.1 Introduction

The sugarcane industry employs 85000 people directly and an estimated 350000 are indirectly employed. Approximately one million people (or 2% of South Africa's population) depend on the sugarcane industry for a living. Annual income for the industry is estimated at more than R14 billion. The industry has a total of 22949 registered sugarcane growers farming on 365000 ha of which approximately 75% is rainfed (SASA, 2019). The remaining 25% under irrigation produces about 43% of the total annual crop (calculated from SASA, 2019).

Sugarcane is grown in the northern parts of Eastern Cape, KwaZulu-Natal and the most Eastern parts of Mpumalanga (Malelane and Komatipoort). Classification of the climate in this region is humid subtropical (Cfa) according to the Köppen-Geiger system (https://www.britannica.com/science/Koppen-climate-classification). This means the minimum temperature of the warmest month is greater than or equal to 10°C, and the maximum temperature of the coldest month is less than 18°C but greater than -3°C. The mean temperature of the warmest month is 22°C or higher. In South Africa, rainfall of at least 600 mm/annum is required to produce a crop. The norm, however, is more than 750 mm annum^{-1}. The annual water requirement (evapotranspiration) for sugarcane ranges from 1100 to 1800 mm depending on the location and climatic conditions (Carr and Knox, 2011). Sugarcane in these regions is produced with full irrigation due to insufficient rainfall.

Maud (1959) reported that the occurrence of alkali (sodic) and saline soils was uncommon back then in the sugarcane region of KwaZulu-Natal and only two areas of severe alkalisation were known. One being in the Heatonville district just west of Empangeni and the other in Nkwaleni, about 40 km west of Empangeni. The Heatonville soils are on Beaufort sediments and the Nkwaleni region comprises mainly Beaufort derived alluvial soils (Maud, 1959). Soils associated with Beaufort sediments was characterised as having the potential to become sodic (Beater, 1970). Today the occurrence of salt affected soils is much more common. MacVicar and Perfect (1971) reported that 20% of irrigated land in the sugar industry is adversely affected by waterlogging or salinity or both. Applying the 20% value to the area irrigated today, it is estimated that about 21000 ha under sugarcane is affected. It is plausible to assume that the problem could have grown substantially since the 1970's but there was no further quantifiable work on salinity and sodicity documented in the literature for the sugarcane industry. Reinders et al. (2016), however, noted that rising water tables is a problem and there is dramatic need for subsurface drainage in large sugarcane irrigated areas of the Pongola mill supply area. Reasons for the water table problem are not clear, but Jumman (2016) noted that the poor adoption of irrigation scheduling in the region is a concern.

3.2 Literature study

Sugarcane is regarded as moderately tolerant to salinity (United States Salinity Laboratory Staff, 1954; Tanji and Kielen, 2003) but less tolerant to sodicity (Nelson and Ham, 2000; Workman et al., 1986) and the degree of sensitivity varies between varieties and even from crop to crop (Alam et al., 2018). Excess sodium in plant tissues increases the utilisation of energy that plants must use to acquire water from the soil and to make biochemical adjustments leading to reduced growth and yield (Yeo, 1983). Workman et al. (1986) found that sugarcane yield decreased from 84 t ha^{-1} to 66 t ha^{-1} over a period of 10 years on a saline-sodic soil. However, following the installation of a subsurface drain, the application and incorporation of gypsum and filtercake (an organic by-product from sugarcane mils) followed by leaching, improved yield to 75 t ha^{-1} over the next 10 years. Salt tolerance information (salinity threshold, slope and tolerance ratings) for sugarcane is given in Table 3.1. Salt tolerance information pertaining to maize, cotton and sugar beet is also given in order to put sugarcane values in perspective (Tanji and Kielen, 2003).

Table 3.1 Salinity threshold, slope and tolerance ratings for selected crops. Adopted from Tanji and Kielen (2003)

Common name	Botanical name	Tolerance based on	Threshold (EC_e) mS m-1	Slope % per 100 mS m-1	Tolerance rating
Maize	Zea mays L.	Ear fresh weight	170	12	Moderately sensitive
Cotton	Gossypium hirsutum L.	Seed cotton yield	770	5.2	Tolerant
Sugar beet	Beta vulgaris L.	Storage root	700	5.9	Tolerant
Sugarcane	Saccharum officinarum L.	Shoot dry weight	170	5.9	Moderately sensitive

Sodic layers deeper than 60 cm are generally considered not to restrict sugarcane growth, but may reduce drainage through the profile (Ham et al., 1995). Nelson and Ham (1998) reported that sugarcane yield was best correlated with exchangeable sodium percentage (ESP) of the 25-50 cm depth layer. In general sugarcane yield decrease linearly at a rate of 1.5 t ha^{-1} (Spalding, 1983) to 2.4 t ha^{-1} (Nelson and Ham, 1998) for every 1% increase of ESP and no yield was obtained at ESP > 60.

Johnston (1977) reported on the reclamation of a saline sodic soil in the Nkwaleni valley where the soils are mostly derived from alluvial Beaufort sediments which are known to be a source of Na salts (Maud, 1959). The initial pHwater, electrical conductivity of the saturated paste (EC_e) and sodium adsorption ratio (SAR) of the 0-36 cm soil layer was 7.2, 770 mS m^{-1} and 18.4, respectively. Additionally, to drainage control, gypsum (31 t ha^{-1}) and sulphur (6 t ha^{-1}) were separately added to compare their efficiencies in ameliorating the soil. Followed over a period of 6 years the effect of gypsum and sulphur on soil EC_e did not differ from that of the control (drainage only) for both the 0-36 cm and 36-90 cm depths. The sulphur treatment was the only treatment to lower soil pH in the surface layer significantly. Both gypsum and sulphur treatments reduced the SAR significantly, relative to the control in both depths. Water infiltration rates relative to the control treatment were increased by factors of 2.63 and 2.32 for the sulphur and gypsum treatments, respectively. Sugarcane stalk yield of the plant crop was significantly increased by 16 t ha^{-1} and 22 t ha^{-1} for the sulphur and gypsum treatments respectively. In the first ratoon crop yield, response to both sulphur and gypsum treatments relative to the control was significant at 17 tons cane ha^{-1} (Johnston, 1977).

The reclamation work in the Pongola district by Swinford et al (1985) had treatments similar to those described above and a few others, which include sulphuric acid (8.5 and 17 t ha^{-1}), filtercake (FC, 350 t ha^{-1}) and a combination treatment consisting of gypsum and FC (G+FC). The initial pHwater, EC_e and SAR of the 0-30 cm soil layer was 9.0, 138 mS m^{-1} and 13.6 respectively. Monitored over a period of 6 years EC_e for treatments, except sulphur, were similar to that of the control. EC_e of the sulphur treatment was for most of the time significantly higher than that of the control and no explanation for this behaviour was offered. The behaviour of sulphur was not noticed in the 30-90 cm depth. The pH values of the soil for all treatments were similar to that of the control over the entire period for both depths. Soil pH of the surface layer did start to drop and final values recorded were in the region of 8.8. The authors concluded that drainage alone was responsible for this drop. With regard to SAR, all treatments followed the pattern of the control treatment (drainage only). SAR values from the FC, gypsum and sulphuric acid treatments were consistently lower than those of the control and had a final SAR value below 6. A similar trend was noticed for the 30-90 cm depth where the SAR values for all treatments were initially above 20. Although all treatments showed a slow but consistent lowering of SAR values, it is only those of gypsum and sulphuric acid that were below 12 for the final measurements. SAR of the control and FC was around 14 and that of the sulphur treatment approximately 16. The accumulative cane stalk yield response over 4 crops compared to the control treatment was 31, 25, 16 and -3 tons cane ha^{-1} for the FC, gypsum, sulphuric acid and sulphur treatments respectively (Swinford et al., 1985). At the current price of R558 per tonne of sugarcane stalks, the accumulated yield response of 31 t ha^{-1} is valued at about R17 298 ha^{-1}.

A common problem with irrigated fields is that there is a real danger of their becoming salt affected (Bauder et al., 2014). Sources of salts in soils include quality of the irrigation water (Fipps 2003; UNEP 2007), over irrigation (Joshi and Nail, 1980), lack of sufficient drainage (Johnston, 1977; Reitz et al., 2001) and salt carrying parent materials (Maud, 1959, Beater, 1970; Johnston, 1980). Rivers are recognised source of salts in the sugarcane industry of KwaZulu-Natal (Van der Laan et al., 2012). With the sugarcane industry located on the eastern seaboard of South Africa it is often the case that the most eastern crop receives the poorest quality water from the rivers which is a result of various anthropogenic activities in the westerly regions of catchments (Van der Laan et al., 2012). These authors recommended that the sodicity hazard should be managed in the lower parts of catchments served by the Komati-Lomati and Pongola rivers.

An essential prerequisite for sustainable production under irrigation is that the soil must be naturally well drained or artificially drained to avoid the accumulation of salts in the soil (Workman et al., 1986; Rietz et al., 2001; Waskom, 2012). Thus, failing to ensure that the land is well drained will eventually result in stunted growth and yield losses (Subbarao and Shaw, 1985; Rietz and Haynes, 2002). Most irrigated land in the sugarcane industry is not well drained and the potential for yield losses is a certainty. Solving the problem requires the installation of an artificial drainage system (Swinford et al., 1985; Reinders, 2010) followed by a reclamation procedure suited for the condition of the particular soil type. Salt-related problems in soils are high pH, high salts of Ca, Mg and K ions (saline problem) and high Na content (Bauder, 2014). Symptoms and causes of salinity, high pH, specific ion toxicity, and sodicity are frequently confused. Each of these conditions can have adverse effects on plant growth, but they differ significantly in their cause and relative impact. Effective management of these problems vary and require proper diagnosis (Waskom, 2012).

3.2.1 High pH

Problems usually arise when the pH(water) is higher than 7.8 (alkaline). This leads to reduced availability of nutrients such as zinc, iron and phosphorus. Deficiency symptoms in plants include yellow stripes on the middle to upper leaves (signs of zinc and iron deficiency) or a dark green or purple colouring of the lower leaves and stems (signs of phosphorus deficiency) (Waskom, 2012). The problem can be solved through the application of acidifying ameliorants such as sulphuric acid, elemental sulphur, aluminium sulphate, iron sulphate, most nitrogen fertilisers and organic mulches. Sulphuric acid will be quickest in lowering the pH, but will be expensive. The other ameliorants will be much slower and could take a year or longer to show a result.

3.2.2 Salinity

Plants growing in saline soils may appear water stressed in a soil that is relatively wet. This is because the high salt content of the soil reduces the osmotic potential between soil and root and, as a result, plants require more energy to take up water. Sometimes a white crust is visible on a saline soil surface. Plants that are sprinkler irrigated with saline water often show symptoms of leaf burn, particularly on young foliage (Waskom, 2012). Saline soils cannot be reclaimed by chemical amendments, conditioners or fertilisers as these will add salts which will aggravate the situation. A field can only be reclaimed by removing salts from the plant root zone (Bauder, 2014).

3.2.3 Options to remove salts from saline soils

- Salts can be moved below the root zone by applying more water than that which the soil can store (leaching requirement method).
- Combining the leaching requirement method with artificial drainage.
- Moving salts away from the root zone to locations in the soil with low rooting density and where they are not harmful (so-called managed accumulation method).
- Using crop residue to reduce evaporation losses, thereby limiting the upward movement of salt (from shallow, saline groundwater) into the root zone and reducing the application of salt carrying water. Evaporation and thus, salt accumulation, tends to be greater in bare soils. Fields require 30 percent to 50 percent residue cover to significantly reduce evaporation. These soils remain wetter for longer, allowing precipitation to be more effective in the leaching of salts, particularly from the surface soil layers where damage to germinating crops is most likely to occur.
- Salts are most efficiently leached from the soil profile under higher frequency irrigation (shorter irrigation intervals). Keeping soil water levels higher between irrigation events effectively dilutes salt concentrations in the root zone, thereby reducing the salinity hazard. Overhead systems (sprinkler systems, centre pivot and linear-move systems) configured with low energy precision application (LEPA) nozzle packages or properly spaced drop nozzles, and drip irrigation systems are the preferred options for this type of salinity management (Bauder, 2014).

3.2.4 Sodicity

In a limited number of C4 plants, Na has a very specific function in the concentration of carbon dioxide. The significance of the role of Na is also shown by the fact that the critical level of K is reduced in the presence of Na in many crops (Subbarao et al., 2003). However, high levels of Na interfere with K and Ca nutrition and disturb efficient stomatal regulation which results in a depression of photosynthesis and growth. Regarding the supply of nutrients, Na is often present in higher concentrations in the environment compared to K (Subbarao et al., 2003). Most plant species are not able to readily absorb Na, but readily absorb K and are termed “natrophobes” (Shone et al., 1969). Natrophobes with limited or no ability to compartmentalize Na expend substantial amounts of energy in preventing Na from entering the plant in order to survive in a saline environment (Subbarao et al., 2003).

A sodic soil condition is where Na is the dominant cation. The most visible sign is dispersion of aggregates at the surface which results in a surface crust leading to impaired infiltration rates, increased runoff and eventually erosion. Sodic soils can develop a brownish-black crust (black alkali) due to dispersion of soil organic matter at the surface. By the time darkened crusts are visible, the problem is severe and plant growth and soil quality are significantly impacted. Reduced seedling emergence and viability are also signs of the problem (Waskom, 2012).

Reclamation of a sodic soil requires more than the application of just water to leach the salt out of the soil as it will take much longer to lower the Na-salt to an acceptable level without the addition of an ameliorant (Johnston, 1977). Ameliorants often included in reclamation trials are sulphuric acid, sulphur and gypsum (Swinford et al., 1985; Johnston, 1977) and calcium chloride (Davis, 2012). For sulphuric acid and elemental sulphur to be effective, free lime (calcium carbonate or calcium bicarbonate) is required in substantial quantities in the profile to act as a source of Ca to replace Na from soil particles. Sulphuric acid will be the quickest to free Ca from the carbonates, but it is an expensive option. Elemental sulphur needs to be converted to sulphuric acid by microbes. To produce the quantities of sulphuric acid required to have a significant impact on Na replacement by Ca, might take months and, in some cases, years. Calcium chloride will also react quickly to replace Na from the soil particles, but it too is an expensive option. Gypsum is therefore the preferred ameliorant as it is a source of both Ca and sulphur and is relatively inexpensive (Davis, 2012). In efforts to reclaim sodic soils, organic residue, along with gypsum should be incorporated in the topsoil. The purpose of organic residues is to prevent the soil from forming a continuous crust and thus create pathways for water to enter the soil to facilitate leaching of the unwanted Na (Swinford et al., 1985; Davis, 2012).

3.2.5 Threshold values

Soil electrical conductivity (EC) values smaller than 200 mS m^{-1} in the top 450 mm soil layer were shown not to affect sugarcane growth, whereas sugarcane growth was drastically affected at values greater than 400 mS m^{-1} and growth was very poor (Table 3.2) or the cane died where EC was greater than 500 mS m^{-1} (Von der Meden, 1966). With regard to exchangeable sodium percentage (ESP), sugarcane growth is not affected where values do not exceed 10. Above an ESP of 10, growth seems likely to be impaired and above 15 seriously reduced (Von der Meden, 1966). In Australia, soils with an ESP value greater than 6 are considered to be sodic (Marchuk et al., 2014). In South Africa, the critical SAR values are 6, 10 and 15 for duplex soils (generally poorly drained, easily dispersed), Vertisols (slow draining black swelling clays) and Oxisols (well drained non-dispersive upland soils), respectively (Van Antwerpen, 2017).

Table 3.2 Effect of exchangeable sodium percentage and electrical conductivity of soils on the growth of sugarcane (modified after Von der Meden, 1966).

Exchangeable sodium percentage (ESP)	Electrical conductivity (mS m^{-1}) in top 450 mm soil depth	Effect on sugarcane growth
<10	<200	Not affected
10-15	200-400	Growth significantly reduced
>15	>400	Yields seriously affected

To quantify the quality of irrigation water in the sugarcane industry pH, EC and SAR are measured routinely. However, EC and SAR values in the irrigation water are adjusted to accommodate the diluting effect of local rainfall and irrigation on EC and the effect of Ca, Mg and carbonates on SAR. A pH value of 8.3 or greater is a signal to prompt analysis of the water sample for carbonates.

Rainfall and irrigation amounts are considered to calculate (Equation 4.1) the effective electrical conductivity (EEC, mS m^{-1}) of the irrigation water (United States Salinity Laboratory Staff, 1954; Johnston, 1979). Where EC is the electrical conductivity (mS m^{-1}), R the annual long-term mean rainfall for the region (mm) and It the annual total irrigation (mm).

$$EEC = \frac{(EC)(lt)}{(R)(lt)} \qquad (3.1)$$

To accommodate the effect of Ca, Mg and carbonates on Na concentration in water, the method by Suarez (1981), as reported by Landon (2014), is used to calculate the adjusted sodium adsorption ratio (ASAR). If calcium (and magnesium) plus bicarbonate ions are added to the soil by irrigation, the following reaction tends to occur (Equation 4.2).

$$Ca^{++} + 2HCO_3^- \rightarrow CaCO_3 \downarrow + H_2O + CO_2 \uparrow \qquad (3.2)$$

If the sample contains no carbonates, the numerical value of ASAR is equal to that of SAR. However, the presence of carbonates reduces the Ca load in the water and lowers the calculated value of SAR and the resultant ASAR value is then larger than the SAR value. The carbonate and bicarbonate hazards are quantified by the pHc value (Equation 4.3). The lower the pHc value, the greater the possibility for carbonate precipitation, where pHc is calculated from Table 3.3.

$$ASAR = SAR(9.4 - pH_c) \qquad (3.3)$$

$$pH_c = (pK_2 - pK_c) + p(Ca + Mg) + p(CO_3 + HCO_3)$$
$$pH_c = p(Ca + Mg + Na) + p(Ca + Mg) + p(CO_3 + HCO_3)$$

The EEC and ASAR threshold values used to assess the quality of irrigation water in the sugarcane industry are given in Figure 3.1 and the interpretation of the water classes is explained in Table 3.4 (Johnston, 1979; Van Antwerpen et al., 2013).

Table 3.3 Values for the calculation of pHc (Landon, 2014)

Sum of ionic concentration (me ℓ^{-1})	**Ca + Mg + Na**	**Ca + Mg**	**CO_3 + HCO_3**
0.05	2.0	4.6	4.3
0.10	2.0	4.3	4.0
0.15	2.0	4.1	3.8
0.20	2.0	4.0	3.7
0.25	2.0	3.9	3.6
0.30	2.0	3.8	3.5
0.40	2.0	3.7	3.4
0.50	2.1	3.6	3.3
0.63	2.1	3.5	3.2
0.75	2.1	3.4	3.1
1.00	2.1	3.3	3.0
1.25	2.1	3.2	2.9
1.50	2.1	3.1	2.8
2.00	2.2	3.0	2.7
2.50	2.2	2.9	2.6
3.0	2.2	2.8	2.5
4.0	2.2	2.7	2.4
5.0	2.2	2.6	2.3
6.0	2.2	2.5	2.2
8.0	2.3	2.4	2.1
10.0	2.3	2.3	2.0
12.5	2.3	2.2	1.9
15.0	2.3	2.1	1.8
20.0	2.4	2.0	1.7
30.0	2.4	1.8	1.5
50.0	2.5	1.6	1.3
80.0	2.5	1.4	1.1

3.3 Materials and methods

3.3.1 Description of the study sites

Two study areas were selected in the KwaZulu-Natal irrigation region to cover sugarcane. They were in the Mkuze (Case study 1) and Heatonville (Case study 2) regions and about 150 km apart. Both were selected based on data from the Fertiliser Advisory Service (FAS) laboratory at South African Sugarcane Research Institute (SASRI) showing the presence of saline-sodic and sodic soil conditions. This was confirmed with comments by the producers and a site inspection, which involved sample collection and analysis.

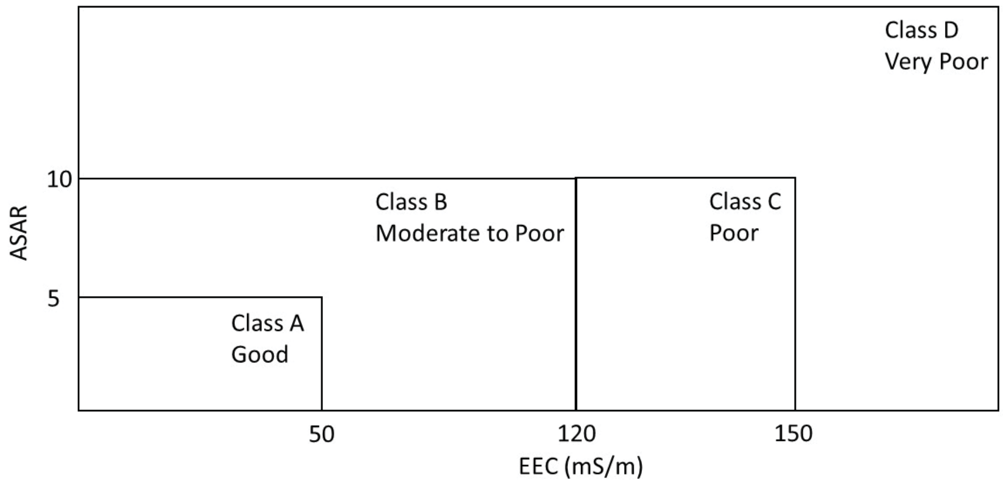


Figure 3.1 EEC and ASAR threshold values used to assess the quality of irrigation water in the sugarcane industry (Johnston, 1979; Van Antwerpen et al., 2013).

Table 3.4 Suitability classes for irrigation water (Johnston, 1979; Van Antwerpen et al., 2013).

Suitability class	Suitability for use as irrigation water
Class A	Suitable for use on all soils except those naturally containing high salt concentrations (derived from parent material) and a restrictive layer that prevents free percolation of water, unless drainage is installed
Class B	Suitable for irrigation on freely draining soils. In instances where Class B water has to be used on soils with restricted drainage, ensure that sufficient drainage is installed
Class C	Suitable for irrigation on freely draining soils provided better quality water is not available. It is important to note that using Class C water for irrigation can affect normal crop growth. Short term salt build-up in the soil is likely to occur particularly during drought periods, but the situation should improve after good rainfall. Particular care should be taken to avoid waterlogging
Class D	Unsuitable for irrigation under normal conditions

Case study 1 was in the Mkhuze district in the northern parts of KwaZulu-Natal at an altitude between 180 and 211 m above sea level. The area is warm and temperate with an average annual temperature of 21.8°C, the hottest being in February at 25.7 °C and coolest in July at 16.5 °C). The average annual precipitation is 592 mm of which 74% is received from October to March (https://en.climate-data.org/africa/south-africa/kwazulu-natal/mkuze-189645/#climate-table). The site is on the foot slopes of the Ubombo mountain range and the underlying parent material is basalt from the Lebombo group (Figure 3.2). The study area was irrigated with a centre pivot covering an area of 60 ha of which 45 ha was used in this study (Figure 3.3). The average slope of the selected field was 11%. The topsoil is dark in colour (predominant Munsell colour 2.5Y/2.5/1), has an average clay content of 58% and carbon content of 2% in the 0-300 mm layer. The site is relatively uniform and the soil from for the total site is a Bonhein (Soil Classification Working Group, 1991).

Case study 2 was in the Heatonville district near Empangeni at an altitude of 70 to 95 m above sea level. The underlying parent material is Beaufort sediments (Figure 3.2), which is known to be a source of Na-salts (Beater, 1970). The area is warm and temperate with an average annual temperature of 21.5°C, the highest being in January (around 25.2°C) and lowest in July (around 17.1°C) with an average annual precipitation of 1082 mm (https://en.climate-data.org/africa/south-africa/kwazulu-natal/empangeni-715226/). The annual water requirement (evapotranspiration) for sugarcane ranges from 1100 to 1800 mm depending on the location (climatic conditions) (Carr and Knox, 2011). Sugarcane in this region is grown with supplementary irrigation due to insufficient rainfall exacerbated by poor distribution during the growing season. The study area stretched over two half circle centre pivots covering areas of 54 ha and 68 ha of which 63 ha was used in this study (Figure 3.4). The larger centre pivot (upper half circle) is split by a high lying ridge, which acts as a watershed. The white areas (without a shade) in Figure 3.3 (left) indicate areas of a continuous catchment draining towards the South West. Only this area was used in this study. The site is highly variable and is represented by four soil forms Katspruit, Tukulu, Swartland and Willowbrook (Soil Classification Working Group, 1991).

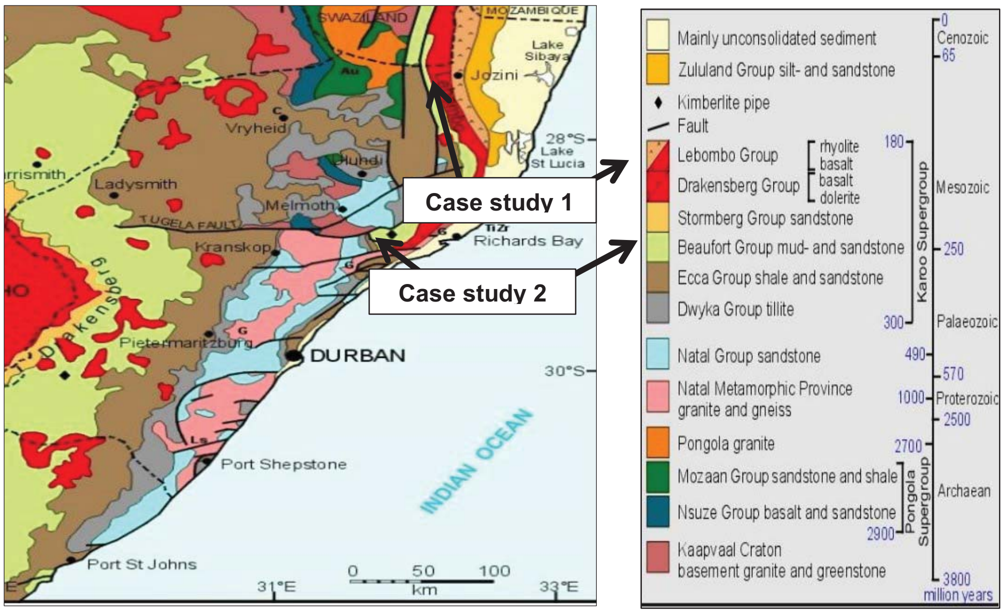


Figure 3.2 Geological map of Kwazulu-Natal showing the geology for most of the KZN region. (Source: http://www.stec.ukzn.ac.za/geologyeducationmuseum/).

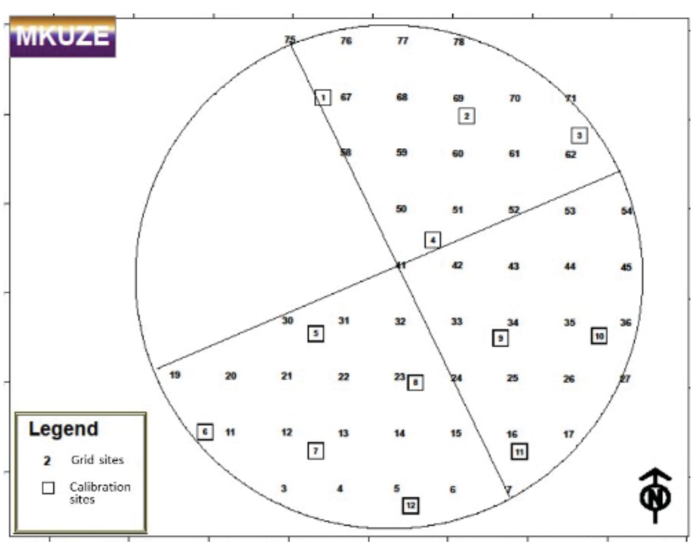


Figure 3.3 Map of case study 1 showing the details of the site divided into grid soil sampling positions and distribution of 12 sampling positions used for calibration.

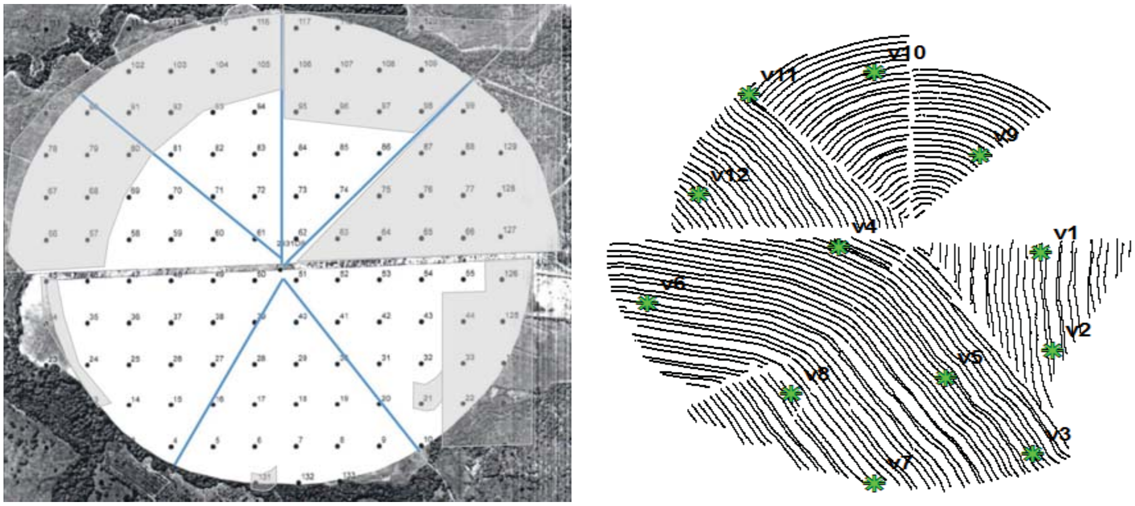


Figure 3.4 Map of case study 2 showing the details of the site divided into grid soil sampling positions (left) and distribution of 12 sampling positions used for calibration (right).

3.3.2 Data collection

3.3.2.1 Electromagnetic Induction survey

Electromagnetic induction (EMI) surveys were conducted on 17 July 2016 and 26 June 2017 (case study 1) and 10-12 October 2016 and 2-4 October 2017 (case study 2). The study sites were scanned with an EMI instrument (EM38-MK2) in both horizontal (depths 0-300 and 0-700 mm depths) and vertical (depths 0-700 and 0-1400 mm) dipole orientations, recoding apparent electrical conductivity (EC_a) in mS m^{-1} (Geonics, 2008). The instrument was carried in a non-metallic container, lifted about 80 mm above the soil surface and pulled 3 m behind a quadbike traveling at less than 8 km hr^{-1}, following sugarcane rows as shown by the travel paths in Figure 3.4 (right). Data from the EMI instrument was logged on a handheld Trimble Dgps Tsc3 controller linked to a Trimble GNSS receiver mounted on the quadbike. Geo-referenced coordinates were received from a stationary Trimble GNSS SPS851 base station. This system had a geo-referenced vertical accuracy of less than 20 mm. Both EC_a and GPS data were recorded at one-second intervals and stored on the controller unit. The number of data points recorded was at least 1200 ha^{-1}. In order to minimise the effect of soil water content on EC_a values, the EMI survey was conducted with no rain or irrigation at least three days before or during the survey. The lateral distance between the parallel travelled lines conducting the scan was 10 m and the total area scanned was 45 ha (case study 1) and 88 ha (case study 2). The data obtained were used to develop EC_a maps for three depth intervals (0-300, 300-600 and 600-900 mm). See Sections 2.1 and 2.2 for details in the second volume report (Van Rensburg et al., 2020b).

3.3.2.2 Soil sample collection and analysis

A 93 x 93 metre grid was super-imposed on the sites and soil samples collected from the geo-referenced grid points resulting at a sampling density of about one sample per hectare (Figures 4.3 and 4.4). The depth interval collection of soil samples from grid positions were guided by changes in clay content and colour to separate layers. The maximum sampling depth using a Thompson type soil auger with extensions was 3.2 metres. Because of the large number of grid samples, these were scanned by SASRIs FAS with a mid-infrared spectroscopy (MIR, Bruker Tensor II equipped with an HTS-XT auto feeder) instrument for clay content and soil organic carbon.

Data from the EMI survey was used to determine 12 EC_a-directed sampling sites (12 plots) from which soil samples were collected at depth intervals of 300 mm to a maximum depth of 1500 mm. These were analysed for salt parameters important to this project namely pH measured in water, EC_e (The Non-Affiliated Soil Analysis Work Committee, 1990), ESP calculated from cations extracted with AMBIC solution (0.25 M ammonium bicarbonate, 0.01 M diammonium EDTA1 and 0.01 M ammonium fluoride), SAR calculated from cations extracted with water and clay content determined with the pipette method (Gee and Bauder, 1986). These samples were also analysed for pH and electrical conductivity from a 1:5 soil-to-water ratio paste (Dellavalle, 1992) and Munsell soil colour was described (Munsell, 2009) for samples collected from the 12 plots.

EMI readings (EC_a values) were made at each plot the last two times it was sampled. Readings were made placing the EM38-MK2 instrument parallel to cane rows and perpendicular to the row direction in both the horizontal and vertical orientations. This data was regressed with the soil data to establish conversions of the EC_a data obtained from the bulk surface to a number of soil parameters (i.e. pH, EC_e, SAR, ESP, and cations). See Section 2.4 for details – Van Rensburg et al. 2020b.

At the end of each case study pits were opened at the 12 plots and disturbed and undisturbed samples collected at depth intervals of 0-300, 300-750 and 750-1000 mm. Steel containers with a capacity of 1000 mL were driven vertically into the soil to collect the undisturbed samples. These samples were used at Van's Lab to determine bulk density and saturated hydraulic conductivity (methods are described in Section 2.4 in Van Rensburg et al., 2020b).

3.3.2.3 Biomass collection and analysis

Biomass samples were collected within an area of 1 m^2 on three occasions from the 12 plots. These were separated into green leaves, brown leaves and cane stalks and analysed by FAS for their nutrient contents (N, P, K, Ca, Mg, S, Si, Na, Zn, Mn, Cu and Fe).

At the end of each case study 3 sugarcane rows of 10 m were harvested from the 12 plots and treated as 3 replications. Stalks were counted, stalk length measured, and biomass separated into green leaves, brown leaves and stalks. A subsample of each component was oven dried at 70°C to determine the moisture content and used to calculate the dry mass before being sent to FAS for analysis (see previous paragraph).

3.3.2.4 Water sample collection and analysis

Water used to irrigate case study 1 was sourced from the Pongolapoort dam. Water sample from case study 2 was collected from the canal carrying water for irrigation. For comparison rainwater was collected from four rain gauges spaced evenly outside the pivot area. Samples were analysed by FAS for pH, EC, K, Ca, Mg, Na and HCO_3 and used to calculate SAR, ASAR and EEC.

3.3.3 Statistical analysis

Statistical analyses included the mean, standard deviation (stdev), standard error (stder), slope, intercept and coefficient of determination (R^2) and were all calculated with Excel functions.

3.4 Results and discussion

3.4.1 Case study 1

Water quality: Quality of water from the regional dam used for irrigation is good with a C2-S1 USDA (United States Department of Agricultural) rating (United States Salinity Laboratory Staff, 1954) and an A SASRI rating (Johnston, 1979). The quality of water draining out of the soil is, however, poor with a C3-S3 rating and very poor with a D rating (Table 3.5). In this table the unit was converted to kg ha^{-1} assuming an annual application of 800 mm of the particular source. A concern is the application of 289 kg Na ha^{-1}, which is a non-essential element from the A rated water compared to only 13 kg K ha^{-1}, which is an essential element (Subbarao et al., 2003). Draining out of the soil is 3318 kg Na ha^{-1} and is an indication of the enormous in situ Na reserves of the soil. Every effort should therefore be made to drain the soil and to prevent Na-salt from reaching the surface via capillary rise and evaporation.

Table 3.5 Comparing the quality of water used for irrigation with that collected in an open drain. The conversion of meq ℓ^{-1} to kg ha^{-1} was based on an annual irrigation of 800 mm

Properties	Source					
	Unit	Dam	Drain	Unit	Dam	Drain
pH	-	7.04	8.03	pH	7.04	8.03
K	meq ℓ^{-1}	0.04	0.07	kg ha^{-1}	13	22
Ca	meq ℓ^{-1}	0.77	1.98	kg ha^{-1}	123	317
Mg	meq ℓ^{-1}	1.27	2.37	kg ha^{-1}	123	230
Na	meq ℓ^{-1}	1.57	18.04	kg ha^{-1}	289	3318
HCO_3	meq ℓ^{-1}	3.24	12.9	kg ha^{-1}	1582	6297
EC	mS m^{-1}	35	205	mS m^{-1}	35	205
EEC*	mS m^{-1}	18	103	mS m^{-1}	18	103
SAR	-	0.26	12.23	SAR	0.26	12.23
ASAR**	-	0.17	30.45	ASAR	0.17	30.45

* = Effective electrical conductivity taking the dilution effect of rainfall into account (United States Salinity Laboratory Staff, 1954; Johnston, 1979); ** = adjusted sodium adsorption ratio taking precipitation of Ca via HCO_3 into account (Abou El-Defan et al., 2016)

Soil analysis: The mean clay content was 58%, 59% and 56% for depth intervals 0-300, 300-600 and 600-900 mm, respectively (Appendix 3.1). The variation within depth intervals was relatively small with standard deviations of 5.5%, 12.0% and 12.5% and standard errors of 1.6%, 3.5% and 3.8% for the respected depth intervals. The mean pH (1:5 soil to water ratio) in the surface layer was 7.62 with only two plots (2 and 6) reflecting values higher than 8. In the next layer (300-600 mm), all but three plots (1, 11 and 12) had pH values higher than 8 (mean pH = 8.16) and in the 600-900 mm layer all values were higher than 8 and higher than 9 in plot 3 (mean pH = 8.80). The mean SAR at the surface was 4.63 with two plots (6 and 7) having values higher than the threshold value of 6. The mean SAR for the second depth interval (300-600 mm) was 8.97 with values below the threshold value only for plots 4 and 11. In the 600-900 mm depth interval the mean SAR was 12.51 with only plot 11 recording a value below the threshold. Standard deviations were 1.3, 3.2 and 3.8 and standard errors 0.4, 0.9 and 1.1 for the respected depth intervals. The mean ESP was at 7.4%, 13.6% and 25.2% above the threshold of 7% in all the depth intervals. Standard deviations were 1.7%, 5.9% and 7.3% and standard errors 0.5%, 1.7% and 2.1% for the respected depth intervals. See Appendix 3.1 for other soil information.

Biomass analysis: Samples collected at the age of 10.6 months and expressed in kg ha^{-1}, show that cane stalks are the dominant accumulator of all nutrients, except Ca and Si which is highest in brown leaves (Table 3.6; Appendix 3.2). However, Na is present in the lowest quantity both in terms of concentration (%) and amount (kg ha^{-1}) indicating that although Na might be present in large quantities in the soil (Appendix 3.1), it is not taken up in significant quantities by sugarcane.

Crop yield ranged between 68 and 152 t ha^{-1} and is an indication of the variable production potential of the field (Table 3.7). It has long been known that sugarcane yields are affected by salts in the soil. Stalk yield was regressed against ESP for three depths and all show a negative relationship (Figure 3.5).

Table 3.6 Analysis of biomass for its nutrient content in percentage and kg ha^{-1}

Part	N	P	K	Ca	Mg	S	Si	Na
	%							
Green leaves	1.014	0.141	1.610	0.330	0.269	0.227	1.387	0.032
Brown leaves	0.522	0.053	0.267	0.930	0.366	0.153	4.500	0.071
Cane stalks	0.520	0.088	1.041	0.076	0.172	0.189	0.335	0.007
Mean	0.685	0.094	0.973	0.445	0.269	0.189	2.074	0.037
Part	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Si**	**Na**
	kg ha^{-1}							
Green leaves	63	8	112	23	16	23	138	1.8
Brown leaves	40	3	19	62	23	9	364	2.7
Cane stalks	142	27	205	27	48	49	95	5.0
Total	244	38	336	112	86	80	597	9.5

Table 3.7 Sugarcane stalk yield (t ha^{-1}) for case study 1

Plot	1	2	3	4	5	6	7	8	9	10	11	12	Mean	Stdev	Stder
Yield	68	82	92	120	88	69	142	133	152	123	150	126	112	31	8.9

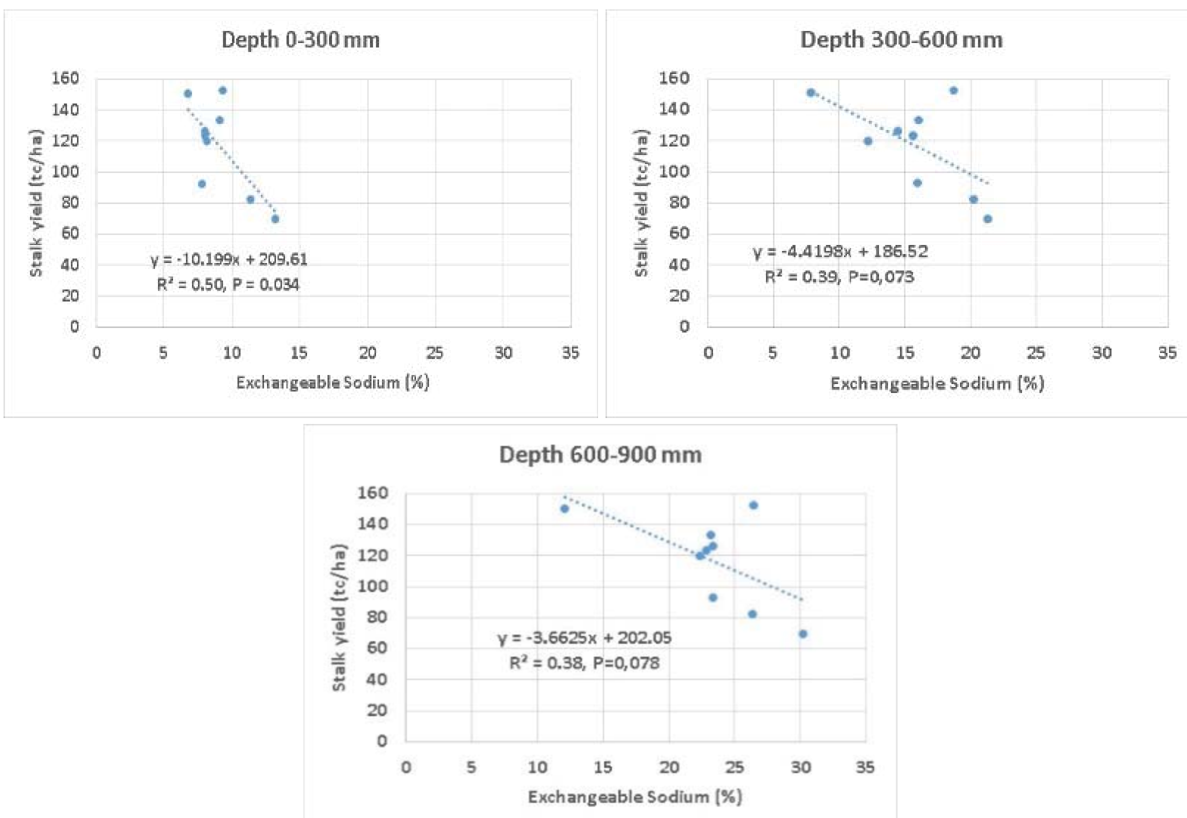


Figure 3.5 Regression between stalk yield and ESP for three depths. Note that the curves start at approximately the threshold value (7%) and that ESP increase with depth.

The slope of the regression for the surface layer indicates that 10.2 t ha^{-1} is lost for every 1% increase in ESP. Regression with ESP from deeper layers indicate losses of 4.4 t ha^{-1} and 3.7 t ha^{-1} for depths 300-600 mm and 600-900 mm, respectively. Thus, although salts are present in much higher levels in the subsoil, its effect on crop yield is much less compared to the relatively low salt levels in the topsoil. It is assumed that high concentration of roots in the topsoil layer make the crop very sensitive to the condition of this layer, relative to the deeper layers with a much lower presence of roots.

Salt distribution: The topographical results, i.e. contour lines (altitude), surface drainage lines, slope classes and aspect, are mapped in Figures 3.7 and 3.8, respectively. From the topographical features it is clear that the site has mainly a southwest aspect, with some smaller areas having western and southern aspect. The infield-slope classes vary between strongly sloping (1-4%) and moderately sloping (4-10%) and surface water drains in a south-western direction. The EC_a data of the 2017 survey was used for this report and the result of its distribution over the field is depicted in Figure 3.6. The results show that EC_a are highly variable over the site, with higher values around the southern and south-eastern edges of the pivot. The distribution of soil properties, derived from the EC_a-soil property models and then applied to the measured EC_a survey data, are also depicted in Figures 3.9 to 3.15. Bulk density increases with depth from a range of 1.25 to 1.59 g cm^{-3} in the 0-300 mm layer (Figure 3.10) and reaching 1.36 to 1.61 g cm^{-3} in the 300-600 mm layer (Figure 3.12) and 1.36 to 1.7 g cm^{-3} in the 600-900 mm layer (Figure 3.14), which is extremely compacted for a soil with a high clay content (Figures 3.10, 3.12 and 3.14). Salinity (as indicated by EC_e) is in places higher than the threshold of 200 mS m^{-1} for sugarcane but is not considered to be a major problem (Figures 3.11, 3.13 and 3.15). The real problem is the very high Na levels detected in the study site and expressed as ESP. It ranged from 9% to 15% in the surface layer, 13% to 25% in the 300-600 mm layer and 34% to 75% in 600-900 mm layer (Figures 3.11, 3.13 and 3.15, respectively).

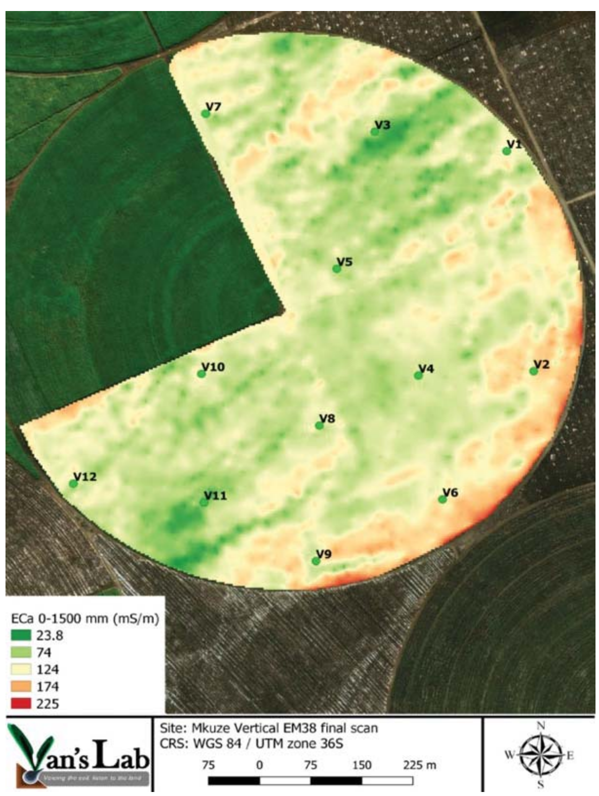


Figure 3.6 Map of EC_a for depth interval 0-1500 mm (case study 1).

Compared with the threshold value of ESP (7%), it is clear that Na levels are exceptionally high and need attention. The source of Na in the profile is the basalt parent material which finds its way to the surface through capillary action in the absence of a drainage system. The result therefore is that Na has become a major yield limiting factor on this site. The loss of stalk yield at a rate of 10.2 t ha^{-1} for every 1% increase in ESP is much higher than that reported in literature which is 2.4 t ha^{-1} for every 1% increase in ESP (Spalding, 1983; Nelson and Ham, 1998).

3.4.2 Case study 2

Water quality: Quality of rainwater is good with a C1-S1 USDA rating (United States Salinity Laboratory Staff, 1954) and an A SASRI rating (Johnston, 1979). Quality of water from the regional dam via the canal and used for irrigation is also good with a C2-S1 USDA rating and an A SASRI rating (Table 4.8). However, an important difference between these water sources is their Na content. A field receiving 800 mm of each will receive approximately 4 times as much Na from the canal water. It is interesting to note that rainwater is not free of Na and contained 0.76 meq ℓ^{-1} (or 139 kg ha^{-1} in 800 mm) in the collected samples.

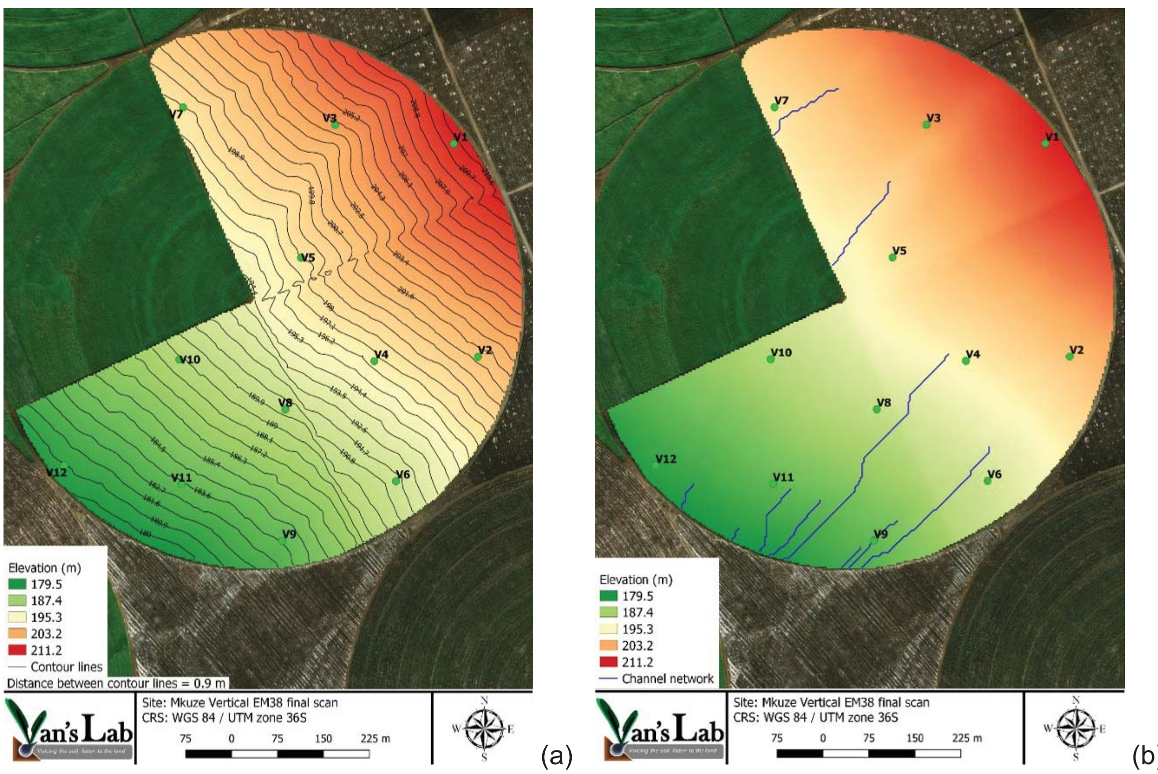


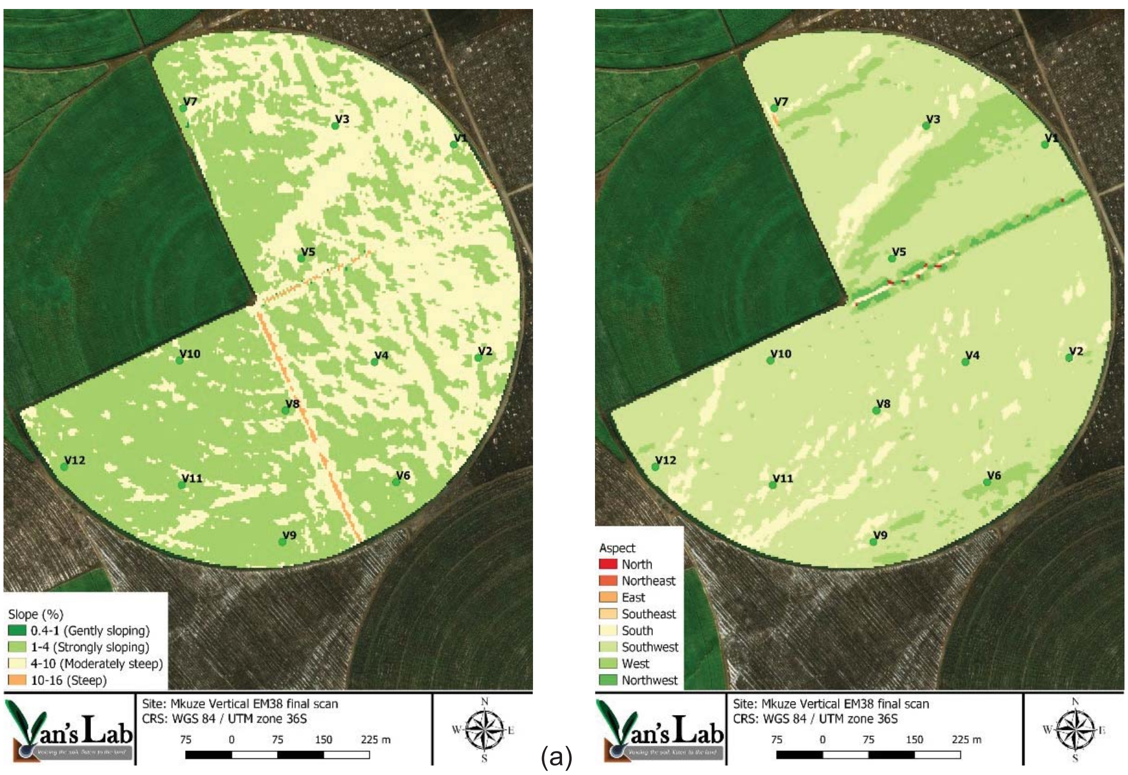
Figure 3.7 Maps of elevation (a) and surface drainage lines (b) for the study area.

Soil analysis: The mean clay content was 35%, 34% and 39% for depth intervals 0-300, 300-600 and 600-900 mm, respectively (Appendix 3.3). The variation within depth intervals was moderately large with standard deviations of 13%, 15% and 12% and standard errors of 3.7%, 4.2% and 3.6% for the respective depth intervals. The mean pH(water) in the surface layer was 6.17 with no values higher than 8. In the next layer (300-600 mm) four plots (1, 3, 6 and 7) had pH values higher than 8 (mean pH = 7.23) and in the 600-900 mm layer two plots (3 and 6) had values higher than 9 (mean pH = 7.99). The mean SAR at the surface was 5.5 with five plots (1, 3, 5, 6 and 7) having values higher than the threshold value of 6. The mean SAR for the second depth interval (300-600 mm) was 12.0, with values below the threshold only for plots 4, 8, 9, 10 and 11. In the 600-900 mm depth interval, the mean SAR was 15.5 with plots 4, 8 and 11 still having values below the threshold. Standard deviations were 4.8, 8.5 and 8.9 and standard errors 1.4, 2.5 and 2.6 for the respective depth intervals. The mean ESP was at 12.1%, 20.1% and 26.2% above the threshold of 7% in all the depth intervals. Standard deviations were 6.1%, 10.2% and 13.2% and standard errors 1.8%, 2.9% and 3.8% for the respected depth intervals. See Appendix 3.3 for other soil information.

Table 3.8 Comparing water quality from a canal used for irrigation with rainwater. The conversion of meq ℓ^{-1} to kg ha^{-1} was based on an annual irrigation of 800 mm.

Properties	Source					
	Unit	Canal	Rain	Unit	Canal	Rain
pH	-	7.32	5.82	pH	7.32	5.82
K	meq ℓ^{-1}	0.06	0.02	kg ha^{-1}	19	5
Ca	meq ℓ^{-1}	0.94	0.11	kg ha^{-1}	151	17
Mg	meq ℓ^{-1}	1.36	0.44	kg ha^{-1}	132	43
Na	meq ℓ^{-1}	2.98	0.76	kg ha^{-1}	548	139
HCO_3	meq ℓ^{-1}	2.77	0.08	kg ha^{-1}	1352	37
EC	mS m^{-1}	53	2.8	mS m^{-1}	53	2.8
EEC*	mS m^{-1}	26.5	1.4	mS m^{-1}	26.5	1.4
SAR	-	2.78	1.5	SAR	2.78	1.5
ASAR**	-	4.7	0.81	ASAR	0.17	30.45

* = Effective electrical conductivity taking the dilution effect of rainfall into account (United States Salinity Laboratory Staff, 1954; Johnston, 1979); ** = adjusted sodium adsorption ratio taking precipitation of Ca via HCO_3 into account (Abou El-Defan et al., 2016)



(a) (b)

Figure 3.8 Maps of slope (a) and aspect (b) for the study area.

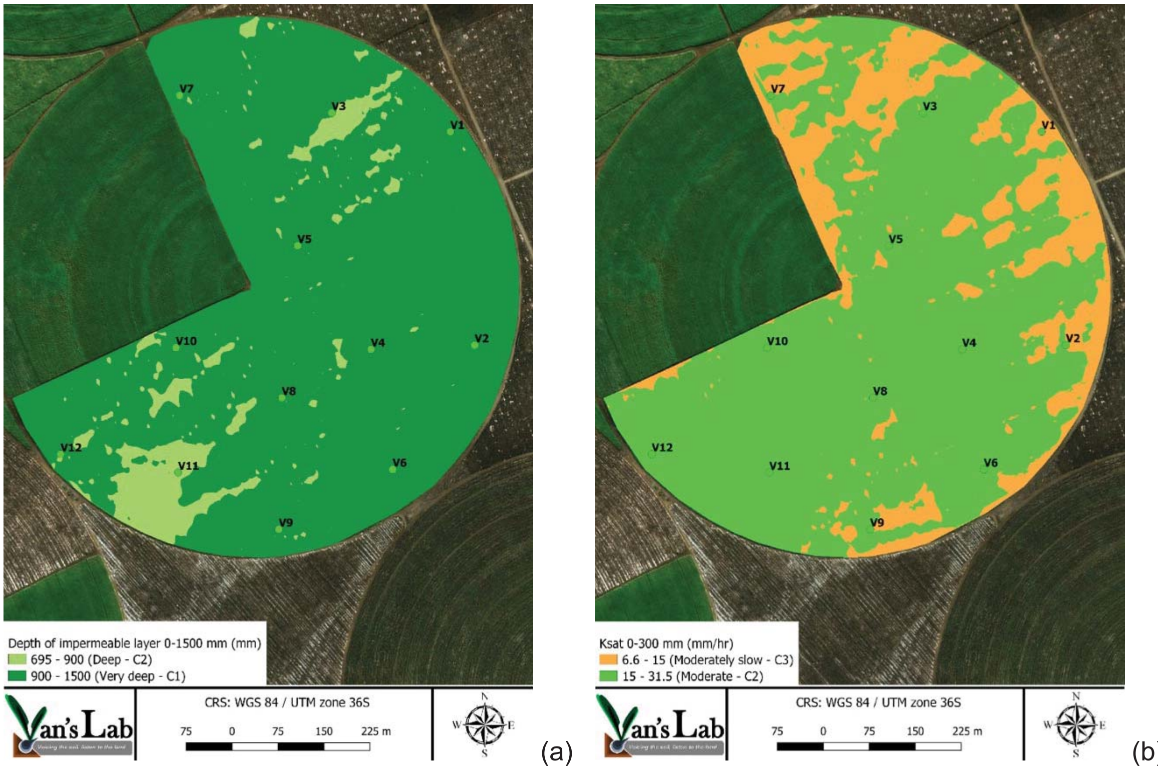


Figure 3.9 Maps of depth to impermeable layer (a) and saturated hydraulic conductivity (b) for the study area.

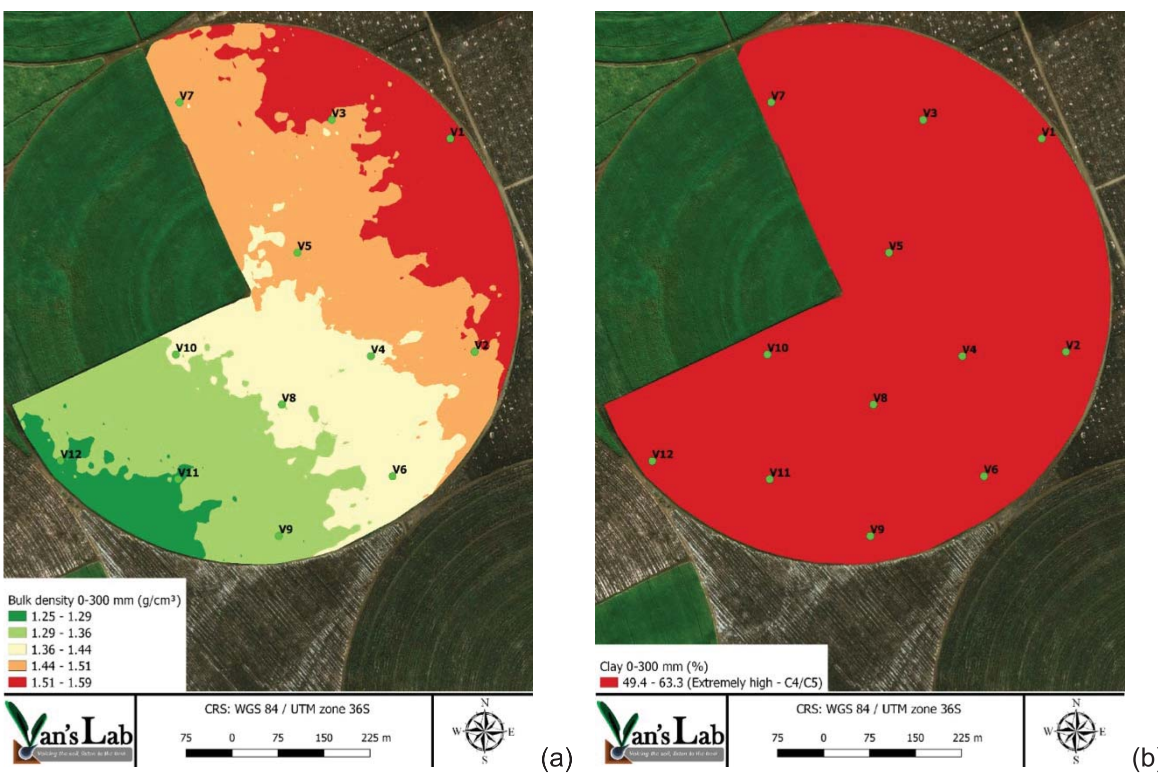


Figure 3.10 Maps of bulk density (a; 0-300 mm) and clay percentage (b; 0-300 mm) for the study area.

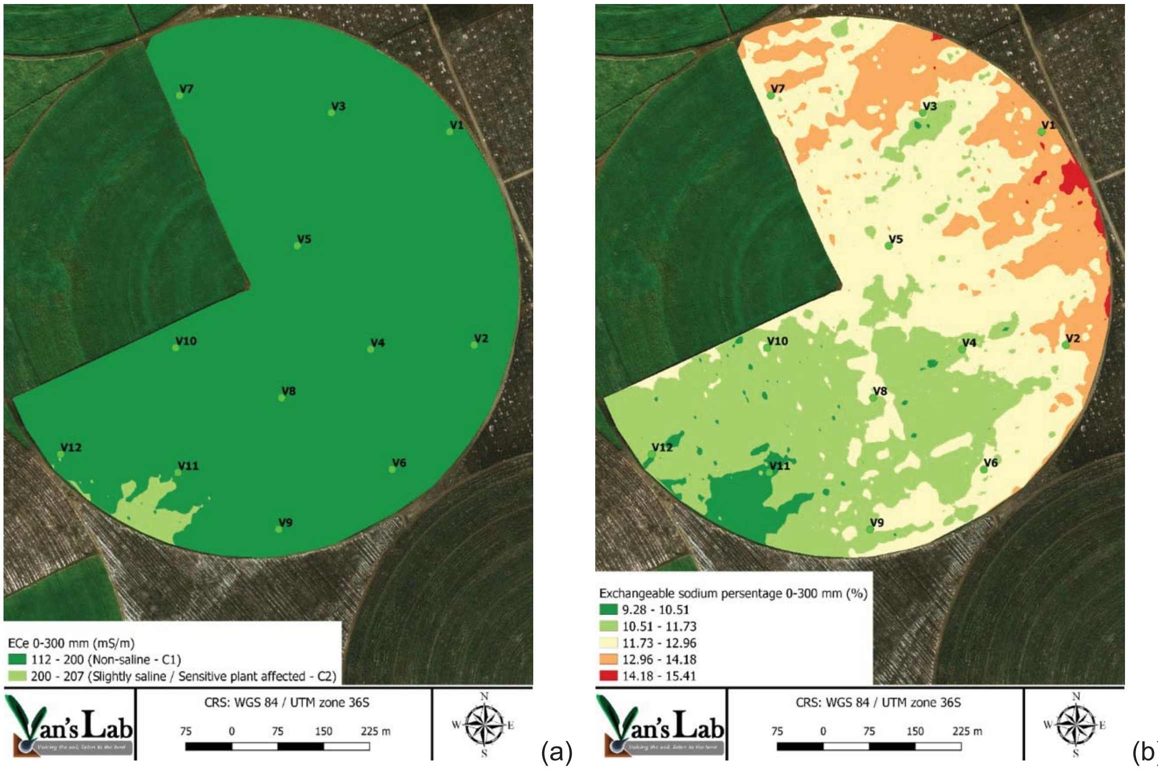


Figure 3.11 Maps of soil salinity (a; EC_e 0-300 mm) and exchangeable sodium percentage (b; ESP 0-300 mm) for the study area.

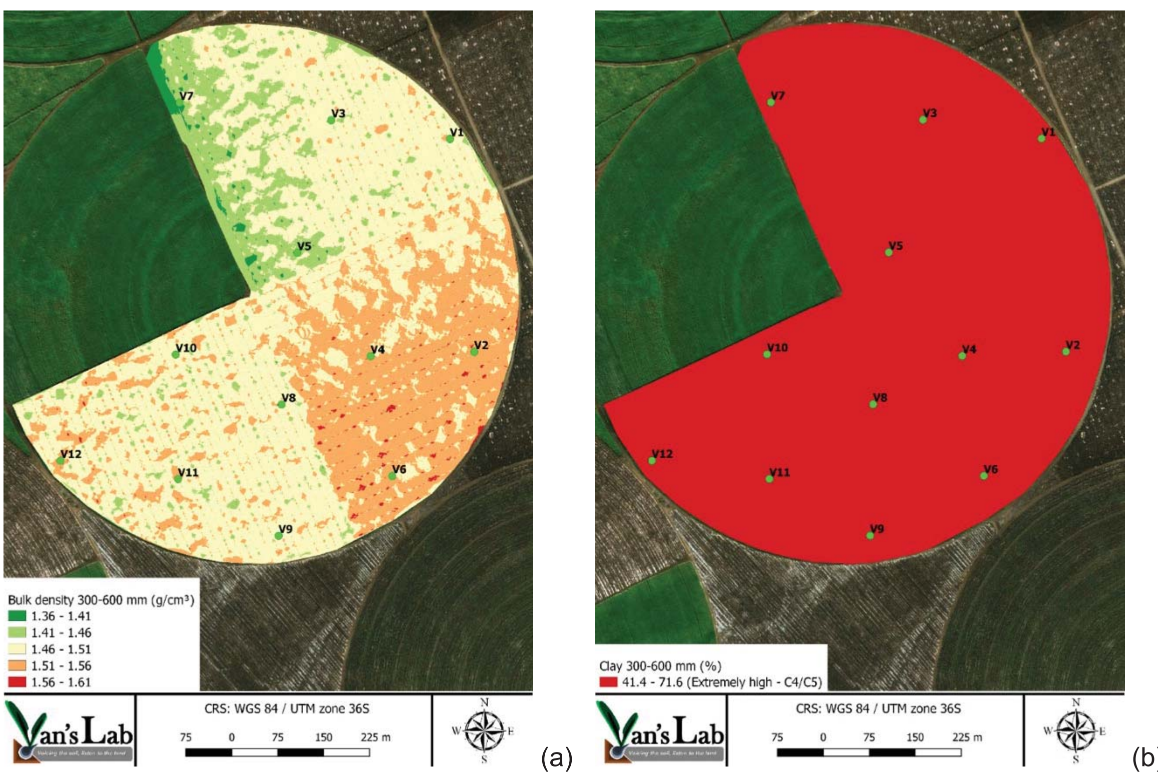


Figure 3.12 Maps of bulk density (a; 300-600 mm) and clay percentage (b; 300-600 mm) for the study area.

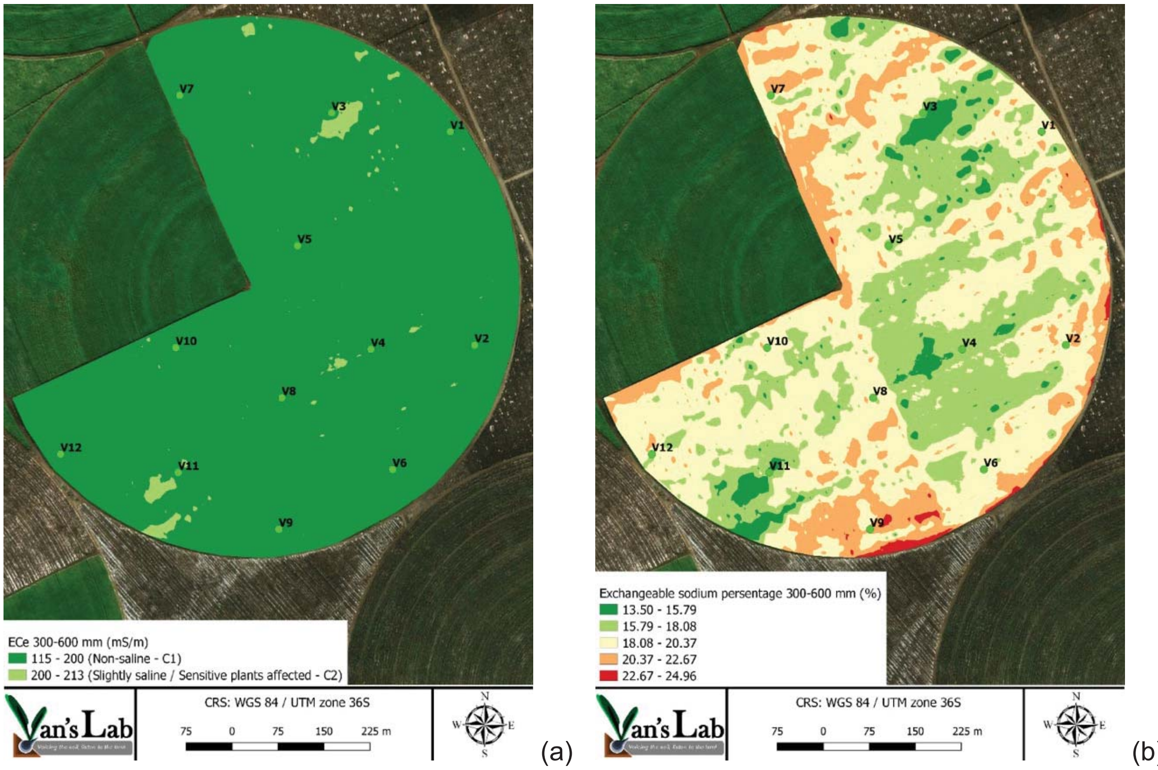


Figure 3.13 Maps of soil salinity (a; EC_e 300-600 mm) and exchangeable sodium percentage (b; ESP 300-600 mm) for the study area.

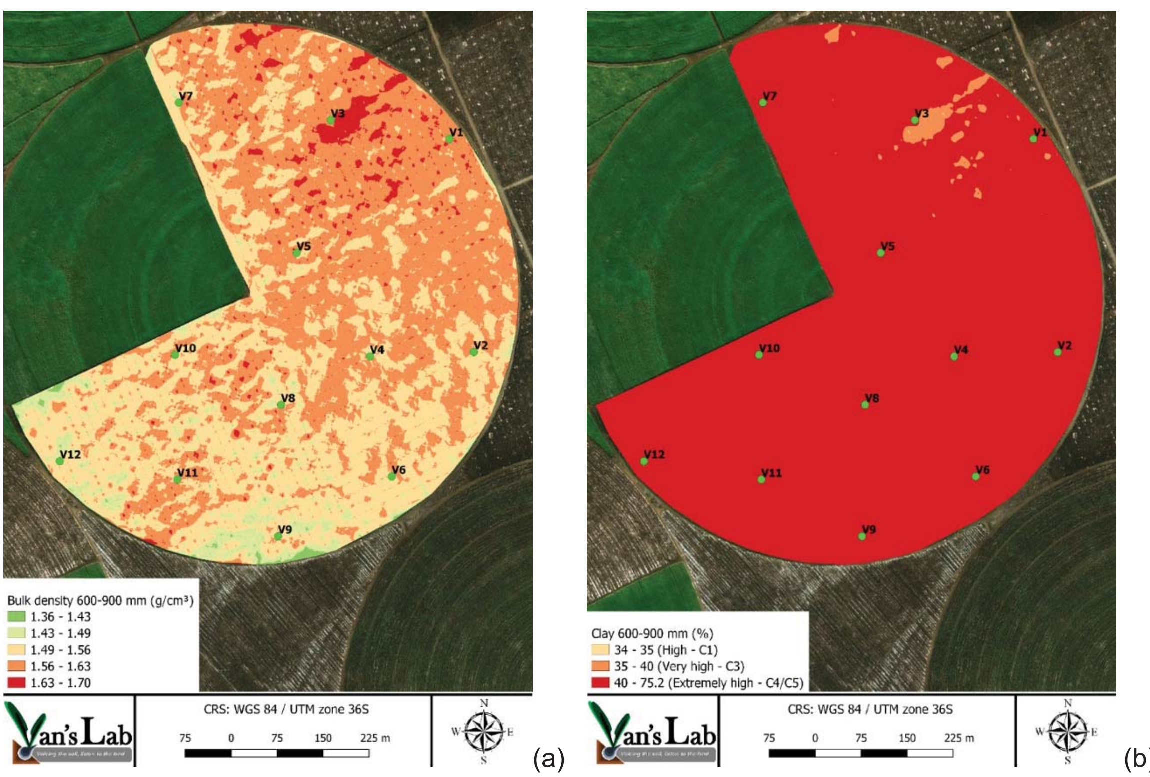


Figure 3.14 Maps of bulk density (a; 600-900 mm) and clay percentage (b; 600-900 mm) for the study area.

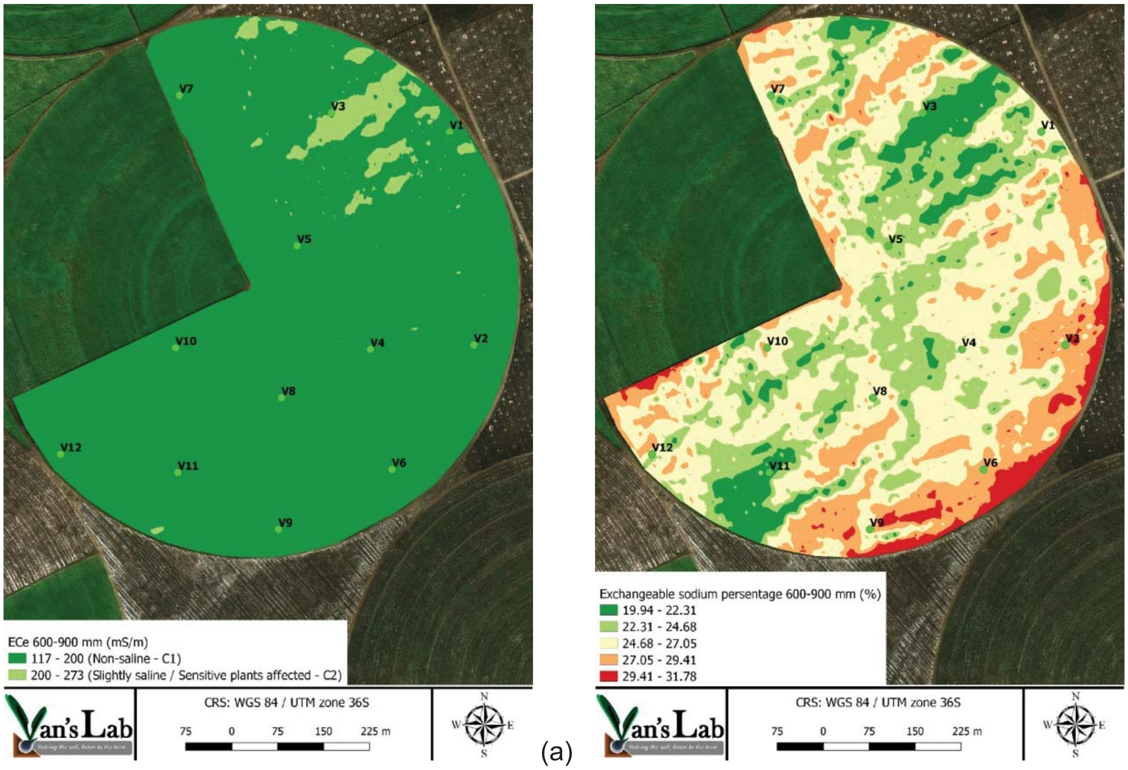


Figure 3.15 Maps of soil salinity (a; EC_e 600-900 mm) and exchangeable sodium percentage (b; ESP 600-900 mm) for the study area.

Biomass analysis: Samples collected at the age of 10.6 months and expressed in kg ha^{-1}, show that cane stalks are the dominant accumulator of all nutrients, except Ca and Si which is highest in brown leaves (Table 3.9; Appendix 3.4). However, Na is present in the lowest quantity both in terms of % and kg/ha indicating that although Na might be present in large quantities in the soil (Appendix 3.3), it is not taken up in significant quantities by sugarcane.

Table 3.9 Analysis of biomass for its nutrient content in percentage and kg ha^{-1}

Part	N	P	K	Ca	Mg	S	Si	Na
	%							
Green leaves	1.05	0.16	1.95	0.27	0.21	0.27	1.44	0.02
Brown leaves	0.45	0.03	0.16	0.52	0.21	0.31	2.27	0.01
Cane stalks	0.32	0.08	0.73	0.05	0.12	0.16	0.24	0.01
Mean	0.60	0.09	0.95	0.28	0.18	0.25	1.32	0.01
Part	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Si**	**Na**
	kg ha^{-1}							
Green leaves	40	6	75	10	8	10	59	0.6
Brown leaves	26	2	9	29	12	18	132	0.8
Cane stalks	145	35	345	20	51	70	115	2.8
Total	211	43	429	59	71	98	306	4.1

Crop yield ranged between 52 and 119 t ha^{-1} and is an indication of the variable production potential of the field (Table 3.10). It has long been known that sugarcane yields are affected by salts in the soil. Stalk yield was regressed against ESP for three depths and all show a negative relationship (Figure 3.16). The slope of the regression for the surface layer indicate that 1.9 t ha^{-1} is lost for every 1% increase in ESP. Regressed with ESP from deeper layers indicate losses of 0.9 t ha^{-1} and 0.5 t ha^{-1} for depths 300-600 mm and 600-

900 mm, respectively. Thus, although salts are present in much higher levels in the subsoil, its effect on crop yield is much less, compared to the relatively low salt levels in the topsoil. It is assumed that high concentration of roots in the topsoil layer make the crop very sensitive to the condition of this layer, relative to the deeper layers with a much lower root presence.

Table 3.10 Sugarcane stalk yield (t ha^{-1}) for case study 1

Plot	1	2	3	4	5	6	7	8	9	10	11	12	Mean	Stdev	Stder
Yield	68	82	92	120	88	69	142	133	152	123	150	126	112	31	8.9

Salt distribution: The topographical results, i.e. contour lines (altitude) and surface drainage lines, are mapped in Figure 3.18. From the topographical features it is clear that site has mainly a western and southern aspect. The field slopes generally in a south-western direction with a 9% slope, except for a small area, where plots V1 and V2 are located, which drains in a western direction. The EC_a data of the 2017 survey was used for this report and the result of its distribution over the field is depicted in Figure 3.17. The results show that EC_a are highly variable over the site, with higher values in a broad strip from the centre towards the southern direction. There is also high EC_a activity within the outer towers in the western side of the pivot. The distribution of soil properties, derived from the EC_a-soil property models and then applied to the measured EC_a survey data, are also depicted in Figures 3.19 to 3.24.

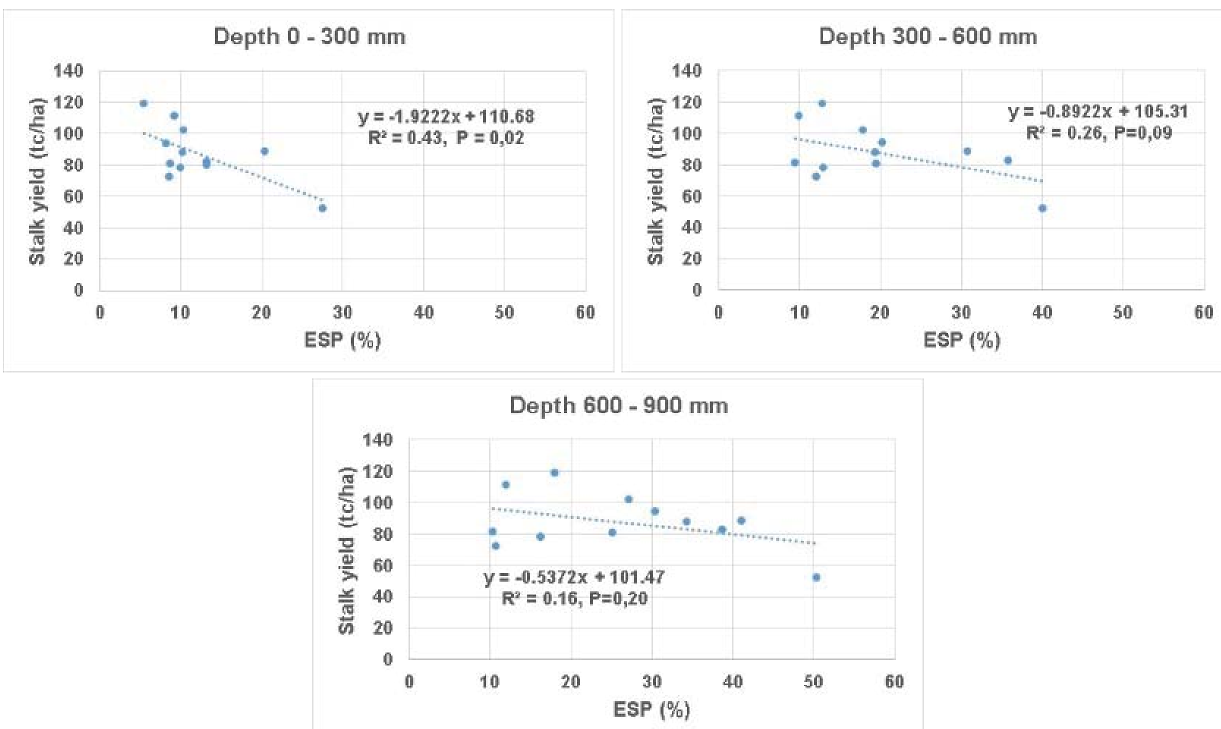


Figure 3.16 Regression between stalk yield and ESP for three depths. Note that the curves start at approximately the threshold value (7%) and that ESP increases with depth.

Bulk density ranged from about 1.7 to 2.0 g cm^{-3} in the 0-300 mm layer (Figure 3.19) and the resemblance with the ESP distribution pattern (Figure 3.20) is noticeable. A similar correlation between bulk density and ESP was obtained for the 600-900 mm depth. This relationship did not work that well for the 300-600 mm depth mainly because the regression statistics between EC_a and bulk density were not significant. The maps showed no meaningful distribution of salinity and clay, mainly because the range was below threshold for salinity (Figures 3.20, 3.22 and 3.24) and too narrow for clay (Figures 3.19, 3.21 and 3.23). The real problem are the very high Na levels in the study site expressed as ESP. Compared with the threshold value of ESP (7%) it is clear that Na levels are exceptionally high and need attention. The source of Na in the profile is the Beaufort sediments parent material from where Na finds its way to the surface in the absence of a drainage system. The result therefore is that Na has become a yield limiting factor on this site. The loss of stalk yield at a rate of 1.9 t ha^{-1} for every 1% increase in ESP is similar to that reported in literature (Spalding, 1983; Nelson and Ham, 1998). With the help of ESP distribution maps from the 0-300 mm and 300-600 mm depths, the installation of meaningful subsurface drainage may be planned.

Figure 3.17 Map of EC_a for depth interval 0-1500 mm (case study 2).

3.5 Conclusions

Fields of both case studies were poorly drained due to the high clay content of the site and local depressions in the field. The main conclusion is that salts are present in large quantities in the subsoil (>300 mm). The major source of Na-salt in both studies is the underlying parent material. Thus, high Na-salts are inherent to the area and demand intensive management. This is to ensure that the surface layer stays low in salts and that the soil's physical condition remains healthy. The obvious method recommended worldwide is the installation of subsurface drains. This is an expensive option (at least R30 000 per ha), but necessary if the production capacity of the field is to be sustained. Making use of an irrigation strategy to keep salts in the surface layers low is not an option – in the long run salts are accumulating. More Na-salt is applied with good quality (C1-S1) irrigation water than the amount of Na taken up by the plant. Even through rainwater the soil receives more than 10 times the amount of Na than that taken up by sugarcane. Therefore, in the absence of a drainage mechanism, salts will accumulate in the profile.

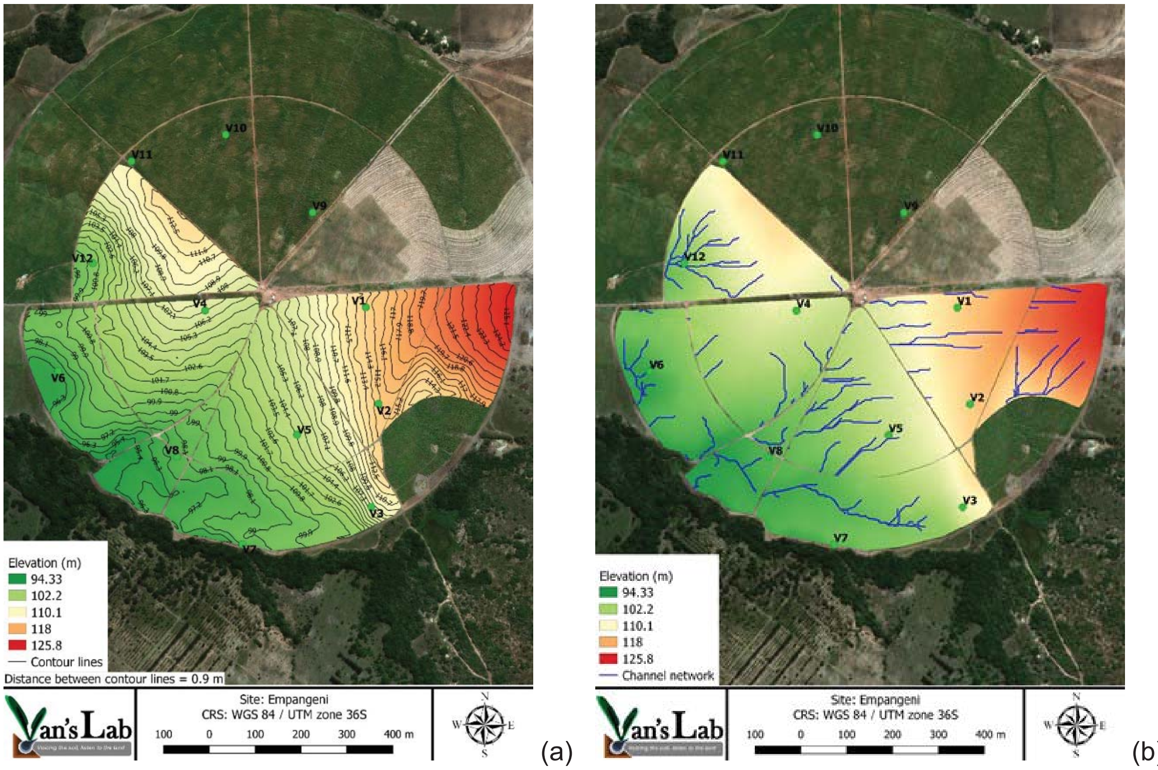


Figure 3.18 Maps of elevation (a) and surface drainage lines (b) for the study area.

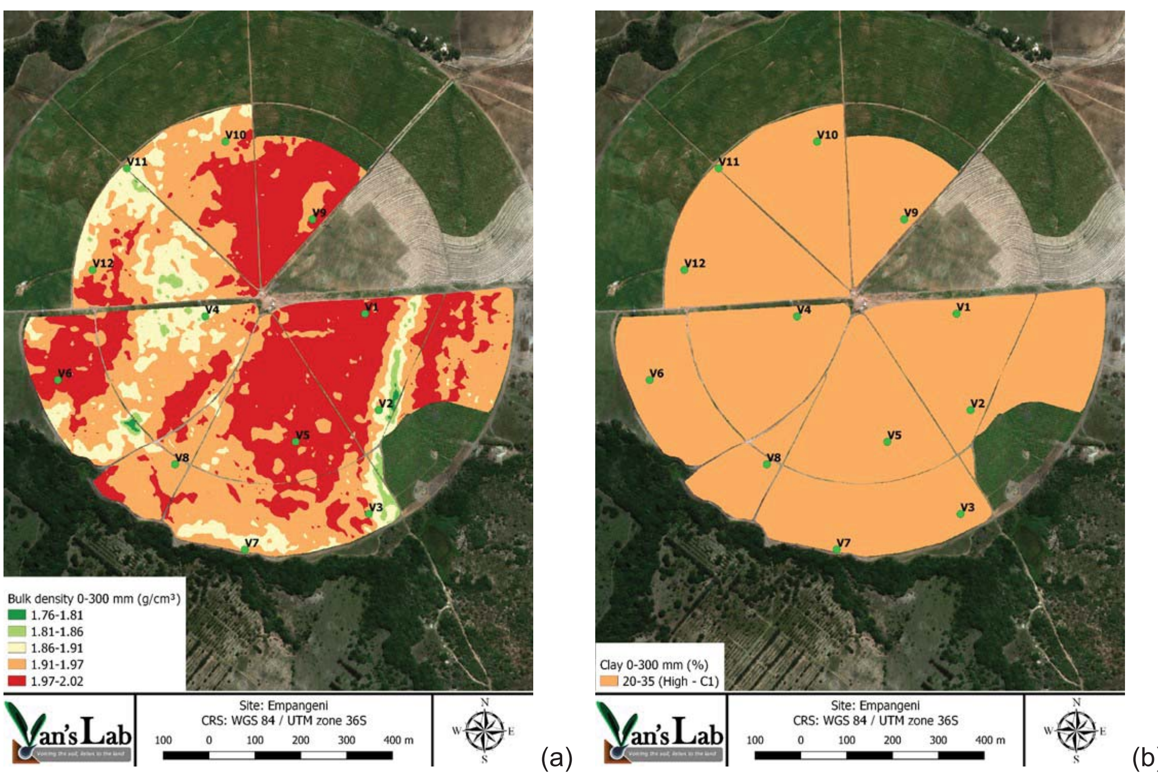


Figure 3.19 Maps of bulk density (a; 0-300 mm) and clay percentage (b; 0-300 mm) for the study area.

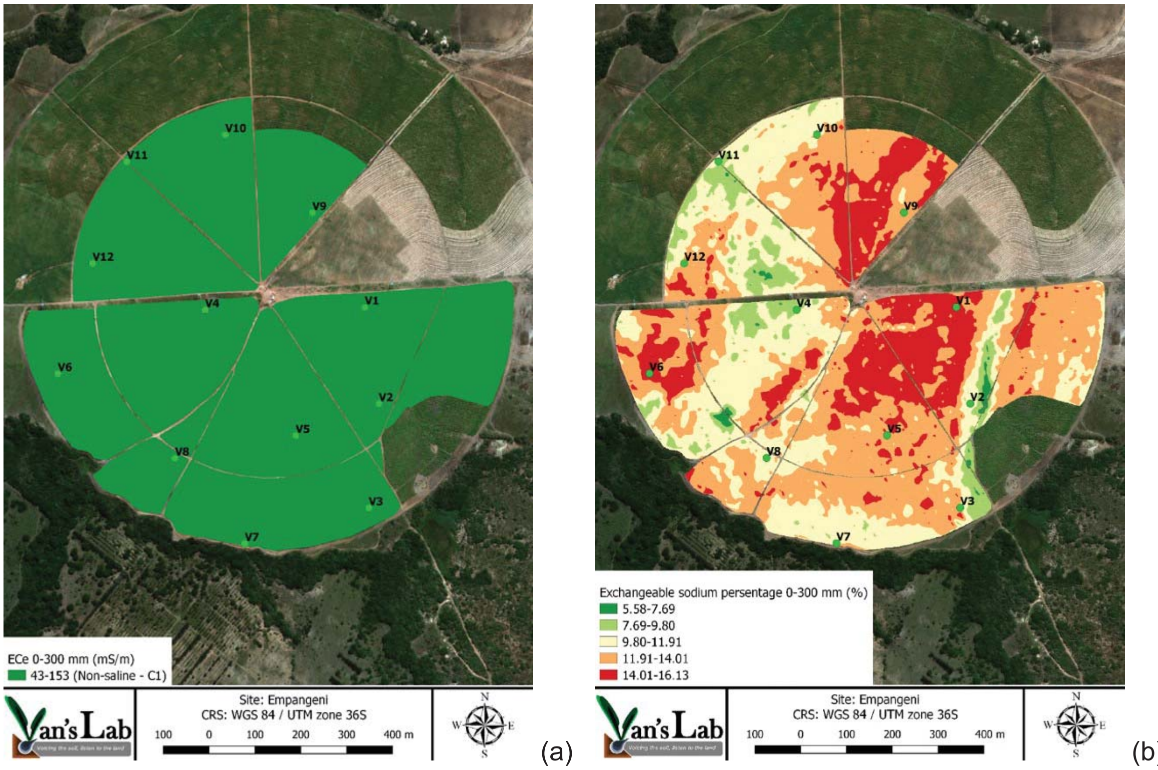


Figure 3.20 Maps of soil salinity (a; EC_e 0-300 mm) and exchangeable sodium percentage (b; ESP 0-300 mm) for the study area.

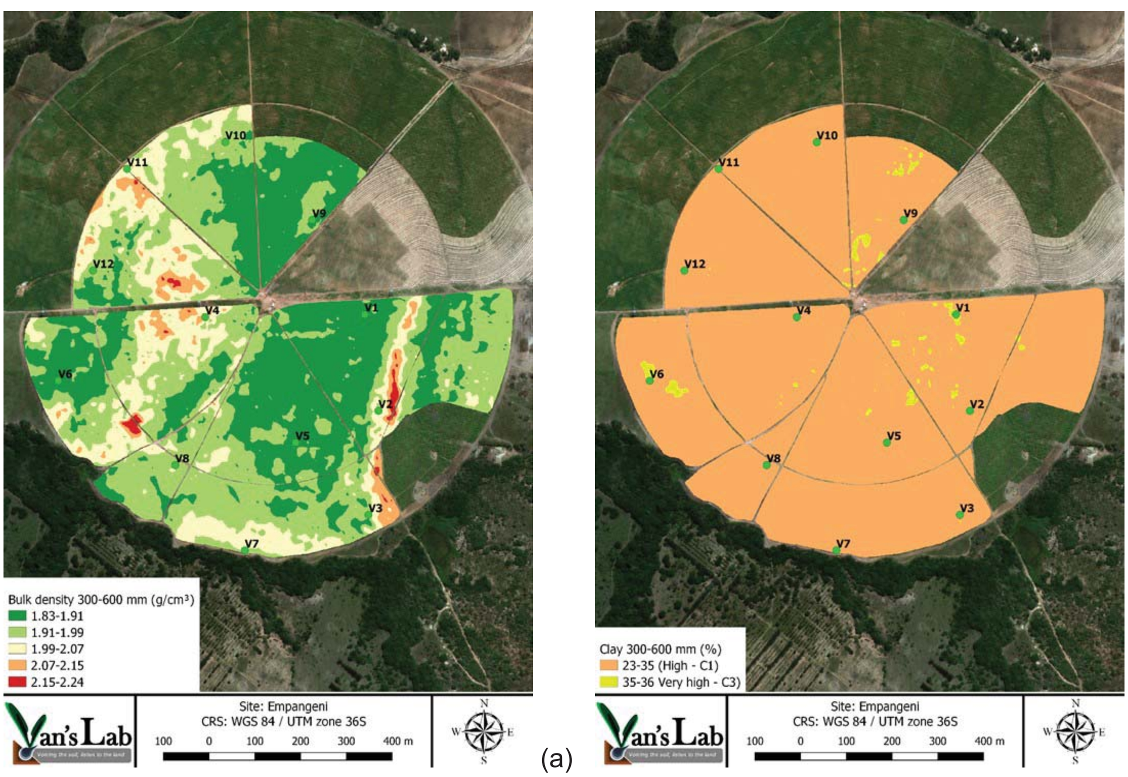


Figure 3.21 Maps of bulk density (a; 300-600 mm) and clay percentage (b; 300-600 mm) for the study area.

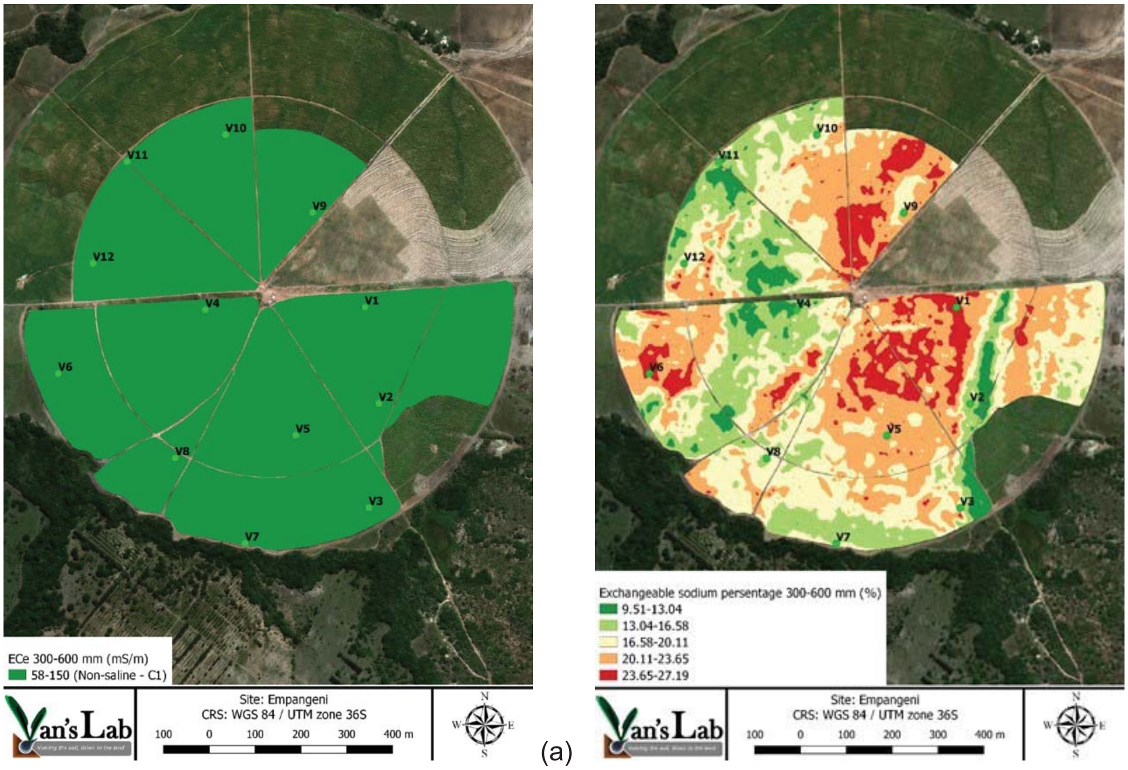


Figure 3.22 Maps of soil salinity (a; EC_e 300-600 mm) and exchangeable sodium percentage (b; ESP 300-600 mm) for the study area.

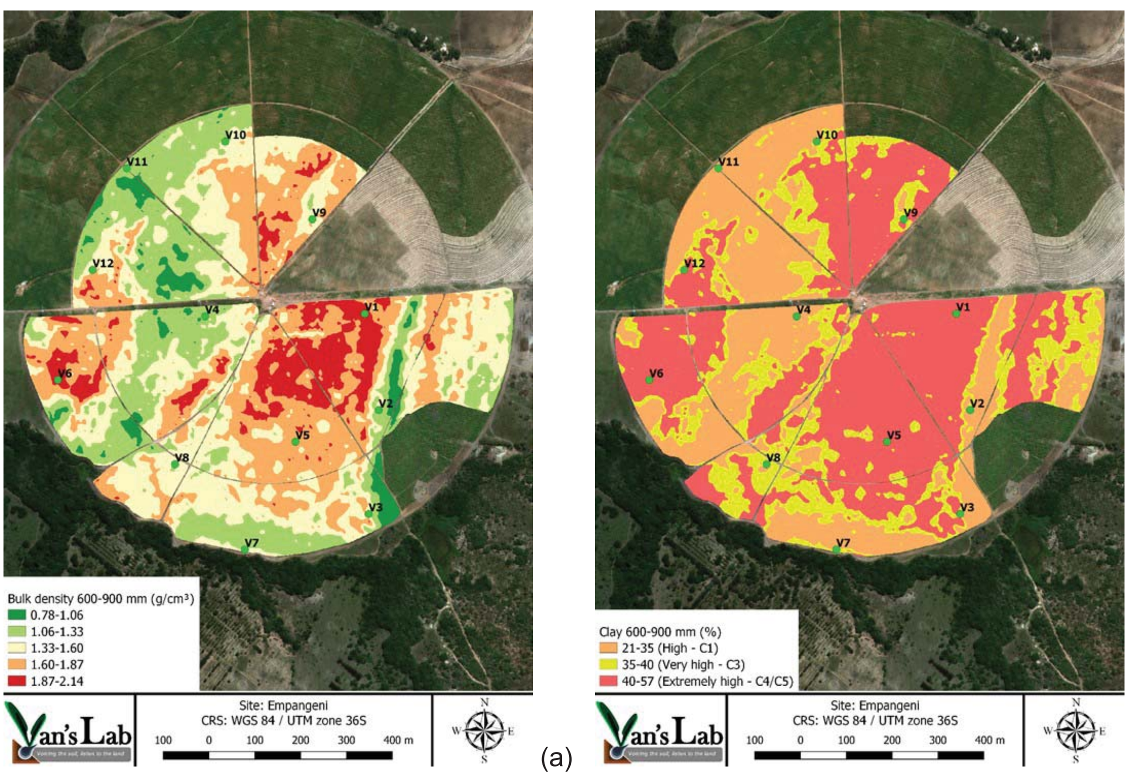


Figure 3.23 Maps of bulk density (a; 600-900 mm) and clay percentage (b; 600-900 mm) for the study area.

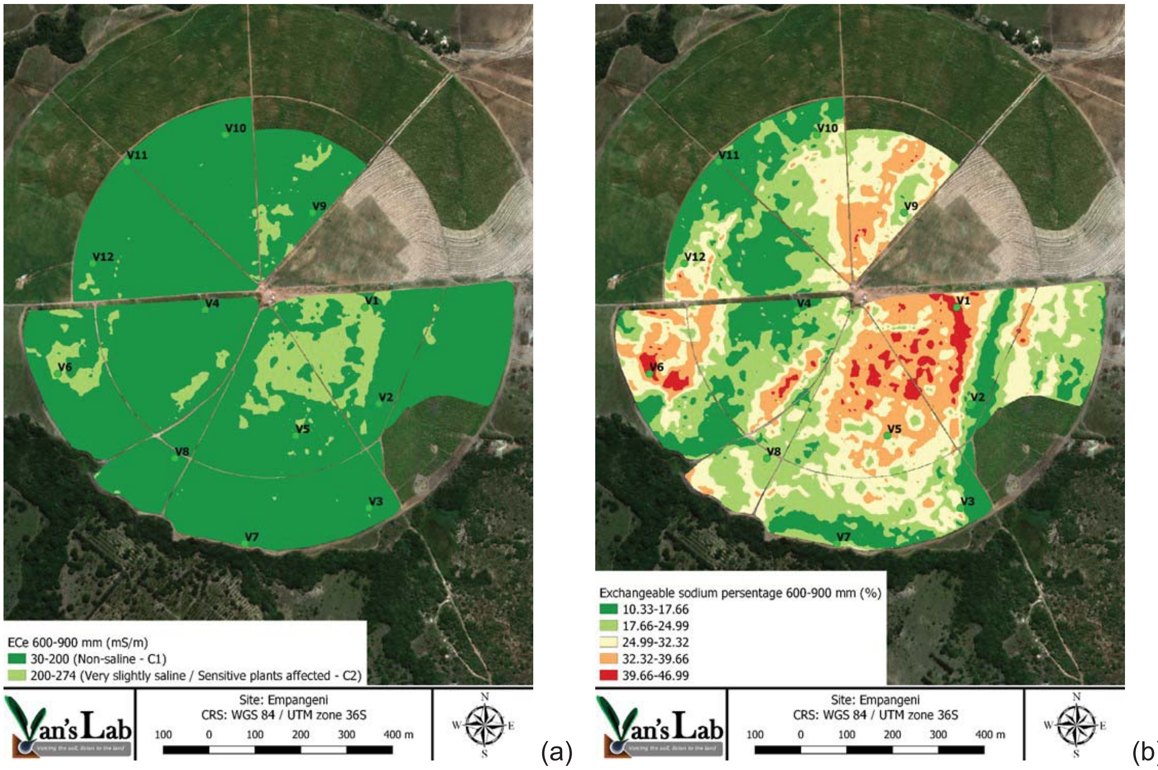


Figure 3.24 Maps of soil salinity (a; EC_e 600-900 mm) and exchangeable sodium percentage (b; ESP 600-900 mm) for the study area.

Sugarcane stalks are the main sink above ground for Na taken up by the plant (50 to 70%). The fact that this is also the part that is processed in the mill supports the idea to export salts from the field. However, the quantity taken up by the total plant (4 to 9 kg ha^{-1}) is a very small fraction of that added (about 250 kg ha^{-1}) to the soil by good quality water or even rain (>100 kg ha^{-1}). This supports the finding by Shone et al. (1969) that Na is abundantly available in the environment but is required in extremely small quantities by the plant.

Although salts are present in much lower levels in the topsoil, its impact on crop yield is much higher compared to the relatively high salt levels in the subsoil. It is therefore essential to ensure that the production zone (i.e. 0-600 mm where nearly all roots are found in irrigated fields) is kept healthy with a low salt content.

Sugarcane is classified as a natrophobe and probably spends vast amounts of energy to keep Na out which might contribute to yield losses. Shone et al. (1969) suggested that the Na taken up by natrophobes is usually retained in the roots with relatively little translocation to the shoot. Thus, should the roots decompose, salts from deeper soils layers is released near the surface. Roots were not analysed, but very little Na (<10 kg ha^{-1}) was found in above-ground biomass.

In case study 1 Na has become a major yield limiting factor. The loss of stalk yield at a rate of 10.2 t ha^{-1} for every 1% increase in ESP is much higher than that reported in literature which indicates 2.4 t ha^{-1} for every 1% increase in ESP (Spalding, 1983; Nelson and Ham, 1998). The major source of Na is the basalt parent material where levels are exceptionally high. In the absence of a drainage system Na is finding its way to the surface. It has reached a stage where Na in the 300-600 mm subsoil layer of plot 6 was very high (SAR = 16 and ESP = 25%). The mean salt load across all 12 plots at this depth was 9 for SAR and 14% for ESP. Threshold values are 6 for SAR and 7% for ESP. In the 300-600 mm depth interval there is an abundance of roots and the high Na load will affect its efficiency and effectiveness to provide for the plant. The high levels of Na, so close to the surface, need urgent attention to ensure sustainable production of this field.

In case study 2 Na in the soil is a major yield limiting factor. The loss of stalk yield at a rate of 1.9 t ha^{-1} for every 1% increase in ESP is in line with than that reported in literature, viz: 1.5 to 2.4 t ha^{-1} for every 1% increase in ESP (Spalding, 1983; Nelson and Ham, 1998). The major source of Na is the Beaufort sediments parent material where levels are exceptionally high. In the absence of a drainage system Na is finding its way to the surface. It has reached a stage where Na in the 300-600 mm subsoil layer of plot 5 was very high (SAR = 16 and ESP = 28%). The mean salt load across all 12 plots at this depth was 5.5 for SAR and 12% for ESP. Threshold values are 6 for SAR and 7% for ESP. In the 300-600 mm depth interval there is an abundance of roots and the high Na load will affect their efficiency and effectiveness to provide for the plant. The high levels of Na so close to the surface need urgent attention to ensure sustainable production of this field.

3.6 Recommendations

To ensure sustainable irrigation farming, farmers must be alerted to the importance of keeping the production zone healthy and free of large quantities of salts. Farmers must also become aware of the Na content in water used for irrigation. Every effort should also be made to prevent salt accumulation via capillary rise and evaporation. Farmers should also make use of a tailored leaching programme to control or remove salts from the profile. In order to achieve this, it is critically important to ensure that fields are sufficiently drained. Most irrigated fields in the sugarcane industry are poorly drained and the use of artificial drains should be common phenomena rather than the exception.

- Monitor irrigation water per source for its salt load at least once per year. Convert the laboratory values (in units of concentration) into units of mass per area (i.e. kg ha^{-1}) taking into account the annual irrigation amount.
- Identify areas in fields where salt load is highest and monitor these spots annually.
- If the salt content is increasing over time install subsurface drains to elevate.
- Also embark on a reclamation programme. For a Na-salt (sodic) soil, this require planting a high biomass Na-salt-tolerant green manure crop (i.e. black oats). At peak biomass the biomass should be flattened, and gypsum applied (minimum 5 t ha^{-1}) and incorporated with the biomass in the plough layer. This should be followed by an application of at least 500 mm irrigation in quantities of 50 mm per irrigation every 14 days.
- Engage with a programme of intent over irrigation to regularly flush salts that have accumulated within the production zone (i.e. 0-600 mm depth interval) and generally referred to as "leaching fraction". This is only possible in the presence of a subsurface draining system.

CHAPTER 4. LITERATURE SYNOPSIS

4.1 Best on-farm water and salt management practices

4.1.1 International

Most of the publications on managing the total dissolvable salt load associated with irrigation demonstrated that sustainable irrigation at farm level is possible (United States Salinity Laboratory Staff, 1954; Rhoades, 1972, 1974, 1977, 1997; Ayers and Westcott, 1976, 1985; Maas and Hofmann, 1977; Abrol et al., 1988; Gupta and Abrol, 1990; Van Schilfgaarde, 1990; Kruse et al., 1996; Hillel, 2000; Oster and Wichelns, 2003; Qadir and Oster, 2004; Hillel and Vlek, 2005; Sharma and Minhas, 2005; Wichelns and Oster, 2006; Kijne, 2006; Letey and Feng, 2007; Letey et al., 2011; Singh, 2014; Wichelns and Qadir, 2015; Ritzema, 2016 Singh, 2018). A generalised ideal strategy for proactive management entails the following: i) minimise salt mobilisation and additions through irrigation water, ii) prevent decreases in crop yield due to excessive dissolvable salt in the root zone, iii) prevent degradation of soil permeability due to excessive sodium concentrations and iv) minimise irrigation-induced drainage and leaching. The strategy proactively not only addresses onsite problems but also offsite issues of water conservation and degradation of groundwater and river water sources as well as leaching of essential nutrients. In fact, according to Wichelns and Qadir (2015), Prof Hilgard as early as 1893 passionately urged farmers and public officials to use irrigation water sparingly and build regional drainage systems. The authors emphasise “that his prescription for achieving sustainable irrigation is as valid in the 21st century as it was in the 19th”.

In the design of an irrigation project many regional salt sources and control factors should be considered, inter alia i) suitability of the soils for irrigation, ii) residual salt content of the soils, iii) irrigation water quality, iv) topography and its effect on subsurface drainage, v) type of system and amount of irrigation, vi) climatic conditions and reliability of the irrigation water supply, vii) environmental impact of drainage water and viii) interception and possible re-use of drainage water. Many of the past irrigation developments, however, took place without proper consideration of these factors. One might even argue that this is worse in developing compared to developed countries. Hence, farmers across the globe are exposed to various levels of design and operation of regional irrigation and drainage infrastructure. Despite these constraints, farmers should however still strive towards the ideal management strategy by implementing best on-farm water and salt management practices, which are discussed below.

The choice of an efficient irrigation system is the first important decision by farmers. This is crucial in reducing the amount of applied salts and decreasing the mobilisation of salts by reducing water loss from drainage and surface runoff (Abrol et al., 1988; Minhas, 1996; Kruse et al., 1996; Hillel, 2000; Oron et al., 2002; Hanson and May, 2004). According to Reinders (2011), the system should apply water at the desired amount, at an accurate application rate and uniformly over the entire field, at the precise time, with the smallest amount of non-beneficial water consumption, and should operate as economically as possible.

Likewise, with continued good decisions on when and how much to irrigate, salt additions through irrigation, excessive drainage and leaching from the root zone and mobilisation of salts through excessive drainage and runoff can be reduced. It is well documented that sound decisions on when and how much to irrigate should be based on scientific theory and/or measurements (Quiñones et al., 1999; Lieb et al., 2002; Annandale et al., 2011; Barnard et al., 2017). Atmospheric-based quantification of evapotranspiration, soil water content measurement, crop-based monitoring and an integrated soil water balance approach, which encompasses real time and pre-programmed techniques, are amongst others some of the methods that can be used to quantify crop water requirements. Where possible rainfall and capillary rise from shallow groundwater tables should be used as water sources for crop water requirements (Ayars et al., 2006; Jhorar et al., 2009; Annandale et al., 2011; Isidoro and Grattan, 2011; Singh, 2013). Capillary rise from shallow groundwater tables can cause rapid salt accumulation, which makes monitoring of root-zone salinity necessary, especially in soils with restricted natural and/or artificial subsurface drainage.

Continuous monitoring of the root zone will also determine the time and magnitude of leaching. Irrigation-induced leaching is only recommended when a reduction in crop yield is expected. Although leaching will always be effective, its efficiency will increase at higher soil salinities (Monteleone et al., 2004; Barnard et al. 2010). The amount of water that drains beyond the root zone relative to the amount of water applied is defined as the leaching fraction (LF). The minimum LF required over the growing season for a particular quality of water to achieve maximum yield of a specific plant is defined as the leaching requirement (LR) and has a specific quantitative value (United States Salinity Laboratory Staff, 1954). Farmers should take note of how the LR is quantified; ideally a transient-state approach, as opposed to a steady-state, must be used. Mathematically if a flow analysis of water and salt are considered, the soil-water content and salt concentration at a given point will remain constant with time in a steady-state system (Letey et al., 2011). Furthermore, typically a mass balance approach is used with the assumption of no dissolution or precipitation of salt in the root zone. According to Letey and Feng (2007) a steady-state analysis also requires the constant continual flow of water. Due to the practicability, these steady-state considerations work well as a first approximation. However, as emphasised by Letey et al. (2011) several shortcomings exist in the steady-state analysis of the LR, namely:

- Under a steady-state analysis the LR concept is based on achieving maximum yields. Maximum yields are not always possible, especially where saline irrigation water is used and where economic benefits exist for reducing the LF, despite yield decreases.
- Under steady-state conditions water is applied uniformly across the field at a constant rate and salinity, which are not realistic. Rainfall frequency, distribution and amount can considerably change the effect of irrigating with high salt concentration water on crop yield and soil quality.
- Unfortunately, despite the fact that the altering of crops with varying salinity tolerance is a common agronomic practice, it cannot be incorporated into a steady-state analysis.
- The fact that leaching should actually be done periodically, i.e. not during every irrigation event, because the efficiency will increase at higher soil salinities, is not incorporated in a steady-state analysis either.
- Furthermore, the assumption that a 20% LF is achieved by applying 20% more water than required by the crop (evapotranspiration, ET) is erroneous. This is because the relationship between applied water ($W_{Applied}$), ET and LF is actually represented by Equation 4.1. A LF of 0.30 requires $W_{Applied}$ / ET to be 1.43, which means 43% more water than ET has to be applied to achieve a 30% LF. ET in Equation 2.1 would be equal to the potential ET (PET) if defined in the context of computing LR with maximum crop yield, because ET in Equation 2.1 represents actual crop evapotranspiration.

$$\frac{W_{Applied}}{ET} = \frac{1}{1-LF} \qquad (4.1)$$

- Plants respond differently to salinity (Maas and Hoffman, 1977) and are influenced by variety, soil texture, climatic conditions, irrigation and agronomic practices, which are not considered with a steady-state analysis (Maas, 1993).

Under steady-state conditions the salt concentration of the drainage water below the root zone will be equal to the water applied divided by the LF (Equation 4.2), where $W_{Drained}$ is the volume of water that drains beyond the root zone, $W_{Applied}$ the volume of water applied and EC the electrical conductivity of drainage (EC_d) and irrigation water (EC_i)

$$EC_d = \frac{EC_i}{LF} \text{ where } LF = \frac{W_{Drained}}{W_{Applied}} \tag{4.2}$$

From Equation 4.2, a number of steady-state models were developed to describe salt accumulation (soil salinity expressed as the electrical conductivity of a saturated paste extract, EC_e) and leaching, five of which will be discussed here. Table 4.1 shows the concentration factors in the root zone (EC_e / EC_i) as a function of LF calculated with the five steady-state models, which is possible because it is assumed that EC_e will be equal to EC_d under steady-state conditions. Hereafter the models will be referred to as the AW, HG, Rh and UC1 and UC2 models of Ayers and Westcot (1985), Hoffman and Van Genuchten (1983), Rhoades (1974) and Hanson et al. (2006) 1 and 2, respectively. These concentration factors together with the well-known Maas and Hoffman (1977) salinity threshold and slope parameters are the critical inputs normally used in steady-state analysis. The difference in concentration factors between the models are because of the difference in the assumptions inherent in the different models (Letey and Feng, 2007; Letey et al., 2011). For example, with a LF of 0.2, the water will be concentrated 1.3-fold; with the AW model, 1-fold; with the HG model and 1.2-fold; with the Rh model. Letey and Feng (2007) reported that of the AW, HG and Rh models, the HG model would be more reliable than the other two models. This is mainly because the assumption of plant response to a linear-average root zone EC, as in the AW model, is not supported by experimental evidence (Van Schilfgaarde et al., 1974; Gardner, 1983). With the HG model, the calculated concentration factors were weighted by water uptake, with the result that the concentration factor was the same for all assumed water-uptake distributions. In contrast, water uptake in the AW model leads to a corresponding increase in salt concentration with depth. In addition, salt concentration will also increase at a specific depth as the LF decreases. The remaining two steady-state models were reproduced by Hanson et al. (2006) from the original publication by Rhoades (1999), which shows the linear relationship between average root zone EC_e and EC_i for different LF values. This relationship was determined for conventional surface and sprinkler irrigation (UC1), and the other for high frequency irrigation systems (UC2) like drip.

Table 4.1 Average salt concentration factor (EC_e / EC_i) due to irrigation with a specific quality water as a function of leaching fraction (LF) of five steady-state models (Letey et al., 2011)

LF	AW	HG	Rh	UC1	UC2
0.05	4.20	1.55	4.20	2.90	1.90
0.10	2.10	1.30	2.20	2.00	1.40
0.15	1.60	1.10	1.60	-	-
0.20	1.30	1.00	1.20	1.50	1.10
0.25	1.20	-	1.10	-	-
0.30	1.00	-	0.85	1.00	1.10
0.40	0.90	-	0.70	0.85	0.90
0.50	0.80	0.70	0.60	0.75	0.75

The only steady-state model that allows for the concentration of individual major cations and anions in water and not just the total salt concentration, is WATSUIT (Rhoades, 1972; 1977; 1984a; 1987b; 1988a; Oster and Rhoades, 1990). Annual average irrigation water composition (equal concentrations of cations and anions) and leaching fraction (0.05, 0.1, 0.2, 0.3 and 0.4) are required as inputs to determine the salinity build-up and consequent effect on crop yield. In addition, amendments like gypsum and sulphuric acid may be chosen, as well as the "saturation with respect to soil lime, to account for the potential effects of dissolution of soil lime, or soil silicates, or both” (Rhoades et al., 1992). The depth distributions of plant water uptake and CO_2 partial pressure are assumed and fixed within WATSUIT.

Overcoming the shortcomings in a steady-state analysis of the LR has called for a rethink, with the emphasis on a transient-state analysis (Letey and Feng, 2007; Letey et al., 2011). There are a multitude of transient-state models that can be used by farmers and agricultural advisors and allow for most or all of the time-dependent variables encountered in the field that determine the accumulation and distribution of salt within a soil profile, and the response of different crops to salinity (Table 4.2). These models in general allow for water and salt flow in irrigated water table soils and the corresponding response of different crops to matric and osmotic stress, due to variable rainfall, irrigation, evaporation, transpiration and water table uptake. In addition, some models will also allow for the chemistry of major dissolved ions in soil water and therefore also account for cation exchange, mineral dissolution and precipitation. The effect of salinity, sodicity and pH on hydraulic conductivity, hence water flow can also be simulated.

Table 4.2 List of popular transient-state models

Model	Reference
ENVIRO-GRO	Pang and Letey, 1998; Feng et al., 2003
SWAP	Ben-Asher et al., 2006; Van Dam et al., 2008
HYDRUS	Šimůnek et al., 2008; Ramos et al., 2011
UNSATCHEM	Suarez and Šimůnek, 1997; Kaledhonkar et al., 2006
SALTMED	Ragab et al., 2005; Montenegro et al., 2010
FAO-Salinity Laboratory SWS	Suarez and Vaughan, 2001/2002
SWB	Annandale et al., 1999
SWAMP	Bennie et al., 1998; Barnard et al., 2013; 2015

Farmers also have the opportunity to select crops that will produce satisfactorily in expected higher root-zone salinity conditions during the growing season, hence postponing leaching. Primarily due to the wide range of available crop salt tolerance (Maas and Hoffman, 1977; Maas, 1990). The socio-economic aspect of selecting crops and the fact that crop salt tolerance can be modified by different fertiliser applications, irrigation methods and frequencies, and a combination of soil, water and environmental factors (Meiri and Plaut, 1985) can, however, complicate this practice. Lastly, it has also been proposed and confirmed that even saline water (re-use of drainage water) can be used safely to irrigate certain crop species and varieties for specific soil and climatic conditions with specific water and salt management practices (Rhoades et al., 1992; Minhas, 1996; Sheng and Xiuling, 1997; Singh, 2004; Malash et al., 2005; Sharma and Minhas, 2005).

When the above-mentioned practices fail to proactively manage water and salt successfully, because of poor implementation or due to uncontrolled highly site-specific factors, productive soils become unproductive. Mitigation of saline and/or sodic soils is possible through controlled strategic leaching as well as soil and water amendments and bioremediation (calcareous soils are reclaimed without the application of amendments through the cultivation of certain salt-tolerant crops).

4.1.2 Regional

In South Africa, research regarding the salt load associated with irrigation and efficient use of irrigation water were mainly funded by the Water Research Commission (WRC) over several decades. These published peer reviewed reports form the basis for the discussion below. Some of the findings in these reports have been published in reputable journals. The aim is not to cite these publications but rather to provide a very concise synthesis of these reports. Table 4.3 shows the major research themes and focal areas of these WRC-funded projects as related to on-farm water and salt-management practices.

Table 4.3 Research themes and foci of Water Research Commission funded projects over a period of four decades as related to on-farm water and salt management practices

Research focus	Research theme		Reference
Irrigation systems	Improved flood irrigation	Development of a model to simulate the hydraulics more accurately.	Du Rand and Kruger (1995)
		Infiltration under dynamic flood conditions on a typical crusting soil.	Russel (1982)
	Computer irrigation design	Irrigation design principles and procedures were studied and evaluated resulting in the development of different design algorithms.	MBB Inc. (1987)
	Containing losses during centre pivot irrigation	A study on spray losses between the emitters on a centre pivot and the plant canopy guidelines in terms of emitter selection, application depth and management of centre pivots were developed.	Van der Ryst (1995)
		To minimise evaporation and runoff losses due to ponding criteria for adaptation of overhead sprinkler systems to the infiltrability of the soil was developed.	Bloem et al. (1992); Bloem and Laker (1993, 1994a, 1994b)
	Performance of sprinkler irrigation emitters	The study illustrated that layout, pressure variation, droplet size and maintenance of sprinkler systems have significant impact on the irrigation system's performance.	Simpson and Reinders (1999)
	Managing surface and subsurface drip irrigation systems	Guidelines for proper choice, maintenance schedules and management of filters and drip irrigation systems.	Reinders et al. (2005); Koegelenberg et al. (2002); Van Niekerk et al. (2006)
Irrigation scheduling	Concept of plant available water	Developed equations for estimating drained upper limit (DUL) from silt-plus-clay content	Boedt and Laker (1985); Bennie et al. (1988); Bennie (1995)
		Define lower limit (LL) of plant available water capacity (PAWC)	Hensley and De Jager (1982); Boedt and Laker (1985); Laker et al. (1987)
		Modelling PAWC	Hensley and De Jager (1982); Laker (1982); Bennie et al. (1988); Bennie et al. (1995); Bennie et al. (1997)
		Determining of PAWC at various growth stages	Vanassche and Laker (1989)
		Irrigation strategies of longer irrigation intervals	Hensley and De Jager (1982); Boedt and Laker (1985); Vanassche and Laker (1989); Bennie (1995)
		Deficit irrigation strategies and soil water management strategies	Laker (1985); Vanassche and Laker (1989); Fischer and Nel (1990); Bennie (1995); Fisher (1995); Nel (1995b); Bennie et al (1997); Beukes et al. (2003); Van Averbeke and Netshithuthuni (2010)

Research focus	Research theme		Reference
	Plant-based irrigation scheduling measurement techniques	Measurement of canopy temperature ('Pistol' type infrared thermometer)	Reginato (1995)
		Leaf-water potential	Hensley and De Jager (1982); Boedt and Laker (1985); Savage and Wiebe (1987); Vanassche and Laker (1989); Nel (1995a); Laker (2004)
	Soil-based irrigation scheduling measurement techniques	Neutron probe	Nel (1995b); Mkhize et al. (1996)
		Wetting front detector	Stirzaker et al. (2004); Stirzaker et al. (2010b)
	Atmospheric-based irrigation scheduling measurement techniques	Class A-evaporation pan, crop factors	Van Zyl and De Jager (1994); Stevens et al. (2005)
	Modelling the soil water balance	BEWAB	Bennie et al. (1988)
		SAPWAT	Van Heerden et al. (2001, 2008); Van Heerden and Walker (2016)
		PUTU	De Jager et al. (1987); De Jager et al. (2001);
		SWB	Annandale et al. (1999); Annandale et al. (2007)
		MyCansim	Singels and Smit (2009)
Drainage management	Artificial drainage	Vaalharts Irrigation Scheme	Streutker (1977)
	Salinisation of the aquifer	Lower Riet River area	Moolman and Quibell (1995)
		Vaalharts Irrigation Scheme	Herold and Bailey (1996); Ellington et al. (2004); Verwey et al. (2011)
Root zone salinity/sodicity management	Salinity measurements	Four-electrode and electromagnetic induction techniques	Johnston (1994)
		Methodological approach to identify, classify and monitor soil salinity and waterlogging at different scales	Nell et al. (2015)
	Leaching requirement	Free State and Northern Cape irrigation schemes	van der Merwe et al. (1975); du Plessis (1986)
	Soil sodicity	Free State and Northern Cape irrigation schemes	van der Merwe (1969); van der Merwe (1973)
	Modelling salt transport in soil	LEACHM; BURNS; TETrans	Moolman (1993)
		Leaching curves	Ehlers et al. (2007)
		Aragües; Szabolcs	Du Preez et al. (2000)
On-farm interception and drainage re-use	Field crops irrigated along the Lower Riet River	Measuring the short-term (4 growing seasons) and modelling the long-term (20 years) impact on field crops at field level	Van Rensburg et al. (2012)
Crop salt tolerance	Grapevines	Breede River water	Moolman et al. (1999)
	Vineyards	Saline water	De Clercq et al. (2001a, 2001b)
	Field crops	Wheat, Peas, Groundnuts, Maize	Ehlers et al. (2007)

Annandale et al. (2011) offers an excellent review of past irrigation scheduling experiences in South Africa over 4 decades as funded by the WRC. Highlights during this period include studies on soil compaction (Burger et al., 1979; Bennie et al., 1979; Du Preez et al., 1979; Botha et al., 1979), which before 1980 was regarded as the primary restriction to efficient irrigation water use in South Africa. The success of deeper root development of irrigated crops grown on sandy soils led to a study on the efficiency of water uptake by different root systems (Botha et al., 1983). The researchers were successful in explaining the mechanisms for the dramatic increase in production and water-use efficiency due to deep soil cultivation, which led to the development of the profile water-supply rate concept (Bennie et al., 1988; Bennie et al., 1997). It was also shown that it is possible to reduce the irrigation requirement of crops (30-65% reductions) by taking into consideration capillary rise from shallow groundwater tables (Ehlers et al., 2003). A large number of topics were studied under the theme of plant available water (Boedt and Laker, 1985; Bennie, 1995; Hensley and De Jager, 1982; Laker et al., 1987; Laker, 1982; Vanassche and Laker, 1989; Fischer and Nel, 1990; Fisher, 1995; Nel, 1995b; Van Averbeke and Netshithuthuni, 2010; Beukes et al., 2003). This includes determining of drained upper limit, defining of the lower limit of plant available water, development of models for estimating plant available water capacity (PAWC) and stretching of irrigation intervals to reduce evaporation. Studies were also done on deficit irrigation and soil water management, namely how starting with a dry or wet profile, influence water availability during peak water demand.

With regard to atmospheric-based measurements, crop factors and Class A-evaporation pan data were used in irrigation scheduling, which was later shown to have serious limitations (Van Zyl and De Jager, 1994; Stevens et al., 2005). The international standardised version of the Penman-Monteith equation that assumes a full cover, well-watered, 12 cm tall reference crop, with an albedo of 0.23 and canopy resistance of 70 s m^{-1} was also adopted in South Africa. Four irrigation scheduling modelling efforts stand out, namely SAPWAT (Van Heerden and Walker, 2016), BEWAB (Bennie et al., 1988), PUTU (De Jager et al., 1987; De Jager et al., 2001), SWB (Annandale et al., 1999; Annandale et al., 2007) and MyCanesim (Singels and Smit, 2009). According to Annandale et al. (2011) WRC-funded research to develop, improve and promote irrigation scheduling tools has been impressive. The challenge, however, still remains to support the application of tools. The uptake of novel technologies has been slow and no single method has been met with universal appeal. In their review the authors proposed four responses to the challenges in irrigation scheduling:

- continue to advance existing soil-water measurement technology;
- further develop new and emerging technologies;
- improvement in the user friendliness and systems that support existing scheduling tools;
- engage irrigators in a process of adaptive learning.

Vital to best on-farm water and salt management practices is the use of efficient irrigation systems. Over 40 years most of the WRC-funded projects involving irrigation systems focused mainly on the engineering aspects (Reinders, 2011). None of these studies directly investigated the salt load associated with irrigation. According to Reinders (2011) the knowledge was consolidated in guidelines to improve irrigation-water management from dam-wall release to root-zone application (Reinders et al., 2010). The approach promotes investigation, namely, to measure, assess, improve and evaluate to improve efficiency rather than mere water accounting.

The earliest non-WRC-funded research on the salt load associated with irrigation was done by Van der Merwe (1969, 1973), which culminated in some guidelines still used today. These guidelines were captured by the Department of Agricultural Technical Services in a document published in 1975 and include (Van der Merwe et al., 1975):

- the chemical characteristics of some dams and rivers in central South Africa;
- classification of salt-affected soils;
- salinity and boor threshold levels for popular crops;

- leaching guidelines in terms of drainage required to remove excess salts for a range of soil textures and;
- amount and type of reactants needed to reclaim sodic soils.

The earliest WRC-funded research on the salt load associated with irrigation was on the evaluation of four-electrode and electromagnetic induction techniques of soil salinity measurement (Johnston, 1994). Moolman (1993) tried to resolve a number of questions and uncertainties regarding the use of solute transport models, while Moolman et al. (1999) investigated the effects of salinity on grapevines and evaluated the salinity criteria used to manage salinity levels in the Breede River. In a continuation of this project, De Clercq et al. (2001a, 2001b) studied the "effects of saline irrigation water and managerial options on soil properties and plant performance" as well as "experimental irrigation of vineyards with saline water". In a project entitled "Water quality information systems for integrated water resource management: For the Riviersonderend-Berg River System", the research by Görgens and de Clercq (2006) was the first step in modelling the very diverse occurrence and variability in soil salinity of the system.

The majority of salinity research was conducted where mainly field crops are grown along the Lower Vaal River in central South Africa. These studies focused on salinisation of the Lower Vaal River and its tributaries (Du Preez et al., 2000), groundwater at Vaalharts Irrigation Scheme (Herold and Bailey, 1996; Ellington et al., 2004; Verwey et al., 2011) and soils along the Lower Vaal River (Du Preez et al., 2000) and the economic feasibility of artificial drainage in central South Africa (Viljoen et al., 2006). Similar to these studies, Volschenk et al. (2005) did a "situation analysis of problems for water quality management in the Lower Orange River region with special references to the contribution of foothills to salinisation". This was done in an attempt to identify problems for water-quality management in the lower Orange River region, specifically to the salinity contribution of the foothills, where extensive irrigation development occurred. The effect of salinity on crop-water use and yield of field crops like maize, wheat, peas and groundnuts were also studied under controlled field lysimeter conditions (Ehlers et al., 2007).

In 2015 Nell et al. (2015) looked at a methodology for monitoring waterlogging and salt accumulation on selected irrigation schemes in South Africa. The authors concluded that approximately 6% of field surveys conducted in nine irrigation schemes were waterlogged (groundwater table < 1.2 m from surface) and salt-affected (electrical conductivity of saturation extract > 400 mS m^{-1}). Recently the 1996 irrigation water quality guidelines of South Africa were revised into a software-based decision support system (DSS), which allows for a risk-based approach and more site-specificity (Du Plessis et al., 2017). With the DSS both a fitness-for-use of irrigation water and establishment of irrigation water, quality requirements are assessed with regard to the effect its constituents have on soil quality, crop yield and quality as well as irrigation equipment. A Tier 1 assessment with the DSS represents a rapid "conservative" irrigation water quality assessment. With Tier 2 the user can choose between selectable site-specific conditions, which, according to Du Plessis et al. (2017), "provide a significantly enhanced assessment of how the specific water composition can be expected to affect a specific crop, under specific climatic conditions with defined, selectable, irrigation management when irrigating a soil with a specific, selectable, texture".

At on-farm level, the irrigation water quality DSS would advise a farmer if the water is ideal, acceptable, tolerable or unacceptable for irrigation. No on-farm practices are provided on how to manage the associated salts irrespective of whether the specific water quality is ideal or unacceptable. However, in 2012 Prof's Bennie, Du Preez and Van Rensburg formulated best on-farm water and salt management practices after an extensive review of literature (as cited above) and assessment of current practices employed by farmers in semi-arid central South Africa. These formulated best on-farm water and salt management practices are provided in Figure 4.1.

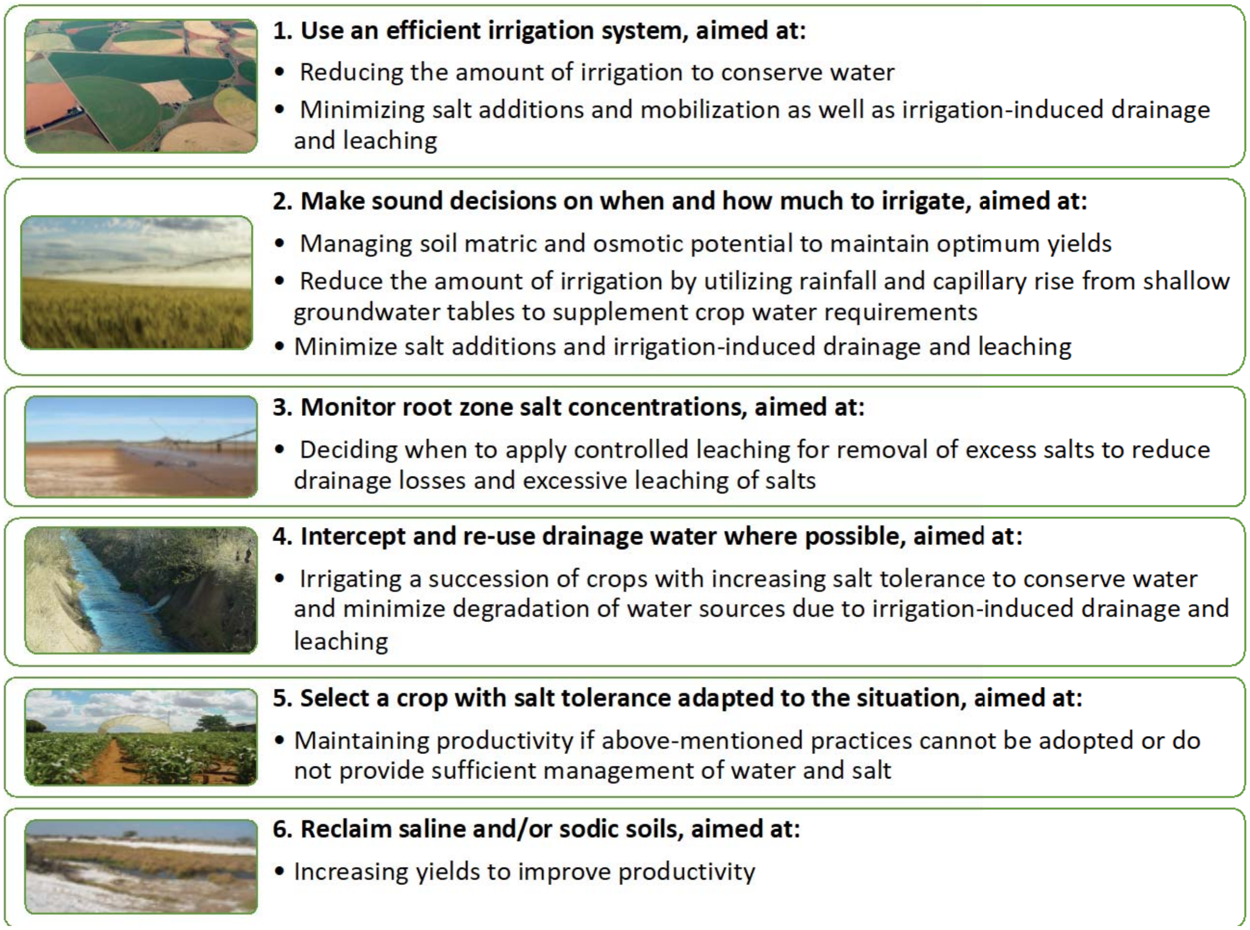


Figure 4.1 Formulated best on-farm water and salt management practices (adapted from Van Rensburg et al., 2012).

4.2 Precision agriculture for within-field water and salt management

4.2.1 Background

Before 1980 precision or site-specific management was at the farm level, i.e. the field was considered the management unit. Soil and/or crop monitoring was done to determine the mean value for the field and the yield as the total harvest taken from the field. According to Olivier (2010) from about 1990 “the term precision agriculture has been driven forward and been underpinned by technology changes based on information technology”. There are many definitions of precision agriculture because there are different ideas of what precision agriculture should be. Four of the most general definitions are listed below:

- Precision agriculture: A management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production. Three components are suggested, i.e. i) obtaining data at an appropriate scale, ii) interpretation and analysis of the data and iii) implementation of a management response at an appropriate scale and time.

- Precision agriculture: An integrated information- and production-based farming system that is designed to increase long-term, site-specific and whole-farm production efficiency, productivity and profitability, while minimising unintended impacts on wildlife and the environment.
- Site-specific management: The management of agriculture crops at a spatial scale smaller than the whole field that takes account of local variation to cost-effectively balance crop productivity and quality, detrimental environmental impacts and the use of resources (e.g. water, fertiliser, pesticides, etc.) by applying them when, where and in the amount needed.
- Site-specific-crop management (SSCM): A form of precision agriculture whereby decisions on resource application and agronomic practices are improved to better match soil and crop requirements as they vary in the field.

Precision agriculture uses state-of-the-art scientific knowledge and technology to address the spatial and temporal complexities of crop fields, which are the result of “a complex interaction of biological (e.g. pests, earthworms, microbes), edaphic (e.g. salinity, water content, organic matter, nutrients, texture), anthropogenic (e.g. leaching efficiency, soil compaction), topographic (e.g. slope, elevation) and climate (relative humidity, temperature, rainfall) factors” (Corwin and Lesch, 2010). SSCM is regarded as a form of precision agriculture whereby decisions on resource application and agronomic practices are improved to better match soil and crop requirements as they vary in the field (Whelan and Taylor, 2013). With SSCM, the focus is on decision-making with regard to resource use and not necessarily on the adoption of information technology. SSCM is predicated on a delicate balance of maximising crop productivity to maintain economic stability, while minimising the use of natural resources and detrimental environmental impacts.

For spatio-temporal management of water and salt, the general objectives of precision agriculture as reported in Whelan and Taylor (2013) can also be adopted. Firstly, SSCM aims to optimise returns across a field. With regard to the salt load associated with irrigation, this can be achieved by ensuring minimal soil water (matric) and salinity (osmotic) stress for crops and reduced soil permeability (sodicity) across the field. Secondly, on-farm management decisions should tailor inputs of water and salt to meet production needs, which will decrease the net loss of the applied input to the environment, i.e. conserve water and minimise salt additions and irrigation-induced leaching. SSCM can also offer producers detailed evidence to contest claims regarding negligent water and salt management across a field. A by-product of SSCM is the general improvement in the understanding of a production system and potential implications of different management options. There can also be future incentives for farmers to capture and use information on the environmental footprint of their salt load. Thirdly, SSCM offers a risk-management solution by improving the understanding of the environment-crop interaction in terms of the salt load associated with irrigation, and a more detailed use of emerging and existing information technologies. However, it will be difficult to change the general opinion by irrigation farmers that minimising production risk, through the application of excess water, is more important than environmental risk; namely “the universal tendency of humans to assume that if a little of something is good more must be better” (Hillel and Vlek, 2005).

SSCM consists of five fundamental components (Corwin, 2013; Whelan and Taylor, 2013), namely i) spatial in situ direct or indirect soil, crop, terrain and climate measurements and monitoring ii) mapping of these attributes iii) decision support and iv) deferential action. Geo-referencing or spatial referencing are then the last component and central to adopting and implementing SSCM. Decision support is used to determine the optimum strategy for production when implementing SSCM. Basically soil, crop, terrain and climate measurements and monitoring are combined with information of possible management options to formulate differential actions. Information of possible management options can be obtained through practical experience, scientific literature or mathematical soil-crop models. Deferential action is defined as a management operation where more than one level of a treatment or activity is undertaken, while variable-rate technology (VRT) is used in the actual application of inputs, i.e. fertiliser and gypsum/lime applications, sowing, spraying and irrigation. Areas are established where these inputs are needed, which are referred to as site-specific management zones or site-specific management units (SSMU). According to Corwin (2013) these units may or may not be temporally or spatially stable. A temporally unstable example is where areas are delineated for gypsum application to reduce Na on exchange sites. Once Na is reduced sufficiently with site-specific gypsum application the SSMU will become irrelevant. In contrast, SSMU for irrigation to meet plant available water, which is predominantly influenced by texture, are generally temporally and spatially stable.

4.2.2 Measuring and monitoring of relevant attributes

Soil, crop and terrain measurements and monitoring are basically done via yield monitoring systems, in situ soil and crop measurements, soil sensing systems, terrain sensing, airborne and satellite optical imagery and proximal crop reflectance sensors (Whelan and Taylor, 2013). The indirect soil and crop sensing techniques that can be applied in spatial water and salt management has become very popular because it is less expensive and time consuming. In addition, these techniques provide a much higher spatial resolution compared to in situ direct sampling. It is important to note however that these indirect soil and crop sensing techniques still require calibration or ground-truthing. Table 4.4 highlights some of the popular techniques for proximal on-the-go monitoring of some physical and chemical soil properties considered important in on-farm water and salt management.

Table 4.4 Currently available and potentially useful techniques for proximal, on-the-go monitoring of important soil chemical and physical properties (Whelan and Taylor, 2013)

Soil property	Techniques that show potential	Calibrating or ground-truthing
Soil sodicity	Electromagnetic induction Resistivity	Laboratory-based test for soil dispersion Laboratory-based test for cation exchange capacity (CEC)
Soil salinity	Electromagnetic induction Resistivity Ground-penetrating radar	Laboratory-based test for electrical conductivity Crop visual indication of growth patchiness
Soil texture	Gamma radiometrics Electromagnetic induction Resistivity Visible/NIR/MIR spectroscopy Ground-penetrating radar	Hand texturing of soil sample Laboratory-based particle size analysis
Soil water (PAWC and PAW)	Electromagnetic induction Resistivity Visible/NIR/MIR/Thermal IR spectroscopy Ground-penetrating radar	Drained upper limit (DUL) estimates Crop lower limit (LL) estimates
Waterlogging / Shallow water tables	Elevation Electromagnetic induction Resistivity	Piezometers/dip wells Visual observation of crop chlorosis Surface water ponding Soil hydraulic properties
Rooting depth	Electromagnetic induction Resistivity Ground-penetrating radar	Soil pit profile description Manual push probe

4.2.3 Attribute mapping

Large spatial intensive data sets are produced by the measurements and monitoring of terrain, soil and crop attributes related to on-farm water and salt management. These data sets need to be cleaned and mapped into a continuous surface to permit analysis, which is done through deterministic or stochastic interpolation methods. Important aspects that need to be considered in making and interpreting maps for SSCM are, data quality, cleaning and presentation, spatial interpolation or prediction, map comparison and map legend and map interpretation.

The generalised workflow by ArcGIS 10.4 software suite geostatistical analyst tool (Figure 4.2) provides an excellent practical summary of the steps that must be taken in geostatistical studies. Firstly, the data must be closely examined and mapped. In this process, a trend analysis is done and the spatial structure and directional variation examined, while delustering to adjust for preferential sampling can also be implemented. The second stage consists of building a geostatistical model, which can involve several steps. During this stage, the complexity of the model is determined together with how good the interpolated and measures of uncertainty would be. Modelling the spatial structure in the dataset is essential to the pre-processing of data. Stochastic methods like Kriging requires that the spatial structure is explicitly determined with semi variogram and covariance functions. Unfortunately, the ease with which one can Kriging these days, at the press of a few buttons without the necessary understanding, produces in most cases, unreliable and even misleading results. Olivier and Webster (2014) highlighted that when Kriging is used it is crucial to estimate the variogram reliable and model it in accordance with valid mathematical functions.

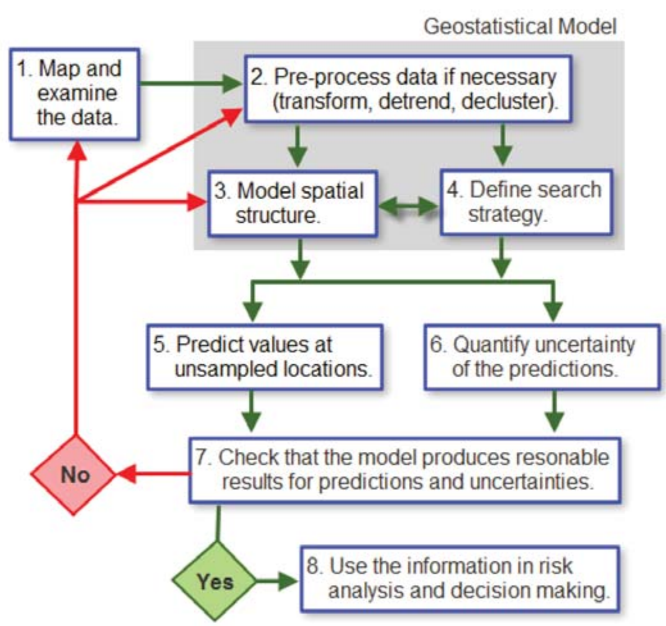


Figure 4.2 Generalised workflow for geostatistical studies as recommended by the geostatistical analyst toolkit of the ArcGIS 10.4 software suit (Esri).

Factors that affect the reliability of the experimental variogram include sample size, lag interval and bin width, marginal distribution of data, anisotropy and trend. In their educational tutorial paper Olivier and

Webster (2014) developed a list of steps and what should be reported in an investigation that requires only straightforward least-squares geostatistical analysis (Figure 4.3).

1. Sample sufficiently without bias. For the variogram aim for a minimum of 100–150 points to provide six to ten estimates within the expected effective range. For mapping by kriging sample evenly to give even coverage at intervals of less than half the effective range.
2. Compute the marginal distribution of each variable, identify outliers and decide what to do about them, and transform the data to stabilize variances if necessary. Summarize the statistics and report your treatment of outliers and any transformation.
3. Compute the variogram on the raw or transformed data by the method of moments (or a more robust method), fit plausible models by weighted least squares approximation. State the steps in which lag was incremented, your binning and the model you finally choose, and display that model on a graph of the experimental variogram.

If you identify a trend then estimate the trend and variogram of the residuals from the trend by REML. State the equation for the trend and display the variogram of the residuals.

4. Krige at points or over blocks of a size suitable for the application. In the absence of trend use ordinary kriging; if there is a trend then use universal kriging. Krige from a global kriging system or local ones in a moving window. State your choices.
5. Map the kriged estimates and their associated kriging variances.

Figure 4.3 List of steps and what should be reported in an investigation that requires only straightforward least-squares geostatistical analysis as suggested by Olivier and Webster (2014).

Unlike stochastic methods (for example Kriging) deterministic methods like inverse distance weighing (IDW) do not determine the spatial structure, but rely on an assumed degree of spatial structure, which must be provided based on prior knowledge of the measured variable. During the search strategy the number of data points used to generate a value for an unsampled location is determined. After using the model to make predictions at unsampled locations, the same model can be used to generate measures of uncertainty for the interpolated values. Not all models, however, have this capability, which makes a classification tree as recommended by a geostatistical analyst, extremely helpful. The decision is based on what your objective is in developing an interpolation model, for example:

i. What information does your decision require, only predictions, or prediction values and errors?
ii. Does the method require measurement or model of spatial autocorrelation?
iii. What type of output do you require (predictions, prediction errors, probability or full distribution of possible values)?
iv. Level of assumptions or complexity of the model
v. Type of interpolation
vi. Smoothness of output
vii. Whether uncertainty of the predicted values is provided
viii. Processing speed.

4.2.4 Decision support with transient soil-crop-water salinity models

In implementing SSSM, a DSS will be extremely useful to determine the optimum strategy for production, namely, an information system that supports decision-making. The DSS basically uses an agronomic and environmental data, i.e. soil, crop and climate measurements and monitoring, combined with information (which includes scientific literature and/or a crop or soil-plant-atmosphere model) of possible management options to formulate differential actions. The aim of this section is not to provide a comprehensive review of all transient-state models, but rather to discuss some of the general approaches adopted by popular models and highlight differences between them.

Soil-water flow: The basic component that any transient-state model must allow for is one-dimensional soil-water flow. It is recognised that some models (for example HYDRUS) can also allow for two and three-dimensional soil-water flow and solute transport. Soil-water models can be categorised according to the degree of complexity the soil profile is treated with (Ranatunga et al., 2008). Complex models incorporate a continuous soil profile and are based on the hydraulic and hydrodynamic behaviour and movement of water through porous media, for example ENVIRO-GRO, SWAP, HYDRUS, UNSATCHEM, SALTMED and FAO-Salinity Laboratory SWS (references listed in Table 4.2). Generally, these complex soil water models focus on numerical solutions (finite-difference and finite-element methods) to solve Richards' equation (Equation 4.3), where θ is the volumetric soil water content, h the soil water pressure head, t time, z the depth, K the hydraulic conductivity and S sinks or sources for water.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} - K(h)\right] - S \qquad (4.3)$$

Hence, in addition to downward water movement these models can also allow for upward flow due to capillary rise from a groundwater table within or just below the potential root zone. To solve Richards' equation, water retention (θ(h)) and hydraulic conductivity functions (K(h)) for a specific soil are required. The parameters that normally describe these functions include the saturated hydraulic conductivity (K_s), residual (θ_r) and saturated volumetric soil water content (θ_s), and empirical m, n and α parameters. Because these models can also use different water retentivity and hydraulic conductivity functions or adaptations to the same relationships, different parameters describing these relationships will be required depending on the specific model. For example, in ENVIRO-GRO, SWAP and UNSATCHEM, typically the parameters α, n and m will be required for a specific soil to describe the relationship proposed by Van Genuchten (1980). In SALTMED a specified air entry pressure head and pore size distribution coefficient are required which are converted internally to α and n, while in HYDRUS any of four relationships can be chosen, i.e. Van Genuchten-Mualem, modified Van Genuchten, Brooks-Corey or Kosugi (Šimůnek et al., 2012) with different parameters. With FAO-Salinity Laboratory SWS an r parameter is also added to allow for the chemical effects on hydraulic conductivity, while in SWAP two sink terms were added to Richards' equation to allow for the extraction rate by drain discharge and the exchange rate with macro-pores. This will be important in soils where artificial drains are installed in the saturated zone below the groundwater table level, and soils that are prone to swelling and shrinking. In addition, models like SWAP and HYDRUS can also account for hysteresis. FAO-Salinity Laboratory SWS has an option of determining the water flow parameters from soil texture (Carsel and Parrish, 1988) with pull down menus. This was done to eliminate detailed studies on water retention and hydraulic conductivity of each soil when evaluating the suitability of a specific water source for irrigation. Other software packages that could be used in combination with water flow models as a plugin, to estimate parameters for water retention and hydraulic conductivity functions from measurements of soil texture and/or bulk density, include SWCT (Soil water characteristic from texture), SOILPAR, ROSETTA and NEUROPACK (Schaap 2004).

In contrast to complex soil-water models, simple soil-water models have a fixed number of soil layers and a cascading (tipping bucket) approach to water movement or redistribution of rainfall and irrigation, for example SWB and SWAMP. Hence, the initial volumetric soil water content ($\theta_{initial}$) of each soil layer and the volumetric soil water content at field capacity (θ_{fc}; drained upper limit or upper limit of plant available water) and permanent wilting point (θ_{pwp}; lower limit of plant available water) are normally required as parameters. Both SWB and SWAMP can also allow for upward flow due to capillary rise from a groundwater table. SWAMP uses the approach of Malik et al. (1989) where the maximum upward flux from a water table is related to a specific height above the water table, which can be applied to apedal sandy to sandy clay soils (Ehlers et al., 2003). In 2004, a new subroutine that simulates infiltration and redistribution in the soil profile by making use of a finite difference solution to Richards' continuity equation for water flow were added to SWB. Thus, the model can also be classified as a complex soil-water model and can allow for upward flow due to capillary rise from a groundwater table (Jovanovic et al., 2004).

Growth and yield: Three of the eight models listed in Table 4.2, i.e. SWAP, SALTMED and SWB, make provision for using a plant growth subroutine. These models, in various degrees of complexity, generally allow for some or all of the growth defining and growth limiting factors. For example, SWAP will allow for growth defining factors like radiation intensity, carbon dioxide concentration, temperature and crop characteristics, which determine potential production of a specific plant in a specific environment (Kroes et al., 2008). The growth limiting factors, i.e. water and/or salinity stress, as quantified by actual water uptake and subsequent actual transpiration, will limit production by reducing the potential gross photosynthesis. A part of the carbohydrates that are produced, is used to provide energy for maintenance of respiration, while the remaining carbohydrates are converted into structural matter. The dry matter is then partitioned among roots, stems, leaves (which determine leaf area development and light interception) and storage organs, with the dry weights of plant organs determined by integrating their growth rates over time. SWAP can also allow during the development of a plant, for a part of the biomass that dies due to senescence (Kroes et al., 2008). Table 4.5 provides the steps or calculation procedures that are followed in simulating plant growth with SWAP and SWB, which require many calibrated parameters for specific crop-climate conditions.

Table 4.5 Steps or calculation procedures that are followed in simulating plant growth with the models SWAP and SWB

Procedure	SWAP	SWB
1	Phonological development stage	Fractional interception of radiation
2	Radiation fluxes above canopy	Crop height
3	Radiation profiles within canopy	Daily dry matter production
4	Instantaneous assimilation rate per leaf layer	Daily harvestable dry matter
5	Daily gross assimilation rate of the canopy	Partitioning of dry matter into plant organs
6	Maintenance of respiration	Leaf area index
7	Dry matter partitioning and growth respiration	Rooting depth
8	Senescence	-
9	Net growth	-
10	Root growth	-

A popular alternative option also included in SWAP and SALTMED and adopted by most of the models listed in Table 4.2, is not to simulate plant growth per se, but rather simulate water uptake and then relate the seasonal uptake to seasonal potential uptake to calculate the relative yield. Potential uptake refers to non-limiting water supply from the soil and is determined only by plant characteristics and climatic conditions, i.e. the product of potential transpiration (T_P) rate and a normalised root distribution function ($\beta(z)$) of which a variety of functions can be used.

Potential evaporation and transpiration: The Penman-Monteith equation (Monteith, 1965, 1981) is generally applied to a reference grass, expressed as the ET of a clipped cool-season grass (ET_0), and combined with crop factors to determine the potential evapotranspiration (PET) of a crop, i.e. FAO-Salinity Laboratory SWS, SWB, SWAP, SALTMED, ENVIRO-GRO and HYDRUS. The ET_0 is normally calculated according to the methodology outlined in FAO 56 (Allen et al., 1998) using routinely measured weather data like air temperature, global radiation, wind speed and relative humidity.

Most of the models listed in Table 4.2 allow for separation of PET into E_P and T_P by using either the leaf area index or soil cover. SWAP also has an additional option where the evapotranspiration rate from a wet and dry canopy, completely covering the soil, and a wet, bare soil are calculated. With this approach values for crop resistance, crop height and reflection coefficient for the three listed surfaces are required.

Actual transpiration and root-water uptake: Two approaches are generally adopted to simulate actual root water-uptake, i.e. microscopic and macroscopic. Microscopic water uptake involves descriptions of radial flow to, and uptake, by individual roots, whereas water uptake modelling with the sink term in Richards' equation is typically a macroscopic approach, i.e. water uptake is averaged over a large number of roots (Skaggs et al., 2006). The pore scale variations in the pressure head or solute concentration in the immediate vicinity of the roots are ignored with this approach. The discussion to follow will be limited to the macroscopic approach, although some of the models listed in Table 4.2 can allow for microscopic water uptake (for example SWAP). Macroscopic water uptake models generally calculate the sink terms for water uptake in Richards' equation from the potential uptake and a dimensionless water-stress response (reduction) function, i.e. Type II formulations (Cardon and Letey, 1992).

The dimensionless water-stress response function (α, reduction function) can be postulated for matric (h = pressure head) and osmotic stress (π = osmotic head) (Skaggs et al., 2006) with piecewise linear or alternative smooth S-shaped reduction function (Table 4.6). Adjustable parameters to reduce water uptake according to critical pressure heads and critical osmotic heads, which corresponds normally to the Maas and Hoffman threshold and slope parameters (Maas and Hoffman, 1977; Maas, 1990) are used (Figure 4.4). In order to combine the matric and osmotic stresses, either an additive or a multiplicative approach is used (Table 4.6). Models like FAO-Salinity Laboratory SWS, SWAP, SALTMED and HYDRUS contains default parameter values for $\alpha(h)$ and $\alpha(\pi)$ from which a selection can be made for different crops. The salinity threshold and slope parameters for $\alpha(\pi)$ should, however, be used with caution, as determining these parameters from literature remains a challenge. According to Skaggs et al. (2006):

- Crop salt tolerance information (salinity threshold and slope) serves only as a guideline. Absolute tolerance will vary, depending on climate, soil conditions and agronomic practices.
- In most cases studies fail to report environmental and agronomic factors affecting yield, hence, crop salt tolerance determined with this insufficient data will be biased.
- These reduction functions are parameterized at local total potential heads, while salinity threshold and slope parameters express salt tolerance at a time and root zone average soil salinity.
- Extensive crop- and site-specific calibration of these parameters, involving inverse modelling is required.

Despite these difficulties, Type II root water uptake formulations remain popular (Oster et al., 2012). This is because Type I formulations were found to be insensitive to salinity and water content (Cardon and Letey, 1992), i.e. Type I describes the physics of water flow from the soil to and through the plant roots.

Table 4.6 Piecewise linear and alternative S-shaped water-stress uptake reduction functions of Feddes et al. (1978) and van Genuchten (1987) as described in Skaggs et al. (2006)

Stress	Piecewise linear	S-shaped
Water	$\alpha(h)=\begin{cases}\dfrac{h-h_4}{h_3-h_4}, & h_3>h>h_4\\ 1, & h_2\geq h\geq h_3\\ \dfrac{h-h_1}{h_2-h_1}, & h_1>h>h_2\\ 0, & h\leq h_4 \text{ or } h\geq h_1\end{cases}$	$\alpha(h)=\dfrac{1}{1+\left(\frac{h}{h_{50}}\right)^{p_1}}$
Salinity	$\alpha(\pi)=\begin{cases}1, & a\leq\pi\leq 0\\ 1+b(\pi-a), & a>\pi>a-\dfrac{1}{b}\\ 0, & \pi\leq a-\dfrac{1}{b}\end{cases}$	$\alpha(\pi)=\dfrac{1}{1+\left(\frac{\pi}{\pi_{50}}\right)^{p_2}}$
Additive	-	$\alpha(h,\pi)=\dfrac{1}{1+\left[\frac{a_1 h+a_2\pi}{\pi_{50}}\right]^{p_2}}$
Multiplicative	-	$\alpha(h,\pi)=\dfrac{1}{1+\left(\frac{h}{h_{50}}\right)^{p_1}}\dfrac{1}{1+\left(\frac{\pi}{\pi_{50}}\right)^{p_2}}$

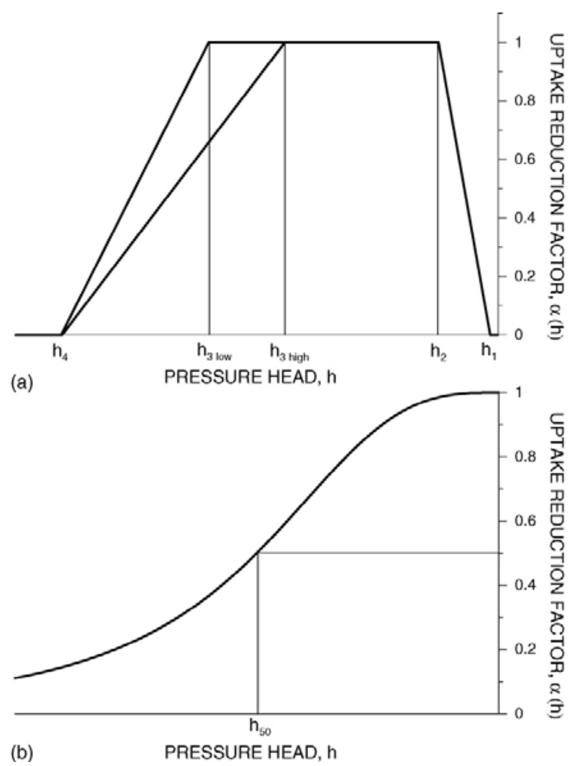


Figure 4.4 Piecewise linear (a) and alternative S-shaped (b) water-stress uptake reduction functions of Feddes et al. (1978) and van Genuchten (1987) as described in Skaggs et al. (2006).

Recently an alternative model (SWAMP), that does not rely on the salinity threshold and slope parameters for the piecewise linear or S-shaped reduction functions, was presented and evaluated with data from a lysimeter trial (Barnard et al., 2015). Water uptake of peas and maize grown in sand to sandy loam soils subjected to osmotic stress was simulated successfully with an algorithm that computes the water supply of a rooted soil layer. The supply of water must be adequate to provide the crop with enough water to prevent any stress and is a function of soil-root conductance, relative soil water content, rooting density and the soil-root hydraulic gradient. As the soil dries and/or salinity increases the water supply will decrease until T_P of the crop cannot be satisfied, which causes a reduction in water uptake. It was found that no extensive calibration of the soil-root conductance coefficient, rooting density and critical leaf water potential parameters for the algorithm during the trial was necessary because these parameters were successfully calculated from measured inputs. Although not tested, but due to the nature of the algorithm, it is anticipated that SWAMP will be able to simulate compensated water uptake, i.e. plants can extract more water from non-stressed (matric and/or osmotic) parts of the root zone to meet T_P. On the contrary, HYDRUS and ENVIRO-GRO were successfully tested and allow for compensated water uptake (Oster et al., 2012).

Salt transport: In complex soil water models like ENVIRO-GRO, SWAP, HYDRUS, UNSATCHEM, SALTMED AND FAO-Salinity Laboratory SWS, salt transport is calculated using the convection-dispersion equation (Equation 4.4), where c is the concentration of salt, D the dispersion coefficient and q the volumetric water flux. Generally, the sink term is not included in the equation because salt uptake by plants is assumed to be negligible. This is not true for models that allow uptake of a specific solute, for example SALTMED.

$$\frac{\partial c\theta}{\partial t} = \frac{\partial}{\partial z}\left[\theta D\frac{\partial c}{\partial z} - q(c)\right] \tag{4.4}$$

Furthermore, the dispersion coefficient can be determined from the dispersivity, molecular diffusion and tortuosity parameters. The equation is normally used for a nonreactive, non-interacting solute. The equation can, however, also allow for total adsorbed or exchangeable concentration of each aqueous component and non-adsorbed solid phase concentration of each aqueous component, for example FAO-Salinity Laboratory SWS, by adding a second and third term on the left side of Equation 2.4. HYDRUS also allows for non-equilibrium flow, which pertains to dual-porosity or dual-permeability flow regimes, where a fraction of the liquid phase is assumed to be mobile and a fraction immobile (Šimůnek et al., 2012). The transport equation in SWAP also includes non-linear adsorption, linear decay and proportional root uptake.

With the overflow of water from one layer to the next, according to the cascading approach, salt is also transported. The relationship between the fraction of salt removed per unit soil depth and volume of percolation per unit soil depth (leaching curves; Barnard et al., 2010), can be used in the cascading transport of salts through miscible displacement (the solution is mixed by a combination of dispersion and diffusion), for example SWAMP. Leaching curves are, however, empirical and will differ depending on soil texture, sodicity and water application rates. Furthermore, salt can also be distributed by assuming complete mixing of rainfall and irrigation water with the soil solution in the top soil layer, for example SWB. Similarly, this will then be repeated for the soil solution percolating to the next lower soil layer. With such a chemical equilibrium approach, chemical precipitation or dissolution of lime and gypsum can be calculated daily for each soil layer. The initial content of ionic species (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-} and SO_4^{2-}) are required for each soil layer, while the EC is calculated daily from individual ion concentrations (McNeal et al., 1970).

Heat transport and concentration/production of carbon dioxide: Some of the models listed in Table 4.5, for example SWAP, HYDRUS SALTMED and FAO Salinity Laboratory SWS, also allow for temperature (heat transport) in the soil. This is important in allowing chemical speciation, mineral equilibrium, plant root growth and prediction of carbon dioxide. In FAO Salinity Laboratory SWS the heat transport routine of Šimůnek and Suarez (1994) are included (Equation 4.5), where $\lambda(\theta)$ is the apparent thermal conductivity coefficient of the soil and $C_P(\theta_w)$ and C_w the volumetric heat capacities of the soil solid and liquid phases, respectively. Furthermore, FAO Salinity Laboratory SWS also allows for carbon dioxide production due to soil microorganism and plant roots, and the subsequent transport through Knudsen diffusion, multi-component molecular diffusion and viscous flow.

$$C_P\left(\theta_w\right)\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left[\lambda\left(\theta_w\right)\frac{\partial T}{\partial z}\right]-C_w q_w\frac{\partial T}{\partial z} \qquad (4.5)$$

4.3 Apparent soil electrical conductivity for spatial characterising soil variability

Geophysical techniques such as electromagnetic induction (EMI) or electrical resistivity (ER) were and are still used in measuring apparent soil electrical conductivity (EC_a) to address field-scale spatial soil variability. There are several commercially available non-invasive electromagnetic induction (EMI) sensors used for soil investigations that measure EC_a (Doolittle and Brevik, 2014), which include the DUALEM sensors (Dualem, Inc., Milton, Ontario), the Profiler EMP-400 (Geophysical Survey Systems, Inc., Salem, New Hampshire) and the EM38 sensors such as the EM38, EM38-DD, EM38-MK2-1 and EM38-MK2 (Geonics Limited, Mississauga, Ontario, Canada). The Veris 3100 system (Veris Technologies) is an example of an invasive commercial ER sensor, while the four-electrode sensors configured as fixed-surface arrays include the equipment developed by Rhoades (1992, 1993) and Carter et al. (1993).

The use of EMI or ER sensors for effective soil investigations in SSCM or soil quality assessments requires an understanding of EC_a, which, although a complex measurement, is reliable and easy to mobilise. The complexity of the EC_a measurement lies in the direct influence of several soil properties on bulk soil conductance, while some soil properties can be indirectly associated with EC_a. In addition, secondary confounding effects like positional offset, metal, surface topography and elevation, surface roughness, irrigation management, compaction and ambient temperature also influence EC_a. These secondary confounding effects should be minimised to obtain reliable data. Primary influences include soil temperature, water content, salinity, texture, bulk density, organic matter and magnetic susceptibility.

According to Rhoades et al. (1989, 1999), as illustrated in Figure 4.5, EC_a is a product of three parallel pathways of conductance. Hence, as emphasised by Corwin and Scudiero (2016), “the ability to measure a particular target soil property or properties with EC_a depends on the property or properties dominating the EC_a measurement at a specific site of measurement”. EC_a-directed soil sampling refers to the approach of characterising soil spatial variability from soil samples guided by variations in spatial EC_a measurements. It is based on the notion that when there is a significant relationship between EC_a and a target soil property or properties, then soil sampling sites selected through spatial variation in EC_a measurements will reflect the range and spatial variability of the property or properties (Corwin and Lesch, 2005b). Thus, soil sampling sites are used for ground-truth to calibrate EC_a to the target property or properties.

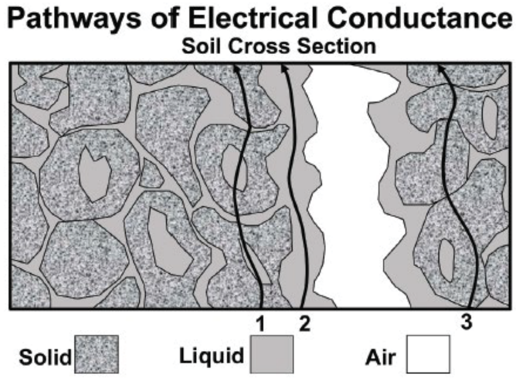


Figure 4.5 Snapshot of a schematic illustration of the three conductance pathways for the apparent soil electrical conductivity measurements (obtained from Corwin and Scudiero, 2016, modified from Rhoades et al., 1989). Pathway 1 = solid-liquid conductance, Pathway 2 = liquid conductance and Pathway 3 = solid conductance.

At pedon scale the models of Rhoades et al. (1990) and Lesch and Corwin (2003) can be used to deal with the inseparable influences of soil properties affecting EC_a. However, soil sampling (obtained from EC_a-directed soil sampling design) to develop a field-specific model to calibrate EC_a to a target property is the best option at field scale to statistically separate the effects (Lesch et al., 2005). Corwin and Scudiero (2016), however, emphasise that numerous EC_a studies have revealed "the site specificity and complexity of spatial EC_a measurements with respect to the particular property or properties influencing EC_a at the measured site", i.e. field-specific calibration models.

Scientists at the USDA-ARS US Salinity Laboratory (Rhoades, J.D., Corwin, D.L. and Lesch, S.M.) over a number of decades have led the way in understanding the primary and secondary influences on EC_a and how to use EC_a in soil investigations related to SSCM. Unfortunately, as emphasised by Corwin and Scudiero (2016) environmental and agricultural scientific literature is unedited with devious soil property spatial data obtained through EC_a measurements. These studies have failed to follow the guidelines and protocols first developed by Corwin and Lesch (2003, 2005b, 2013) that are based on the EC_a-directed soil sampling methodology. In terms of commercial application, the grain industry in Australia realised that contractors who use EMI or ER technology collect and process data with varying quality and procedures, because of the complex nature of the EC_a measurement. The Grains Research and Development Corporation (CRDC) in Australia funded a workshop for the development of a grains industry standard, which is based on the guidelines and protocols developed by Corwin and Lesch (2003, 2005b, 2013). This standard for electromagnetic induction mapping in the grain industry was published in 2006 by the Grains Research and Development Corporation, Australia. Corwin and Scudiero (2016) provide an excellent overview that encapsulates decades of research regarding EC_a measurements. The objective of the publication was to provide an overview of the standardised methodology for spatial characterisation of soil variability using EC_a measurements. The reader is referred to this publication by Corwin and Scudiero (2016). Detail is provided on the background and rationale for EC_a-directed soil sampling and spatial characterising of a specific soil property, mobilised EC_a measurement equipment as well as, strengths, limitations and interferences. The majority of the discussion in Corwin and Scudiero (2016) is on the 10-step protocols as a standardised methodology for using EC_a measurements in spatial soil investigations (Table 4.7).

Table 4.7 Snapshot of the apparent soil electrical conductivity protocols for mapping spatial variability (obtained from Corwin and Scudiero, 2016, who modified it from Corwin and Lesh (2005b, 2013).

1. Metadata, site description, GPS, and EC_a survey objective
   a. Record metadata (e.g., equipment used, data format, date and time of data collection, etc.).
   b. Study site description: site location, soil survey information, presence or absence of vegetation, type of irrigation, topography, and surface condition.
   c. Select GPS coordinate system, establish control points and boundary points.
   d. Define the project's/survey's objective (e.g., inventorying, spatiotemporal monitoring, site-specific management, etc.).
   e. Establish the target property (i.e., the property to be mapped) or properties based on the project's objective.
2. EC_a survey design
   a. Establish EC_a measurement intensity (i.e., number and location of traverses and space between EC_a measurements with careful consideration of edge effects).
   b. Minimise secondary influences on EC_a (e.g., compaction, surface roughness and geometry, metal).
   c. Special EC_a survey design considerations
      (1.) presence of beds and furrows: perform separate surveys for the beds and for the furrows
      (2.) vineyards with metal trellising
         (a.) maximize distance from metal for surveys with electromagnetic induction (EMI)
         (b.) place an insulator between metal posts and trellis wires to break the conductance loop from the soil to the posts along the wires and back into the soil (this applies to both ER and EMI surveys)
      (3.) presence of drip lines: perform separate EC_a surveys over and between drip lines
      (4.) variations in surface geometry or roughness: perform separate surveys with separate sampling designs for each area differing in surface roughness or surface geometry (i.e., disked, beds and furrows, etc.)
      (5.) temporal studies
         (a.) reference all EC_a measurement to 25°C or
         (b.) conduct EC_a surveys at same time of day and same day of year
3. EC_a data collection with mobile GPS-based EC_a equipment (e.g., electrical resistivity or EMI)
   a. When using EMI, conduct drift runs to determine the effect of ambient temperature on EMI instrumentation.
   b. Georeference site boundaries and significant physical geographic features with GPS.
   c. Assure that water content at study site is at or near field capacity (370% field capacity) throughout the field (if water content is <70%, then do not conduct EC_a survey).
   d. Measure georeferenced EC_a data at the pre-determined spatial intensity and record associated metadata.
   e. Keep speed of mobile GPS-based equipment <10 km h^{-1} to reduce GPS positional errors.
4. Soil sample design based on geo-referenced EC_a data
   a. Statistically analyse EC_a data using an appropriate statistical sampling design (i.e., model- or design-based sampling design) to establish the soil sample site locations.
   b. Establish site locations, depth of sampling, sample depth increments, and number of cores per site (>100 soil samples are desirable but the total number of samples is largely determined by the resources available to analyse the soil properties of concern).
5. Soil core sampling at specified sites designated by the sample design
   a. Obtain measurements of soil temperature through the profile at selected sites.
   b. At randomly selected locations obtain duplicate soil cores within a 1-m distance of one another to establish local-scale variation of the target property (and other soil properties) for 20% or more of the sample locations.
   c. Record soil core observations (e.g., temperature, color, $CaCO_3$, gleying, organic matter, mottling, horizonation, textural discontinuities, etc.).
6. Laboratory analysis of target property and other EC_a -correlated soil properties relevant to the project objectives
7. Stochastic and/or deterministic calibration of EC_a to target property (and to other soil properties)
8. Spatial statistical analysis to determine the soil properties influencing EC_a
   a. Perform a basic statistical analysis of the target property (and other relevant soil properties) by depth increment and by composite depth over the depth of measurement of EC_a.
   b. Determine the correlation between EC_a and target property (and between EC_a and other soil properties) by composite depth over the depth of measurement of EC_a.
9. GIS database development
10. Graphic display of spatial distribution of target property (and other properties correlated to EC_a) using various interpolation methods (e.g., inverse distance weighting, cubic spline, geostatistics)

Step 1 to 3 are basically guidelines to collect metadata of the field, describe the field and objectives of the survey, design the survey and best practices when the EC_a measurements are collected. The ESAP-95 Version 2.01R (Electrical conductivity Sampling Assessment and Prediction) software was developed (at the US Salinity Laboratory) by Lesch et al. (2000) specifically to facilitate with step 4, 7, 8 and 10 of the protocols in order to obtain reliable data, interpretations and maps, namely: soil sampling design based on spatial EC_a measurements, stochastic and/or deterministic calibration of EC_a to EC_e or other target properties, spatial statistical analysis and graphical display.

With Step 4 a soil sampling design is provided by ESAP based on geo-reference EC_a measurements. The ESAP-RSSD module within the ESAP software uses a model-based (i.e. prediction based) response-surface sampling design. According to Corwin (2013) these sites are chosen to represent i) approximately 95% of the observed range in the bivariate EC_a-measurements, ii) represent the average of the EC_a readings for the entire field and iii) be spatially distributed across the field to minimise any clustering. Since the average separation between two sampling locations is maximized, any possibility of spatially correlated residuals (autocorrelation) from the linear regression is reduced. This ensures that the independent regression model residual error assumption remains approximately valid. It is then possible to use the regression model to predict a calibrated soil property at all non-sampled (remaining) EC_a measurements. Hence, ESAP-RSSD aims to select a minimum number of soil sampling locations to optimise the estimated model parameters and minimise the spatial-dependent error structure on the estimation process. Further details of this multi-step RSSD optimisation process can be found in Corwin and Scudiero (2016), Lesch et al. (2000) and Lesch (2005a). A design-based sampling scheme (i.e. probability-based) can also be used, but is not available as part of ESAP, for example simple random sampling, stratified random sampling, unsupervised classification and cluster sampling. Corwin and Scudiero (2016) concluded that there is no reason not to use the model-based sampling design of ESAP-RSSD. This was based on validation and comparison studies (Lesch and Corwin, 2008; Corwin and Lesch, 2010) of model- and design-based sampling strategies for characterisation of spatial-soil salinity with EC_a-directed soil sampling.

There is plenty of evidence where EC_a have been calibrated to a target soil property or properties, which are significantly influenced by the EC_a measurement. For example, soil salinity (Rhoades, 1992; 1996; Rhoades et al. 1989; Leach et al., 1995a), clay content (Williams and Hoey, 1987) and soil water content (Kachanoski et al., 1988) just to mention a few. Basically, the data analysis and interpretation of the majority of these studies can be classified in two modelling categories, namely stochastic and deterministic (Step 7). These approaches were described in detail by Lesch et al. (1995a, 1995b, 2000) and incorporated in the ESAP software. The deterministic approach typically requires additional soil property information. Basically, theoretical or experimental models are used to convert EC_a to EC_e and are regarded as static, i.e. the model parameters are considered known and EC_e need not be determined. The dual-pathway parallel conductance (DPPC) model of Rhoades et al. (1989) is an example of a deterministic approach (Figure 4.5), where measurements of clay or saturated percentage, soil water content and bulk density are used to estimate EC_e. The ESAP-Calibrate module within the ESAP software contains the deterministic DPPC model, which is used as a very powerful analytical procedure. Firstly, as described by Lesch et al. (2003) the DPPC model can be used through a correlation analysis to determine the degree of internal data validity and consistence of the overall EC_a survey process. Secondly, by using information of several soil properties (EC_e, SP or clay, soil water and bulk density) an expected correlation between EC_a and a specific soil property at a field can be estimated before the EC_a survey is done. Stochastic calibration models in general are dynamic because the parameters are estimated with soil sample data collected during the EC_a survey. These calibration models (for example co-kriging, regression kriging and linear modelling) are based on some form of objective sampling methodology used in combination with various statistical calibration techniques. ESAP-Calibrate uses (as a stochastic approach) a spatial referenced multiple linear regression model, which includes both EC_a measurements (and for example two depths) and trend surface parameters (spatial coordinate locations). It is important to note that decorrelated EC_a measurements are used with the spatial regression model and the scaled location coordinates to address autocorrelation and multicollinearity. As part of ESAP-Calibrate various numbers of EC_a measurements and trend surface parameters can be mixed together for the final model parameter combination. The software also contains an option where a number of possible parameter combinations are automatically examined. The parameter combination which generates to lowest cumulative PRESS score (PRESS score represents the sum of squares of the “jack-knifed” prediction errors) are then selected.

The risk of applying EC_a measurements to SSCM is the fact that EC_a is a function of several soil properties (for example soil salinity, texture and soil water content). With saline soils EC_e will in most cases dominate the EC_a measurement, however, in areas other than arid zone soils, texture, soil water content or even organic matter may dominate the EC_a measurement (Corwin and Scudiero, 2016). To apply EC_a measurements in SSCM requires (as part of Step 8) an understanding of what factors are most significantly influence the EC_a measurements within the field. The first approach is to use a wavelet analysis (Lark et al., 2003), which is a powerful tool but not as practical for determining spatial distributions of soil salinity (or another correlated soil property) from EC_a measurements (Corwin and Scudiero, 2016). The second approach is to use statistical correlation and graphical display as first developed by Lesch et al. (1995a, 1995b, 2000). Basic statistical parameters and an ANOVA analysis of the multiple linear regression calibration model are provided by ESAP.

The ESAP software also contains a SaltMapper module for graphical display of soil salinity or another correlated soil property. Any geospatial software package apart from ESAP-SaltMapper can be used in Step 10. The focus of this step is on the methods of interpolation to display the spatial distribution of a target soil property. Corwin and Scudiero (2016) highlights the fact that comparing interpolation methods have been met with mixed results. Sometimes Kriging (a stochastic method) has performed the best and in other cases the Inverse Distance Weighting (a deterministic method, IDW) method. The aim of Section 4.3 however is not to provide a detailed explanation of different interpolation methods. The reader is referred to Corwin and Scudiero (2016) and Section 4.2.3 for more information regarding determining which interpolation method suits the data best.

4.4 Summary and conclusion

Salt mobilisation in soils due to irrigation and additions through irrigation water causes onsite field related problems with soil salinisation and/or sodification decreasing crop yields and soil permeability. Offsite problems include groundwater and river water degradation due to excessive drainage and leaching, which waste valuable freshwater resources and leach essential nutrients from the root zone. Almost all irrigation, crop and soil science textbooks provide detailed discussions regarding the variables encountered in the field that determine the accumulation and distribution of salt within a soil, the response of different crops to salinity, the deterioration of soil permeability due to sodicity and associated environmental degradation due to the salt load.

Chapter 4 of this report (Volume 3) provided a synopsis of international and local literature regarding on-farm water and salt-management practices. These formulated on-farm practices (Figure 4.1) are regarded as “best practices” to address the on-site and offsite issues associated with irrigation. The practical guidelines on how to accomplish a specific best practice can be found in Volume 1 of the project and publications by the USDA-ARS US Salinity Laboratory and Food and Agriculture Organizations of the United Nations (FAO). The formulated best on-farm water and salt management practices are intended to complement the recently revised software-based irrigation water-quality guidelines of South Africa. For example, the best practices aim to sustainable (on-site and offsite) address the salt load associated with irrigation, whether a specific water is considered to be ideal or unacceptable for irrigation.

With the ever-increasing availability and affordability of technology to support decisions within a field, the need also exist for spatial water and salt management. The literature synopsis provided a discussion on how to accomplish this. This discussion is based on the published general framework for precision agriculture or rather site-specific-crop management, namely i) spatial in situ direct or indirect soil, crop and terrain measurements and monitoring ii) mapping of these attributes iii) decision support and iv) deferential action. Each of these components were briefly discussed in a general site-specific-crop management context and how it relates to spatial salinity management. From this discussion it was evident that the spatial measurement of EC_a through EMI or ER has and continues to play a significant role in characterising soil properties relevant to salinity management. As with site-specific-crop management mapping, these soil properties, through deterministic or stochastic interpolation methods need special attention when adopting site-specific-salinity management. In terms of decision support for salinity management, differences in the approaches adopted by popular transient state soil-crop-water salinity models were briefly highlighted.

From the synopsis of the literature, the following conclusions can be made.

- Enough local and international evidence exists to warrant the formulation of on-farm best water and salt management practices as provided in Figure 4.1.
- The general framework for adopting precision agriculture or rather site-specific-crop management will work well to address spatial site-specific-salinity management, i.e. measuring and/or monitoring, mapping and decision support through soil-crop-water salinity models.
- In fact, researchers at the USDA-ARS US Salinity Laboratory have already developed protocols (now published as a standardised methodology) over a number of decades to assist in measuring and/or monitoring and mapping of relevant soil properties by using EC_a measurements.
- The ESAP software developed by the USDA-ARS US Salinity Laboratory provides a valuable tool for the adoption of this standardised methodology.

CHAPTER 5. WHEAT AND MAIZE CASE STUDIES: SPATIAL CHARACTERISATION OF SOIL PROPERTIES RELATED TO WATER AND SALT MANAGEMENT

5.1 Introduction

Spatial soil measurements and monitoring is needed as a first step in adopting precision agriculture to manage the salt load associated with irrigation at field level. Relevant soil properties include soil salinity, sodicity, water content, texture, bulk density etc. To spatially characterise these soil properties apparent soil electrical conductivity (EC_a) readings obtained through electromagnetic induction (EMI) or electrical resistivity (ER) gained in popularity over the last few decades. Unfortunately, as highlighted in Chapter 4, EC_a surveys to spatially characterise these and other soil properties have and continue to produce dubious results due to the complex nature of the measurement, and incorrect interpretations.

Primary soil property effects on EC_a include temperature, salinity, water content, texture, bulk density and organic matter and secondary influences such as metal, surface roughness, soil compaction and surface geometry. When investigating a target soil property such as for example salinity, the influences of other primary properties (for example clay content, water content and bulk density) on EC_a need to be understood and the secondary influences minimised. The 10 step protocols (Corwin and Scudiero, 2016) for using EC_a-directed soil sampling to measure and map spatial variability of a target soil property (standardised methodology), described in Chapter 4, was developed explicitly to accomplish this, viz: to avoid confounding secondary influences and minimise the effects of soil properties outside the target property under investigation. Central to the protocols are step 4: the response-surface soil sampling design based on spatial EC_a readings, step 7: stochastic and/or deterministic calibration of EC_a to target soil properties, step 8: spatial statistical analysis to determine the soil properties influencing EC_a and step 10: graphical display. The ESAP-95 Version 2.01R (Electrical conductivity Sampling Assessment and Prediction) software package was explicitly developed to aid in completing these steps. In addition, the software can be used for a Dual Pathway Parallel Conductance (DPPC) correlation analysis, which is a very powerful analytical procedure. The analysis can be used to determine the feasibility of doing an EC_a survey to spatially characterise a target soil property, and to determine if the acquired EC_a survey and soil property data exhibit a high degree of internal validity and consistency. The ESAP software consists of three modules, namely ESAP-RSSD, ESAP-Calibrate and ESAP-SaltMapper, which were described in Chapter 4.

Chapter 5 will focus on using EC_a surveys through EMI and the software package ESAP to characterise spatial variability of soil salinity, water content, clay content and bulk density across seven fields located in three different irrigated regions of South Africa. This will highlight the feasibility and effectiveness of EC_a surveys in order to map all four of these properties on irrigated South African soils.

5.2 Theoretical and operational considerations of ESAP

5.2.1 DPPC correlation analysis

The DPPC correlation analysis contained within ESAP-Calibrate encompasses determination of EC_a with the DPPC model (Equation 5.1) of Rhoades et al. (1989). Basically the model describes the relationship between bulk soil electrical conductivity (EC_a), volumetric water content (T_w) and electrical conductivity of the soil water (EC_w). Mathematically it assumes that EC_a can be represented by conductance via three pathways acting in parallel; a solid-liquid series coupled pathway, a liquid pathway and a solid pathway. Rhoades et al. (1999) provides a thorough review of the model with proof of the inherent assumptions. According to the authors, the first pathway is "conductance through altering layers of soil particles and the soil solution that envelops and separates these particles", the second pathway is described as "conductance through a continuous soil solution pathway" and the third pathway conductance through or along the surfaces of soil particles in direct and continued contact with one another". Where T_{ws} is the volumetric water content in the soil-water pathway, T_{wc} the volumetric water content in the continues liquid pathway, T_s the volumetric content of the solid phase of the soil, EC_{ws} the electrical conductivity of the soil-water pathway, EC_{wc} the electrical conductivity of the continuous liquid pathway and EC_s the electrical conductivity of the solid particles.

$$EC_a = \frac{(T_s+T_{ws})^2 EC_{ws}(EC_s)}{T_s(EC_{ws})+T_{ws}(EC_s)} + T_{wc}(EC_{wc}) \tag{5.1}$$

Equation 5.1 can be rewritten as Equation 5.2 by assuming T_w = T_{ws} + T_{wc} (T_w = total volumetric water content) and EC_w = average electrical conductivity of the soil-water and assume that under equilibrium EC_w = EC_{ws} = EC_{wc}.

$$EC_a = \frac{(T_s+T_{ws})^2 EC_w(EC_s)}{T_s(EC_w)+T_{ws}(EC_s)} + (T_w - T_{ws})(EC_w) \tag{5.2}$$

Rhoades et al. (1989) found that the parameters on the right of Equation 5.2 can be determined provided that measurements of saturation extracts to determine electrical conductivity (EC_e), clay content or saturation percentage (SP), gravimetric soil water content (and bulk density (BD) are known. The relationships published by Rhoades et al. (1989) are provided by Equations 5.3 to 5.7, where BD can be estimated from SP with Equation 5.8 when not measured. This estimated EC_a from these measured soil properties are then referred to as a "calculated" value in ESAP, namely EC_{ac}. The DPPC correlation analysis within ESAP-Calibrate also has an option of entering clay content when SP values are not available.

$$T_w = \frac{(\theta_g)(BD)}{100} \tag{5.3}$$
$$T_{ws} = 0.639(T_w) + 0.011 \tag{5.4}$$
$$T_s = \frac{BD}{2.65} \tag{5.5}$$
$$EC_s = 0.019(SP) - 0.434 \tag{5.6}$$
$$EC_w = \frac{(EC_e)(BD)(SP)}{100(T_w)} \tag{5.7}$$
$$BD = 1.73 - 0.0067(SP) \tag{5.8}$$

Lesch et al. (2000) mention in the user manual and tutorial guide of ESAP that when soil salinity levels across the survey exceed 1.5 dS m^{-1} (150 mS m^{-1}), then Equation 5.2 can be simplified to Equation 5.9 (often referred to as the linear version). This is because the product T_s (EC_w) tends to be significantly larger than the product T_{ws} (EC_s), of which proof can be found in Rhoades et al. (1999).

$$EC_a = \frac{(T_s+T_{ws})^2(EC_s)}{T_s} + (T_w - T_{ws})(EC_w) \tag{5.9}$$

As described by Lesch and Corwin (2003) the DPPC model provides a powerful analytical tool that can be used to: i) "accurately predict the expected correlation structure between EC_a and various soil properties of interest before a survey is done and ii) provides a useful data validation procedure as well as quantitative technique for describing how different soil properties correlate with acquired EC_a data". The authors also showed how to dynamically adjust the DPPC model to substantially improve the accuracy when the water content is significantly below field capacity. This capability is part of the ESAP-Calibrate module.

To use the DPPC correlation analysis as an analytical tool with regard to the first example mentioned above, (feasibility of an EC_a survey to spatially characterise a target soil property) a profile file (.pro) is required by ESAP-Calibrate, which contains measurements of EC_e, clay content or SP, and BD can also be included if available. For the second example, i.e. data evaluation and general data interpretation perspective, a survey file (.svy) and a .pro file are required. The survey file contains EC_a readings (at one or two effective depth ranges) through either EMI or ER across a specific field, together with an identification of several EC_a-directed soil sampling sites. These sampling sites can be identified by using ESAP-RSSD as explained below. The .pro file contains the EC_e, clay content or SP, θ_g and BD measurements at these EC_a-directed sampling sites.

5.2.2 EC_a-directed soil sampling design

The ESAP-RSSD module within the ESAP software package uses a model-based response-surface sampling design as described in Chapter 4. A .dat file containing the coordinates, the EC_a readings obtained through EMI or ER as well as transect number are imported into the software (only two effective depth ranges of EC_a readings can be imported). A histogram of EC_a readings are drawn by the software from where a natural logarithm transformation can be done. To facilitate the response-surface design and the stochastic spatial multiple linear regression (MLR) of EC_a to a target soil property, all transformed EC_a readings are first centered, scaled and decorrelated by ESAP-RSSD (Lesch et al., 1995b) to produce a survey file (.svy).

Raw EC_a readings are referred to by ESAP as s1 and s2 for the two effective depth ranges of EC_a readings, which can be log transformed. In general s1 represents the deeper EC_a reading ($EC_{a\ deep}$) and s2 the shallower reading ($EC_{a\ shallow}$). The decorrelated EC_a readings are referred to as z1 (Equation 5.10) and z2 (Equation 5.11), where a_1, a_2, a_3 and a_4 are determined by the principle components algorithm. If only one effective depth range EC_a reading was collected in the survey, then Equation 5.12 is used, where stdev is the standard deviation.

$$z1 = a_1\big(s_1 - mean(s1)\big) + a_2\big(s2 - mean(s2)\big) \tag{5.10}$$

$$z2 = a_3\big(s_1 - mean(s1)\big) + a_4\big(s2 - mean(s2)\big) \tag{5.11}$$

$$z1 = a_1\big(s1 - mean(s1)\big) \text{ where } a_1 = \frac{1}{stdev(s1)} \tag{5.12}$$

All z1 and z2 data are expressed in standard deviation units. As part of signal validation, ESAP-RSSD detects outliers and removes these values. For example, if the site outlier level is set to 4 then all survey sites with EC_a readings more than 4 standard deviations away from the mean are masked and removed. In all cases the default levels for site masking and outlier detection were used, namely values of 3.5 and 4.5. Raw location coordinates are referred to as u (easting) and v (northing) and the scaled location coordinates x (Equation 5.13) and y (Equation 5.14), where k is the greater of max(u) – min(u) or max(v) – min(v).

$$x = \frac{(u - min(u))}{k} \tag{5.13}$$

$$y = \frac{(v - min(v))}{k} \tag{5.14}$$

5.2.3 Spatial multiple linear regression analysis (stochastic calibration)

As a first step when using the ESAP-Calibrate module to do a spatial MLR analysis of EC_a readings and a target soil property, the survey file at each field (.svy) must be imported. Next a profile file (.pro) containing the measured soil property data for each EC_a-directed sampling site should be imported, which are then merged with the survey file. Soil property data can be imported for composite depths of 0-0.3, 0-0.6, 0-0.9, 0-1.2 and 0-1.5 m. This is done to determine the approximate depth the instrument (EM38-MK2) measures because the depth of EC_a readings will vary from one location to another (Corwin and Scudiero, 2016). The highest correlation (r) between EC_a readings and for example EC_e is the estimated depth of penetration. Spatial MLR or calibration of EC_a and a target soil property is consequently done for the composite depth with the highest r (Corwin and Scudiero, 2016).

As explained in Chapter 4 (Figure 4.5) EC_a is a multiplicative function of soil salinity, tortuosity (depending on texture, density and particle geometry, particle pore distribution and organic matter content) and water content (Archie, 1942; Rhoades et al., 1976). Soil salinity (EC_e) will be used as an example in the discussion below, but any property directly measured by EC_a or correlated with spatial EC_a measurements will apply. According to Corwin and Lesch (2014) as cited by Corwin and Scudiero (2016) the following power model (Equation 5.15) can be used for the relationship between EC_e and EC_a. Where α and β are coefficients influenced by non-target edaphic factors and ε^* a multiplicative random error component. When a natural logarithm transformation is performed the multiplicative nature of the EC_a-EC_e relationship becomes additive. Equation 5.15 is then parameterised using an ordinary least squares approach (Equation 5.16), where ε is now a random (additive) error component equal to $ln(\varepsilon^*)$.

$$EC_e = \beta\ EC_a{}^{\alpha} \varepsilon^* \tag{5.15}$$

$$ln(EC_e) = ln(\beta) + \alpha\ ln(EC_a) + \varepsilon \tag{5.16}$$

To develop a spatially referenced regression model both trend surface parameters and EC_a readings are included as shown in Equation 5.17, where u and v are easting and northing UTM coordinates (m) and β_0, β_1, β_2, β_3 and β_4 empirical regression model coefficients (Corwin and Scudiero, 2016). When EC_a readings at two different effective depth ranges are reliable and there is no multicollinearity, Equation 5.17 remains unchanged. However, if for example a deep EC_a reading ($EC_{a\ deep}$) is unreliable with respect to the target property the term $\beta_1\ ln\left(EC_{a\ deep}\right)$ is removed, and vice versa for a shallow EC_a reading ($EC_{a\ shallow}$) and a target property, i.e. $\beta_2\ ln(EC_{a\ shallow})$. It is important to note that ESAP-Calibrate uses decorrelated readings and scaled location coordinates in Equation 5.17, as explained in Section 5.2.2. The software can mix together various numbers of EC_a and trend surface parameters to form the final model parameter combination. Equation 5.18 and 5.19 show, amongst other combinations, two examples, where b = β. The combinations can also include first (1^{st} OT) and second (2^{nd} OT) order trend surface parameters. Lesch et al. (2000) recommend that the automatic model identification and analysis of all possible model options in ESAP-Calibrate be used when the user has little experience in model fitting. The software then provides the spatial MLR model with the parameter combination that produces the minimum PRESS score, which generally indicates more accurate models. Jack-knifing is used, whereby each data point is temporally removed and the model estimated using the remaining data. At the removed site the predicted value is compared to the true value. These prediction errors (difference between predicted and true values) are then squared and summed to create the PRESS score.

$$ln(EC_e) = \beta_0 + \beta_1\ ln\left(EC_{a\ deep}\right) + \beta_2\ ln(EC_{a\ shallow}) + \beta_3(u) + \beta_4(v) + \varepsilon \tag{5.17}$$

$$ln(EC_e) = b_0 + b_1(z_1) \tag{5.18}$$

$$ln(EC_e) = b_0 + b_1\,(z_1) + b_2(x) + b_3(y) \tag{5.19}$$

5.3 Methodology

To address the objectives of this chapter, two data sets, which have been acquired from seven fields located in three different regions of central South Africa will be used. Figure 5.1 shows the location of the fields in the Northern Cape, Free State and Eastern Cape, near the towns Douglas (Field 1), Luckhoff (Fields 2 to 5) and Hofmeyr (Fields 6 and 7).

The first data set consists of samples collected on a grid basis of about 1 site per hectare. At Fields 1 to 5 samples were collected at 300 mm depth intervals up to 1.5 m if possible, to determine the EC_e (mS m^{-1}), clay content (determined with the pipette method) and θ_g (%) during June 2017. The fields near Hofmeyr (Field 6 and 7) were sampled during February 2017 according to diagnostic horizons. The soils at each grid sampling sites were also classified according to the Taxonomic Soil Classification System of South Africa (Soil Classification Working Group, 1991).

The second data set consists of EC_a readings taken at the various fields and soil samples collected from 12 EC_a-directed soil sampling sites per field. At these sites the samples were collected in 300 mm depth intervals up to 1.5 m if possible (except at Field 6 and 7) and EC_e, clay content, θ_g and bulk density (with the core method, BD, kg cm^{-3}) were determined.

5.3.1 Location and description of fields

The mean long-term annual rainfall, atmospheric evaporative demand (ET_0, reference evapotranspiration of a well-watered short clipped cool-season grass) and maximum and minimum temperatures at the various fields are shown in Figure 5.1. Figure 5.2 shows the mean long-term monthly data. The data are from quaternary drainage regions C51M, D33C and Q12C for the various fields, respectively, as supplied by SAPWAT 4 (Van Heerden and Walker, 2016). The mean long-term electrical conductivity (EC) and sodium adsorption ratio (SAR) of the irrigation water, as obtained from the nearest stream gauge, according to the database of the Centre for Water Sciences and Management, North-West University, are also provided (Huizenga et al., 2013). Figure 5.3 and 3.4 show the mean long-term monthly EC and SAR of the stream gauges at the various fields.

Figures 3.5 and 3.6 show a box and whisker plot of measured clay contents from samples taken on a grid basis (dataset 1) at each field. The name of each soil form at the various fields are included (the number of grid locations of a specific soil form are shown in brackets). The lower and upper lines of the box represent the 1st quartile (25% of data lie below Q1) and 3rd quartile (75% of data lie below Q3), while the middle line is the median and the cross the mean; the difference between Q3 and Q1 represent the interquartile range (IQR).

The 40 ha field near Douglas (Field 1) along the Lower Riet River in the Northern Cape is primarily cultivated with wheat and maize (double-cropping system). The farmer terminated irrigation activities on this field around the year 2000. At this time production was severely affected by waterlogging and salinisation, caused by a combination of border-flood irrigation and poor-quality irrigation water from the Lower Riet River. The field was therefore left uncultivated until 2015, when a centre pivot was constructed.

Douglas case study | Luckhoff case study | Hofmeyr case study

Case study	Douglas	Luckhoff	Hofmeyr
Quaternary catchment	C51M	D33C	Q12C
Mean annual ET_0 (mm day^{-1})	4.5	4.3	3.9
Mean annual T_{Max} (°C)	26.8	25.8	23.6
Mean annual T_{Min} (°C)	9.7	10.1	7.5
Mean annual rainfall (mm)	337	323	371
Stream gauge	C5H048	D3H012	Q1H014
Measuring period	1990-2009	1980-2009	1981-1998
± n per month	70	41	26
Mean EC (mS m^{-1})	139 (58)	18.2 (2.3)	16.9 (2.7)
Mean SAR	3.4 (1.2)	0.31 (0.07)	0.33 (0.10)
Number of fields (ha)	1 (30)	4 (60 x2, 40, 20)	2 (55 x2)
Crops	Primarily wheat and maize		

(standard deviation)

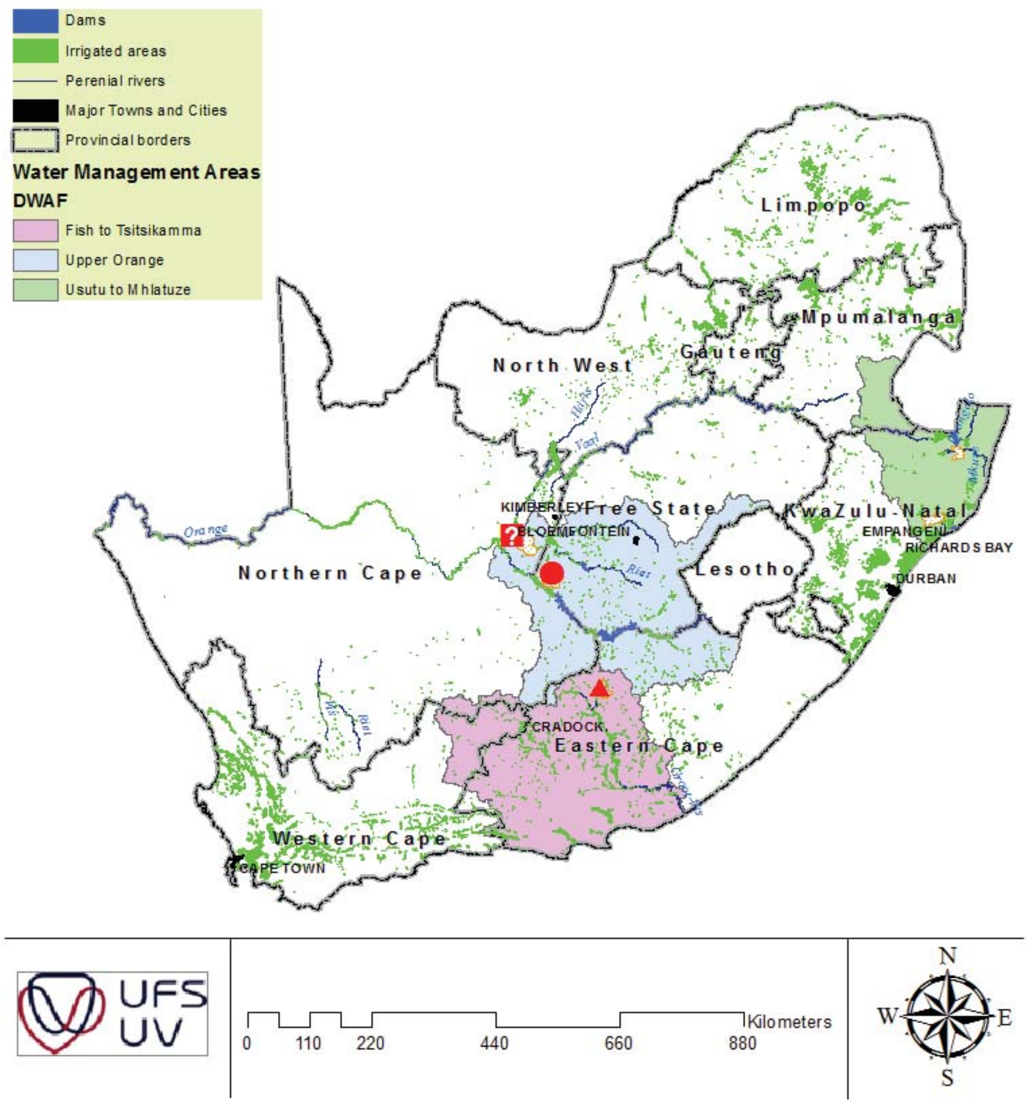


Figure 5.1 Location of the fields (Douglas, Luckhoff and Hofmeyr) in South Africa and mean long-term annual climatic data. The mean long-term electrical conductivity (EC_i) and sodium adsorption ratio (SAR_i) of water from the nearest stream gauge (database of the Centre for Water Sciences and Management, North-West University; Huizenga et al., 2013), size of the fields, and primary crops grown are also included.

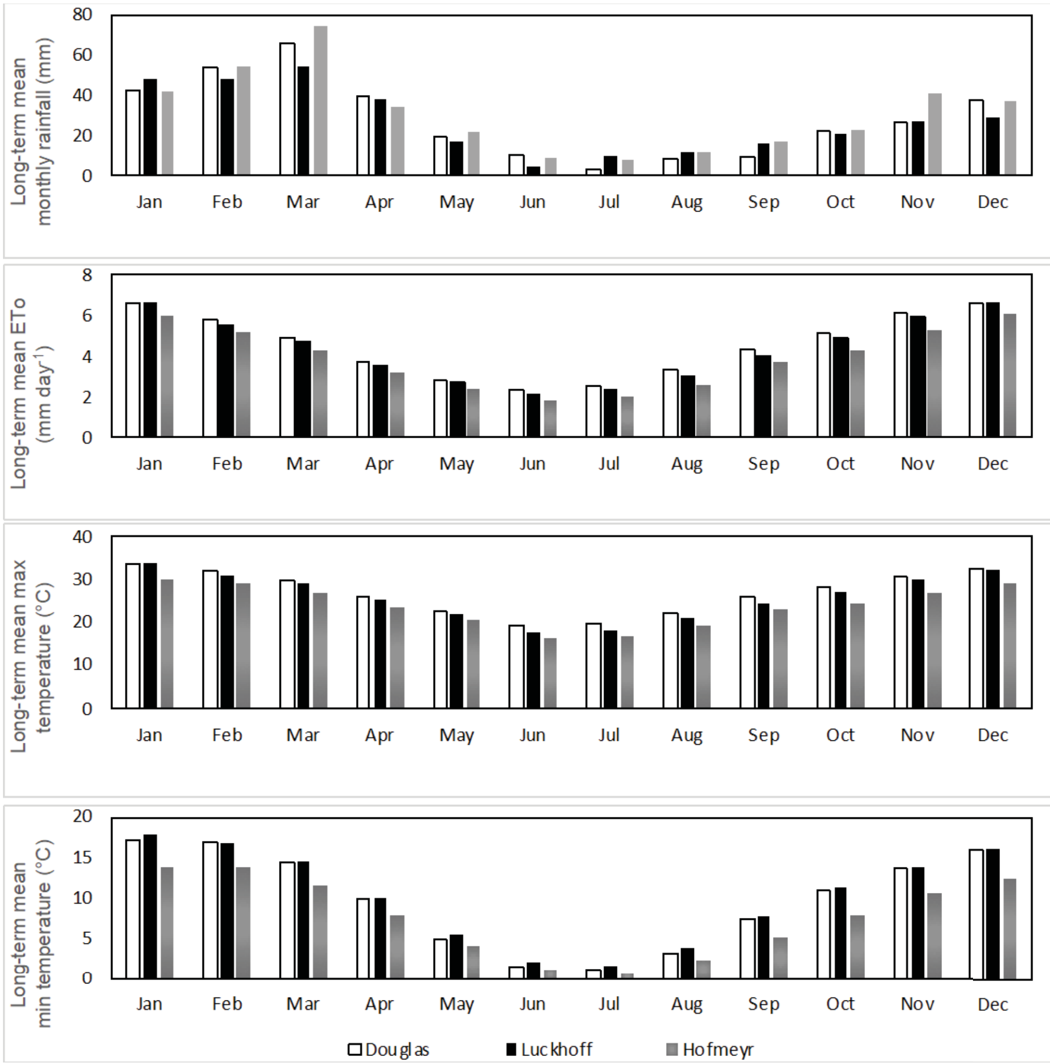


Figure 5.2 Mean long-term mean monthly rainfall, evaporative demand of atmosphere (ET_0, reference evapotranspiration of a well-watered short clipped cool-season grass) and minimum and maximum temperature at the various case studies (data obtained from quaternary drainage regions C51M, D33C and Q12C as supplied by SAPWAT 4, Van Heerden and Walker, 2016).

For a June planting and November harvesting of wheat, the mean long-term ET_0 and minimum and maximum temperature amounts to 3.9 mm day^{-1}, and 6.3 and 24.3°C, respectively, while the mean long-term rainfall during this period amounts to 80 mm. For a December planting and early June harvesting of maize, the mean long-term values amount to 5.1 mm day^{-1}, and 13.1 and 29.3°C, respectively, with a total mean long-term rainfall of 260 mm during this period. The mean long-term EC of the nearest stream gauge (C5H048Q01, Riet @ Zoutpansdrift) during the wheat and maize growing seasons is 180 (standard deviation = 152 mS m^{-1}) and 105 (standard deviation = 33 mS m^{-1}) mS m^{-1}, respectively. The mean long-term SAR during these periods are below 5. The dominant soil forms are Augrabies and Clovelly with a mean clay content of 23% and 22% up to a depth of 1.5 m. In terms of clay content these soils are however considerably heterogeneous both in depth and spatially across the field, as indicated by an IQR of $\pm$ 20%.

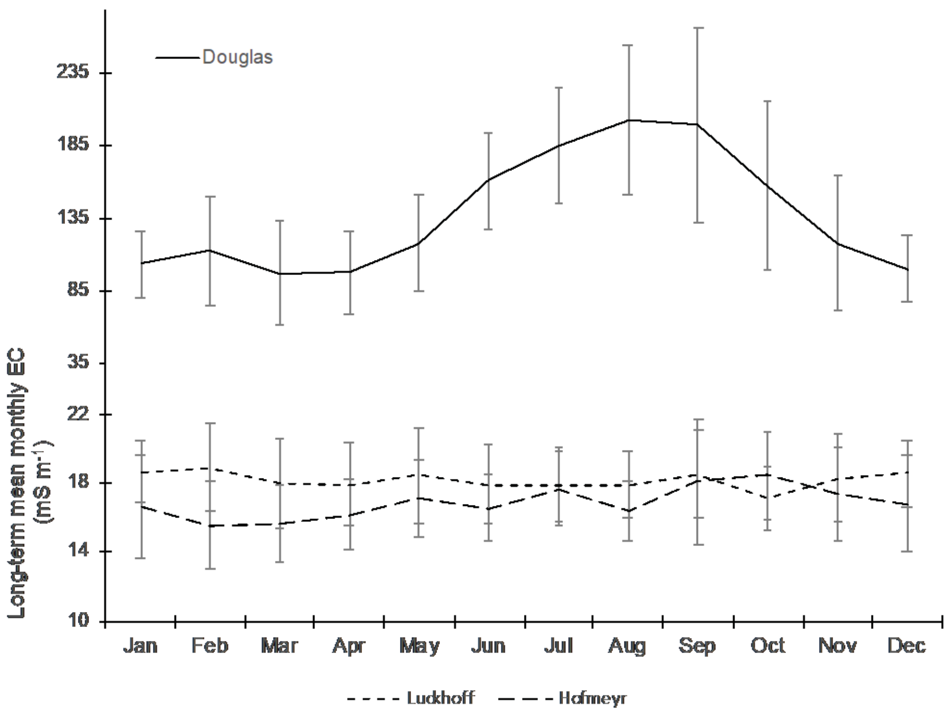


Figure 5.3 Mean long-term monthly electrical conductivity of water from the nearest stream gauge at the various case studies (database of the Centre for Water Sciences and Management, North-West University; Huizenga et al., 2013).

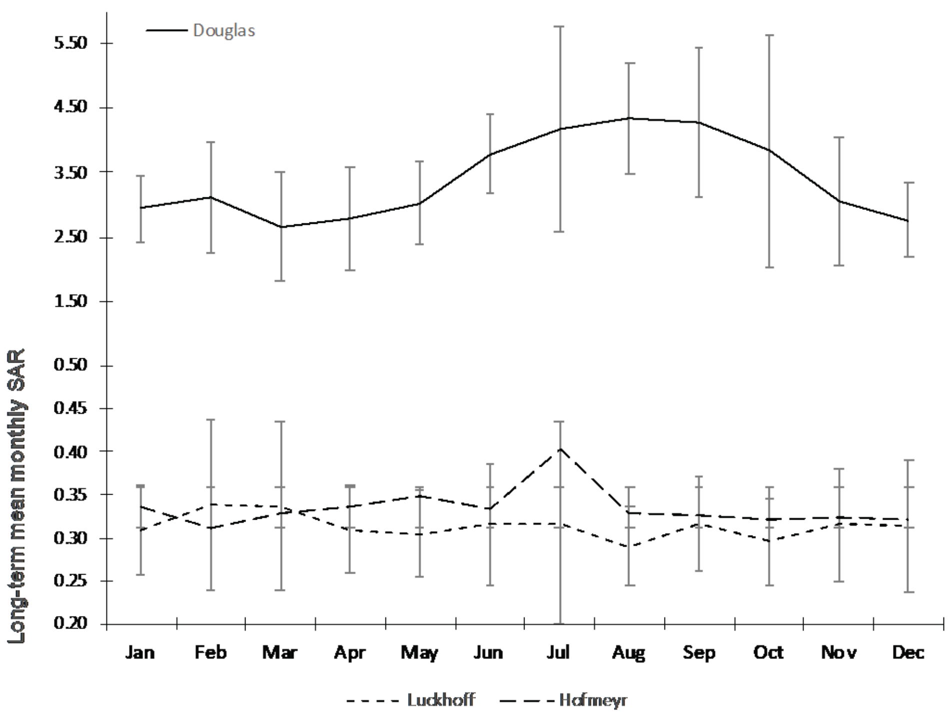


Figure 5.4 Mean long-term mean monthly sodium adsorption ratio of water from the nearest stream gauge at the various case studies (database of the Centre for Water Sciences and Management, North-West University; Huizenga et al., 2013).

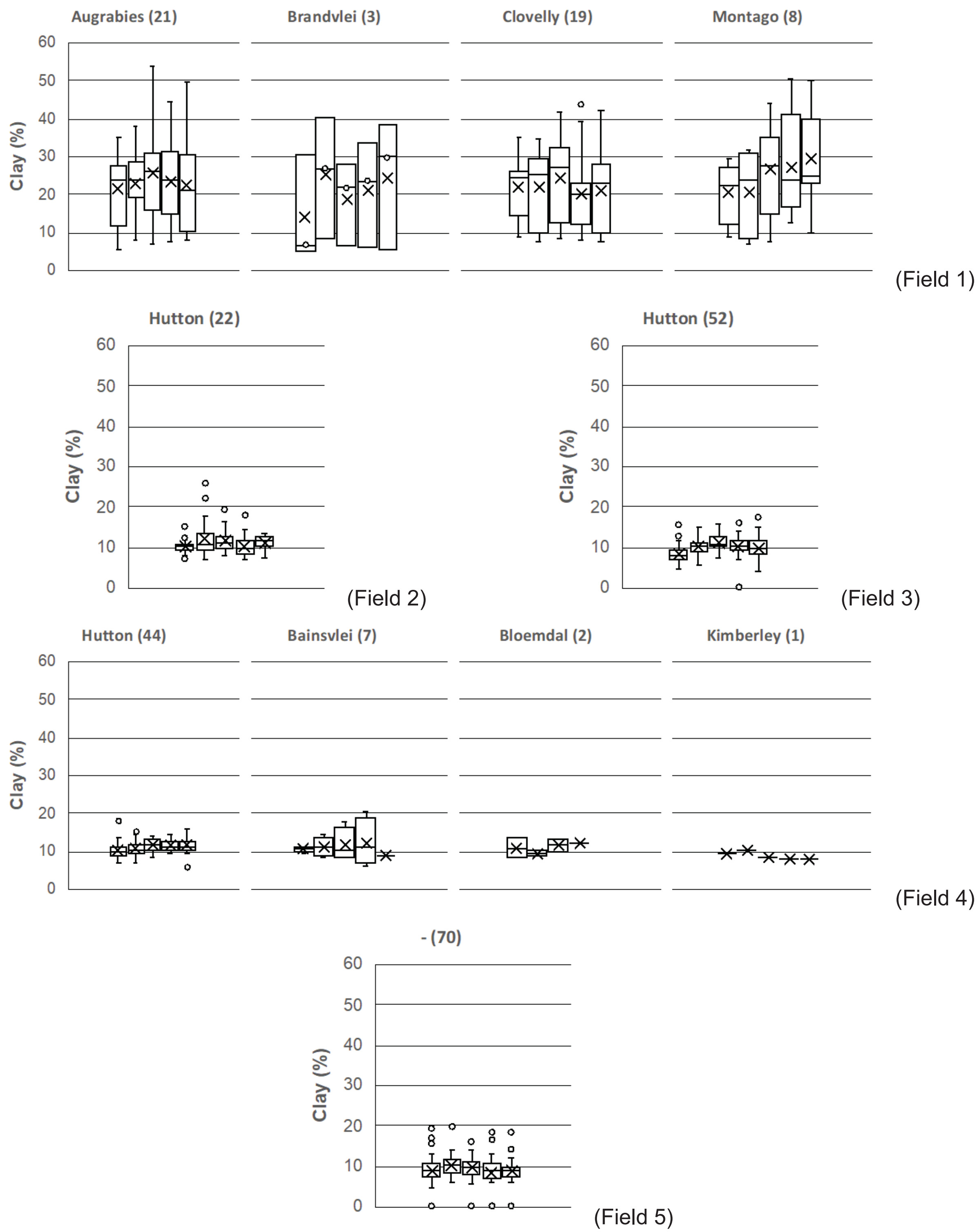


Figure 5.5 Box and whisker plot of clay content measured at the various fields (Field 1 = Douglas: 40 ha, Field 2 = Luckhoff: 20 ha, Field 3 = Luckhoff: 40 ha, Field 4 = Luckhoff: 60 ha NE and Field 5 = Luckhoff: 60 NW) from soil samples collected at a grid density of about 1 per hectare. The names of each soil form at the various fields are also included (the number of grid locations of a specific soil form are shown in brackets). The clay content per 0.3 m depth interval up to 1.5 m is shown from left to right.

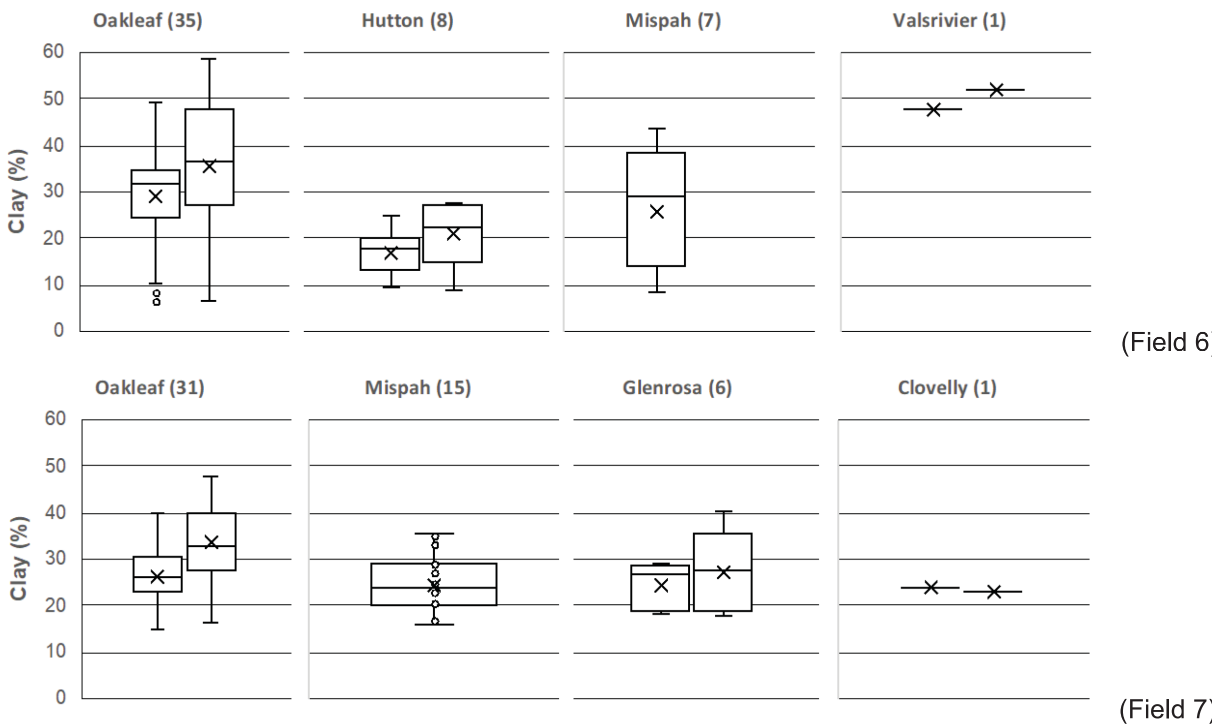


Figure 5.6 Box and whisker plot of clay content measured at the various fields (Field 6 = Hofmeyr SE 55 ha, Field 7 = Hofmeyr NW 55 ha) from soil samples collected at a grid density of about 1 per hectare. The names of each soil form at the various fields are also included (the number of grid locations of a specific soil form are shown in brackets). The clay percentage per diagnostic horizon is shown from left to right.

Fields 2 to 5 are located near Luckhoff along the Orange-Riet canal in the Free State (Orange-Riet Irrigation Scheme) and cultivated primarily with wheat and maize (double-cropping system) under centre pivot irrigation. Fields 2 (20 ha) and 3 (40 ha) are located in the south west and south eastern corner of the farm, respectively. The north eastern (NE) and north western (NW) part of the farm has a 60 ha field each, namely Field 4 and 5, respectively. Orange River water from the Orange-Riet canal is used as the primary water source. Drainage water from an artificial drainage system is reused periodically to irrigate the 20 ha field. The 60 ha field on the north western part of the farm is the main source of drainage water. The field is artificially drained because lateral drainage towards the south west is restricted by the physical presence of the Orange-Riet Canal that supplies water to the Jacobsdal Settlement section of the scheme. The mean long-term ET_0 and minimum and maximum temperature are very similar to Douglas for the same wheat and maize growing seasons; namely 3.7 mm day^{-1}, and 6.7 and 23°C, respectively, for wheat and 4.9 mm day^{-1}, and 13.5 and 28.7°C, respectively, for maize. During the wheat growing season the mean long-term rainfall is approximately 10 mm more and 30 mm less during the maize growing season compared to Douglas; namely 91 and 234 mm for wheat and maize. Three of the four fields at this case study are irrigated, however, with better quality water than Douglas, i.e. approximately 9 times better. For the wheat and maize growing seasons, the mean long-term EC (D3H012Q01, Orange @ Dooren Kuil) is 17.9 (standard deviation = 2.3 mS m^{-1}) and 18.5 (standard deviation = 2.4 mS m^{-1}) mS m^{-1}, respectively. Most of the time the SAR is below 1. All four fields are dominated by a deep (1.5 m) sandy Hutton soil form with a clay content around 10%. The low IQR (5%) value suggests that the soil is very homogeneous in depth and spatially across these fields in terms of clay content.

The last two fields are 55 ha each (Field 6 and 7) and located near Hofmeyr between Steynsburg and Middelburg in the Eastern Cape. Like the farm near Luckhoff there are also 4 centre pivot irrigated fields. The fields are well isolated, i.e. no off-site interference as the fields are not part of an irrigation scheme. Field 6 is located in the South Eastern part of the farm and Field 7 in the North Western part. Primarily, wheat and maize are cultivated at the fields but as part of a single crop system, which is combined with an animal grazing component. After harvesting, crop residue is grazed by cattle until the next planting date. Water from the Gariep Dam is used for irrigation (located in the Orange River), via the Orange-Fish Tunnel, which stretches from the Gariep Dam to Teebus a few kilometres from the fields. For the same wheat growing season as Douglas and Luckhoff the mean long-term ET_0 is 3.28 mm day^{-1}, with a minimum and maximum temperature of 4.53 and 20.88°C, which is approximately 3°C slightly cooler than Douglas and Luckhoff. The mean long-term rainfall (110 mm) during this period is higher than at Douglas and Luckhoff, and the mean long-term EC similar to Luckhoff (16 mS m^{-1}; Q1H014Q01). Compared to Fields 2 to 5 the soils at Field 6 and 7 can be regarded as marginal for crop production in terms of clay content and depth. The A and B horizon of primarily an Oakleaf soil form at Field 6 has a mean clay content of 29% and 36%, respectively. At Field 7, the mean clay content of the Oakleaf soil form amounts to 26% and 34%, respectively. The mean soil depth across Field 6 amounts to about 1 m with an equal standard deviation, while the soil at Field 7 is much shallower (mean = 0.51 m; standard deviation = 0.30 m).

5.3.2 EC_a surveys

Table 5.1 shows the EC_a survey dates at the various fields taken with an EM38-MK2 instrument (Geonics Limited, Mississauga, Ontario, Canada) at a transect width of about 10 m. Each measurement was geo-referenced with a Trimble R4 RTK GNSS surveying system. Metal objects were removed from wrists, fingers, neck and pockets and standard procedures used, as described in the EM38-MK2 ground conductivity meter operation manual (Geonics Limited, 2008), when preparing the instrument for survey operation, namely i) battery test, ii) initial Inphase nulling iii), instrument zero and iv) final Inphase nulling. At each field the EC_a survey design was similar, i.e. 1 geo-referenced EC_a reading was taken per second while the instrument was towed behind an off-road vehicle (Quade bike) at a speed of approximately 8 km hour^{-1} (Sudduth et al., 2001). A reference 50 m transect to the side of each field was measured at the beginning and end of the survey. Fields 2 and 3 were surveyed three times, i.e. June 2016 (first survey), December 2016 (second survey) and June 2017 (final survey). At Field 4 and 5 the total 60 ha's were surveyed only once. At other times, only 30 ha (half) were surveyed. Fields 1, 5 and 6 were surveyed only twice, i.e. a first and a final survey. On average it took about 9 min to survey 1 hectare, with a fast rate of about 4 min ha^{-1} and slow rate of about 19 min ha^{-1}. The mean EC_a readings per hectare amounted to 354 with a coefficient of variation of 25%.

It is important to note that the instrument reads a non-linear depth-weighted soil electrical conductivity and that EC_a readings were obtained for two effective depth ranges with the EM38-MK2. This is possible because of the two-transmitter receiver coil separations at 1 and 0.5 m. In the vertical dipole orientation of the instrument, the effective depth range is $\pm$ 0-1.5 m ($EC_{a\ deep}$) and $\pm$ 0-0.75 m ($EC_{a\ shallow}$), which was used at all fields accept the two fields near Hofmeyr. For these fields the instrument was used in the horizontal dipole mode of orientation with an effective depth range of $\pm$ 0-0.75 m ($EC_{a\ deep}$) and $\pm$ 0-0.35 m ($EC_{a\ shallow}$). All material below 1.5 m (1 m coil separation) and 0.75 m (0.5 m coil separation) contributes about 30% to the EC_a reading in the vertical dipole orientation. In the horizontal dipole orientation all material below 0.75 m (1 m coil separation) and 0.35 m (0.5 m coil separation) contributes about 30% to the EC_a reading. These values are based on the cumulative response functions provided in the EM38-MK2 ground conductivity meter operation manual (Geonics Limited, 2008).

Table 5.1 General information of the apparent soil electrical conductivity (EC_a) surveys done at the various fields with an EM38-MK2 (Geonics Limited, Mississauga, Ontario, Canada), namely: the date of survey, the amount of days to complete a specific survey, the number of transects and total EC_a readings taken per field

Field (ha)		Survey	Date	Survey days	Survey time	Transects	Readings per field
Douglas	1 (40)	First	Jun 2016	1	4 h 20 min	50	10482
		Final	Jun 2017	1	12 h 38 min	53	11972
Luckhoff	2 (20)	First	Jun 2016	1	3 h 10 min	49	8191
		Second	Dec 2016	1	2 h 1 min	21	5660
		Final	Jun 2017	2	2 h 40 min	24	6731
	3 (40)	First	Jun 2016	2	5 h 41 min	62	17063
		Second	Dec 2016	1	6 h 33 min	48	12981
		Final	Jun 2017	1	3 h 56 min	27	12364
	4 (60, NE)	First	Jun 2016	2	10 h 28 min	81	28660
	4 (30, NE)	Second	Dec 2016	2	3 h 27 min	29	9806
	4 (30, NE)	Final	Jun 2017	1	3 h 44 min	36	10927
	5 (60, NW)	Frist	Jun 2016	4	8 h 17 min	69	22166
	5 (30, NW)	Final	Dec 2016	1	4 h 37 min	14	7946
Hofmeyr	6 (55, NW)	First	Apr 2016	3	9 h 24 min	43	27460
		Final	Feb 2017	1	4 h 5 min	21	11110
	7 (55, SE)	First	Aug 2016	3	10 h 32 min	45	27713

5.3.3 EC_a-directed soil sampling design

Twelve sampling sites per field were chosen from the first EC_a survey by selecting the spatial response surface sampling algorithm (SRS) option within ESAP-RSSD. After each EC_a-directed soil sampling design ESAP-RSSD calculates an optimisation criterion, which represents the extent of the sampling design's spread across the field (Lesch et al., 2000). At all fields the value was between 1.15 and 1.30 indicating excellent to reasonable uniformity. ESAP-RSSD also contains an option for manual sample-site selection. This option was used to identify the same EC_a-directed sampling sites during the second and final surveys as determined in the first survey.

5.3.4 Soil sample collection and analysis

After an EC_a survey, soil samples were collected at each of the 12 EC_a-directed sampling sites with the usual sampling protocols and associated quality control and quality assurance procedures (i.e. dataset 2). Soil samples were collected at 300 mm depth increments to a depth of 1.5 m, except at the fields near Hofmeyr (Field 6 and 7), which had a sampling depth of 0.9 m where possible. The soils were dried at 40°C, crushed to pass through a 2 mm sieve and analysed using standard methods (The Non-Affiliated Soil Analysis Work Committee, 1990). The following measurements were taken; EC_e, (mS m^{-1}), clay content (%), θ_g (%) and BD (kg cm^{-3}).

5.3.5 Data analysis and graphical display

Dataset 1 was first used in ESAP-Calibrate through a DPPC correlation analysis to evaluate the feasibility of performing EC_a surveys to spatially characterise EC_e, clay content, θ_g and BD at the various fields. Basically the module provides correlations between the mean EC_{ac} values over the depth of a profile and mean measured EC_e, clay content and θ_g values over the same depth. In addition, correlations between EC_{ac} and estimated volumetric soil water content (θ_v) and BD are also provided (please note BD was not determined at all the grid sampling sites). These correlations were then examined to obtain an idea of how beneficial an EC_a survey would be, i.e. an expected correlation between EC_a readings obtained through EMI and EC_e, clay content and θ_g at a given field.

Next the same DPPC correlation analysis was used as an objective technique to judge the validity of EC_a readings and measured soil property data, i.e. dataset 2. In the analysis the software calculates the correlation between mean EC_{ac} over a specific depth and $EC_{a\ deep}$ and/or $EC_{a\ shallow}$ readings. In practice mean calculated conductivity estimates over the effective depth range of true EC_a instrument readings tend to be highly correlated (Lesch et al., 2000). This correlation multiplied by the correlation between EC_{ac} and a target soil property provides then a predicted (Prd) $EC_{a\ prd}$--soil property correlation together with a 95% confidence interval for this prediction. If the DPPC model is accurate and the errors associated with the $EC_{a\ deep}$ and/or $EC_{a\ shallow}$ readings are minimal then two results occur. First the correlation between $EC_{a\ deep}$ and/or $EC_{a\ shallow}$ and EC_{ac} should approach 1, and second, the observed $EC_{a\ deep}$--soil property (and/or $EC_{a\ shallow}$--soil property) correlation should be reasonably close to the $EC_{a\ prd}$--soil property correlation. When these two results occur then the overall survey process (EC_a readings and soil property data) exhibit a high degree of internal data validity and consistency (Lesch and Corwin, 2003).

To determine the predominant soil properties influencing EC_a readings (taken with the EM38-MK2) simple statistical correlation and regression statistics of the spatial MLR calibration functions, discussed in Section 5.2.3, were interpreted. These calibration functions were developed from $EC_{a\ deep}$ and/or $EC_{a\ shallow}$ readings and measured soil properties at the 12 EC_a-directed sampling sites (dataset 2). In case of a significant relationship the calibration function was used by ESAP-Calibrate to estimate the target soil property at the remaining EC_a readings across the field. Relevant 2D raster maps of the target soil property were made by using the ESAP-SaltMapper module within the ESAP software package. The smoothness of the interpolation process was controlled by adjusting the kernel size, which defines the size of the surrounding area that is searched for each interpolation point. At all fields the kernel values were set to 6% due to high density of EC_a readings across the field. This provided a smooth interpolation of the target soil property across the field without blank areas.

5.4 Results

5.4.1 Feasibility of performing EC_a surveys at the fields

Results from the DPPC correlation analysis between mean EC_{ac} and the corresponding mean EC_e, clay content, θ_v and BD at the grid sampling sites of each field are shown in Table 5.2. At Fields 1, 2, 3 and 5 the mean values represent a depth of 0-1.5 m, Field 4 0-0.9 m, Field 6 the diagnostic A-horizon and Field 7 the diagnostic A and B1 horizons. It should be noted that θ_v and BD were estimated by ESAP-Calibrate. The aim of this section was however not to analyse the accuracy of θ_v and BD estimations, but rather to investigate theoretical correlations between EC_{ac}--EC_e, EC_{ac}--clay content, EC_{ac}-- and EC_{ac}--BD, namely how beneficial an actual EC_a survey would be at the 7 fields to spatially characterise the above-mentioned soil properties.

The results showed that an EC_a survey at these fields would potentially be beneficial to spatially characterise EC_e. This is because at all the fields the mean EC_{ac} was highly (> 0.9) positively correlated with mean EC_e. However, the potential to use $EC_{a\ deep}$ and/or $EC_{a\ shallow}$ readings to spatially characterise clay content, θ_g and BD at Fields 1 to 5 are low. Only at Field 3, EC_{ac} correlated well (> 0.70) with the estimated θ_v. At Fields 6 and 7 mean clay content and the estimated BD correlated reasonably with mean EC_{ac}. As expected, clay content and BD were highly correlated because BD was estimated by ESAP-

Calibrate. With the DPPC correlation analysis the EC_e-EC_{ac} signal deterioration (as a percentage) due to spatial variation in remaining primary soil properties (texture, water content and bulk density) is also calculated. Table 5.2 shows mean signal deterioration values over the soil profiles. At Field 7 signal deterioration was moderate (> 15%). When the remaining primary soil properties are fairly constant across the field then signal deterioration will be minimal (< 15%). Extreme signal deterioration generally results from a high variability in remaining soil properties and poor correlation with soil salinity.

Table 5.2 Dual-Pathway Parallel Conductance (DPPC) correlation analysis results of data from the grid soil sampling sites at Fields 1 to 7. All data were log transformed before performing the correlation analysis

Field (grid samplings)	Soil property	ln EC_{ac}	ln EC_e	ln Clay	ln	ln BD	EC_e-EC_{ac} signal deterioration (%)
1 (41)	**ln EC_{ac}**	1.00	-	-	-	-	6.3
5 depths of 0.3 m	**ln EC_e**	**0.97**	1.00	-	-	-	
	ln Clay	0.15	-0.10	1.00	-	-	
	ln θ_v	-0.45	-0.47	-0.03	1.00	-	
	ln BD	-0.18	0.06	-0.98	0.05	1.00	
2 (21)	**ln EC_{ac}**	1.00	-	-	-	-	2.9
5 depths of 0.3 m	**ln EC_e**	**0.99**	1.00	-	-	-	
	ln Clay	0.29	0.25	1.00	-	-	
	ln θ_v	0.40	0.25	-0.05	1.00	-	
	ln BD	-0.30	-0.27	-1.00	0.05	1.00	
3 (52)	**ln EC_{ac}**	1.00	-	-	-	-	5.3
5 depths of 0.3 m	**ln EC_e**	**0.97**	1.00	-	-	-	
	ln Clay	0.16	0.05	1.00	-	-	
	ln θ_v	**0.75**	**0.59**	0.26	1.00	-	
	ln BD	-0.18	-0.07	-0.99	-0.25	1.00	
4 (53)	**ln EC_{ac}**	1.00	-	-	-	-	11.6
3 depths of 0.3 m	**ln EC_e**	**0.94**	1.00	-	-	-	
	ln Clay	0.28	0.09	1.00	-	-	
	ln θ_v	0.13	-0.20	0.40	1.00	-	
	ln BD	-0.30	-0.11	-0.99	-0.40	1.00	
5 (42)	**ln EC_{ac}**	1.00	-	-	-	-	1.7
5 depth of 0.3 m	**ln EC_e**	**0.99**	1.00	-	-	-	
	ln Clay	-0.03	-0.12	1.00	-	-	
	ln θ_v	0.13	0.01	0.37	1.00	-	
	ln BD	0.01	0.10	-0.99	-0.39	1.00	
6 (37)	**ln EC_{ac}**	1.00	-	-	-	-	7.2
A-horizon	**ln EC_e**	**0.96**	1.00	-	-	-	
	ln Clay	**0.66**	**0.50**	1.00	-	-	
	ln θ_v	0.30	0.24	-0.20	1.00	-	
	ln BD	**-0.66**	**-0.50**	-0.99	0.20	1.00	
7 (31)	**ln EC_{ac}**	1.00	-	-	-	-	17.1
A-horizon	**ln EC_e**	**0.91**	1.00	-	-	-	
B-horizon	**ln Clay**	**0.71**	0.38	1.00	-	-	
	ln θ_v	0.49	0.34	0.32	1.00	-	
	ln BD	**-0.75**	-0.41	-0.97	-0.44	1.00	

EC_{ac} = calculated apparent soil electrical conductivity; EC_e = electrical conductivity of a saturation extract; θ_v = volumetric soil water content; BD = bulk density; θ_v and BD were estimated from measurements of EC_e, clay content and gravimetric soil water content with ESAP-Calibrate

A box and whisker plot of EC_e grid samplings (Figure 5.7) at Field 1 shows a considerable increase in salinity with an increase in soil depth (mean EC_e of 157, 173, 252, 283, 236 and 323 mS m^{-1} for the 0.3 m depth intervals) and a high spatial variability across the field (IQR of 60, 82, 162, 153, 117 and 179 mS m^{-1} for the 0.3 m depth intervals).

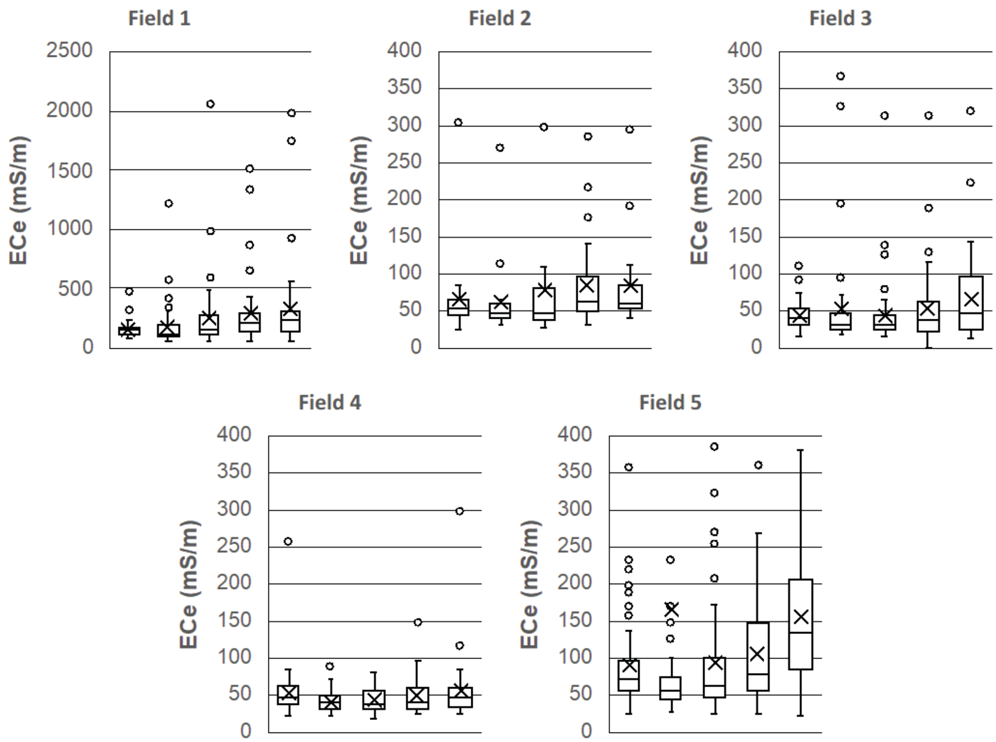


Figure 5.7 Box and whisker plot of electrical conductivity of a saturation extract (EC_e) from the grid soil samplings. The box and whisker plot from left to right represents 0.3 m depth intervals up to 1.5 m.

The EC_e of most (> 75%) grid samplings at Field 2, 3, 4, 6 and 7 were less than 100 mS m^{-1} irrespective of soil depth. At Field 2 and 3 higher EC_e values were in general associated with deeper soil layers compared to Field 4. Field 5 had the second highest EC_e values spatially across the field which increased considerably with an increase in depth. In terms of salinity, it seems that a regular soil profile dominates at the various fields, i.e. where EC_e increases with depth, except Field 4 and 7. The soil profile at these fields is more uniform in EC_e with an increase in depth.

Figure 5.8 shows that θ_g at Fields 1 and 4 with an increase in soil depth was relatively constant, fluctuating around 15% at Field 1 and between 5 and 10% at Field 4, with a low spatial variability (IQR < 5%). The θ_g of the A horizon at Fields 6 and 7 (Figure 5.9) were similar ($\pm$ 15%) also with a low spatial variability (IQR < 5%), while the B-horizon at Field 7 had a higher spatial variability in θ_g (IQR > 5%). In general, the clay content of the dominant Hutton soil at Field 4 was low (just above 10%) and relatively constant over a depth of 1.5 m (Figure 5.5). The dominant Augrabies and Clovelly soils at Field 1 were considerably more clayey with a high variation over a depth of 1.5 m and spatially across the field (Figure 5.5). The correlation between clay and θ_g at both these two fields was poor (r < 0.23). Figure 5.8 shows, however, a noticeable increase in θ_g with an increase in depth spatially across Fields 2, 3 and 5, from less than 10% in the top 0.3 m to more than 15% in the bottom 1.2-1.5 m layer. At these fields the correlation between clay and θ_g was also poor. Hence, there is a possibility of a shallow groundwater table being present within or just below 1.5 m at these fields. Similar to EC_e (at these fields) a regular soil profile where θ_g increases with depth dominates spatially across the fields. At none of the 7 fields the general spatial soil profile across the field is inverted, i.e. where EC_e, clay content and θ_g decreases with depth. This is important when interpreting $EC_{a\,deep}$ and/or $EC_{a\,shallow}$ readings, which will be discussed in the next section.

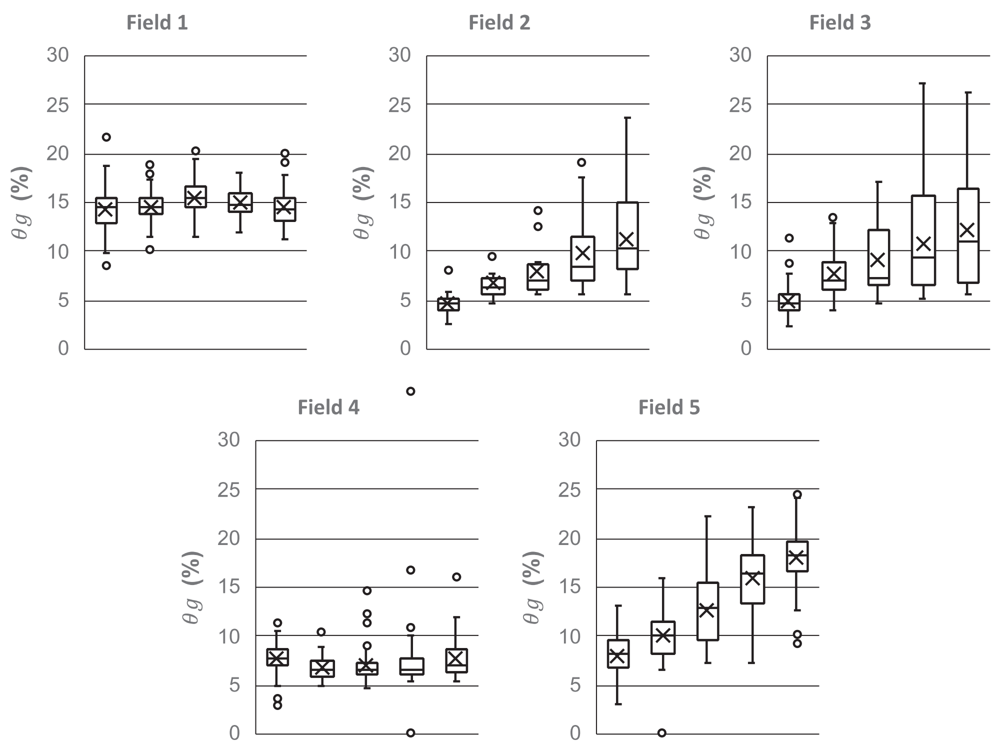


Figure 5.8 Box and whisker plot of gravimetric soil water content (θ_g) from the grid soil samplings. The box and whisker plot from left to right represents 0.3 m depth intervals up to 1.5 m.

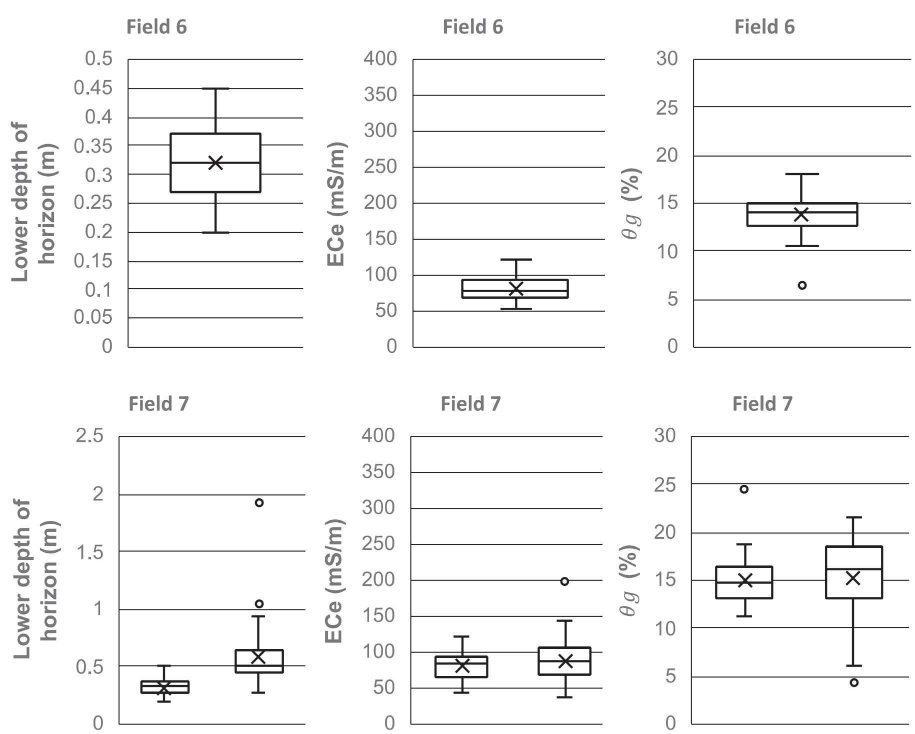


Figure 5.9 Box and whisker plot for lower depth of diagnostic horizons, corresponding electrical conductivity of a saturation extract (EC_e) and gravimetric soil water content (θ_g) from the grid soil samplings. The box and whisker plot from left to right represents the A and B1 diagnostic horizons.

5.4.2 Reliability of EC_a readings and soil property data

Table 5.3 shows descriptive statistics of $EC_{a\ deep}$ and $EC_{a\ shallow}$ readings obtained with the EM38-MK2 for the two effective depth ranges taken during the first survey at the various fields (Fields 1 to 5 = vertical dipole orientation, Fields 6 and 7 = horizontal dipole orientation). The mean EC_a readings for the two effective depth ranges of the reference transects taken during the survey are also included. At all the fields the mean $EC_{a\ deep}$ readings of the reference transects remained relatively constant over time. The mean change in $EC_{a\ deep}$ readings for all the reference transects at the fields were 2% with a highest value of 12% at Field 3. Fields 1 and 2 were surveyed in one day, Fields 3, 4 and 5 in two days and Field 6 and 7 in three days. The mean change in $EC_{a\ shallow}$ readings at the various reference transects were, however, considerably more compared to the $EC_{a\ deep}$ readings. For Fields 1 to 5 the mean change in $EC_{a\ shallow}$ readings for all the reference transects were 5% and varied between 2 and 29%. At Field 6 the mean change in $EC_{a\ shallow}$ readings of the reference transects were more than 50%. The survey at this field was done over three days with 20 mm of rain that fell at the end of the second day. $EC_{a\ shallow}$ readings of the reference transects at Field 6 and 7 were also low (< 10 mS^{-1}), hence, any change in $EC_{a\ shallow}$ readings are exacerbated. The results of the first survey show that in general instrument drift during the day did not significantly influence $EC_{a\ deep}$ readings at the various fields. It also seems that surveying over two days did not considerably influence $EC_{a\ deep}$ readings if the instrument setup was done properly the next day, i.e. initial inphase nulling, instrument zero and final inphase nulling. Care should however be taken when interpreting $EC_{a\ shallow}$ readings at these fields as instrument drift can considerably influence the readings.

Table 5.3 Mean, standard deviation (stdev) and inter quartile range (IQR = quartile 3 minus quartile 1) of apparent electrical conductivity (EC_a) readings for the two effective depth ranges (deep and shallow) taken during first survey at each field. The mean EC_a readings of the reference (ref) transects taken during the survey are also included as well as the correlation (r) between the two effective depth ranges

Field	EM38-MK2	n	Mean	stdev	IQR	r	ref 1	ref 2	ref 3	ref 4	ref 5	ref 6	ref 7
1	$EC_{a\ deep}$	10 482	92	28	38	0.99	73 *	73 *	-	-	-	-	-
	$EC_{a\ shallow}$		62	17	22		44 *	46 *	-	-	-	-	-
2	$EC_{a\ deep}$	8191	51	5	6	0.93	63 *	61 *	-	-	-	-	-
	$EC_{a\ shallow}$		27	4	6		39 *	34 *	-	-	-	-	-
3	$EC_{a\ deep}$	17063	48	7	9	0.88	33 *	33 *	33 **	37 **	-	-	-
	$EC_{a\ shallow}$		27	4	5		18 *	19 *	22 **	15 **	-	-	-
4	$EC_{a\ deep}$	28660	40	3	3	0.68	37 *	35 *	37 **	34 **	-	-	-
	$EC_{a\ shallow}$		22	3	4		21 *	15 *	18 **	16 **	-	-	-
5	$EC_{a\ deep}$	22172	51	7	9	0.86	60 *	59 *	57 **	58 **	-	-	-
	$EC_{a\ shallow}$		31	4	5		41 *	42 *	41 **	42 **	-	-	-
6	$EC_{a\ deep}$	27460	59	6	8	0.62	50 *	51 **	48 **	50 ***	46 ***	-	-
	$EC_{a\ shallow}$		18	5	8		9 *	8 **	4 **	14 ***	14 ***	-	-
7	$EC_{a\ deep}{}^{h}$	27713	71	7	12	0.65	62 *	61 *	61 *	61 *	64 **	59 **	62 ***
	$EC_{a\ shallow}{}^{h}$		14	8	10		11 *	10 *	9 *	10 *	-0.05 **	-2 **	15 ***

* = day 1 of survey; ** = day 2 of survey; *** = day 3 of survey; h = horizontal dipole orientation

Figure 5.10 on the left show interpolated maps (using the ESAP-SaltMapper software) of $EC_{a\ deep}$ readings taken across the various fields during the first survey. On the right, interpolated maps of $EC_{a\ deep}$ readings taken across the fields during a subsequent survey are shown. The kernel size for interpolation at each field was set at 6%, while the blue squares indicate the location of the EC_a-directed sampling sites. At Fields 1 to 3 the spatial pattern of $EC_{a\ deep}$ readings remained relatively constant over time. The magnitude of $EC_{a\ deep}$ readings however changed as shown in the legend of each map. Compared to the first survey, Field 1 had higher values across the field, while Field 2 and 3 lower values during the subsequent survey. The December 2016 survey of Field 4 however shows the result of surveying over two days without proper instrument setup. The area indicated by the arrow was surveyed the next morning and clearly shows an unnatural linear pattern of $EC_{a\ deep}$ readings in the middle of the field. Instrument drift can have a profound effect on EC_a readings as shown by the unnatural circular pattern at Field 6 during the February 2017 survey. The survey started at 10:00 in the morning on the outside of the centre pivot, finishing at 14:00 in the afternoon on the same day in the middle of the centre pivot.

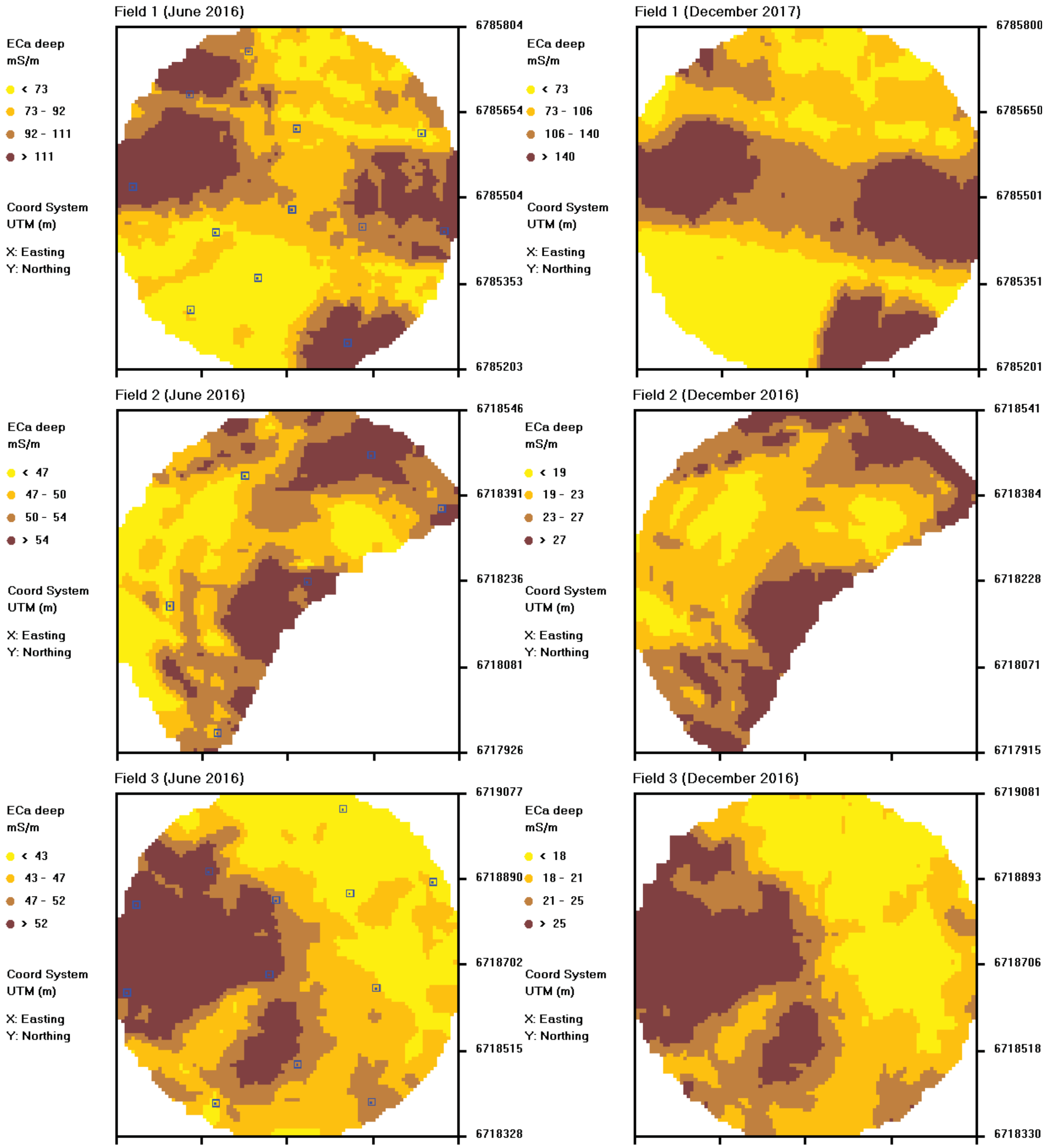


Figure 5.10 Interpolated maps (using the ESAP-SaltMapper software) of apparent electrical conductivity readings taken in the vertical (Fields 1 to 5 = $EC_{a\ deep}$) and horizontal (Field 6 amd 7 = $EC_{a\ deep}$) dipole orientation at the various fields during two different surveys. The kernel size for interpolation was 6%, while the blue squares indicated the location of EC_a-directed sampling sites.

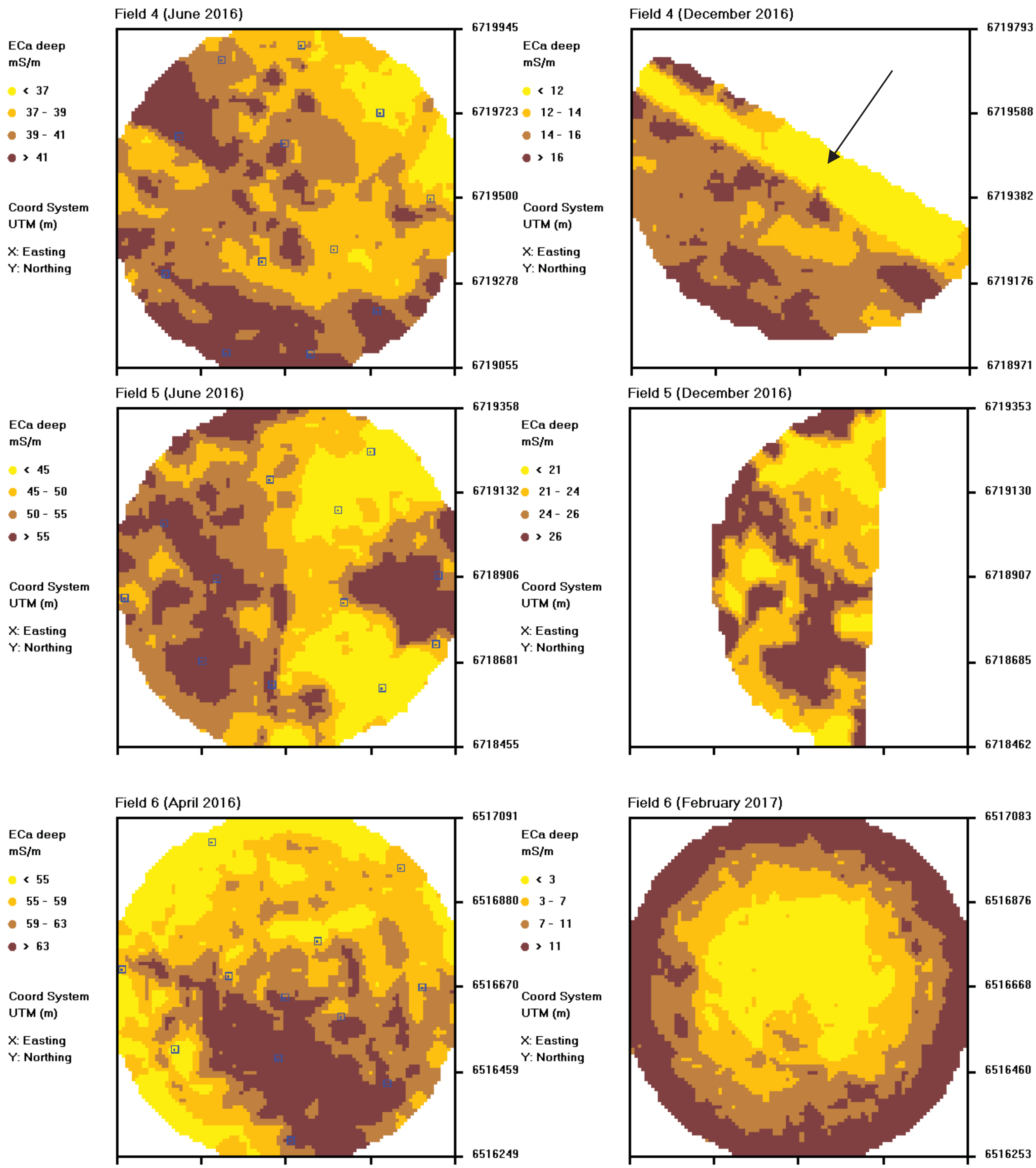


Figure 5.10 (continued)

Ambient temperature, humidity and atmospheric electricity can affect EC_a readings obtained with the EM38. Sudduth et al. (2001) found that the stability of EM38 readings to be quite variable and reported cases of instrument drift, as much as 3 mS m^{-1} per hour. The authors concluded that it was not possible in a reproducible manner to relate drift to changes in ambient temperature, namely “drift per time was fairly constant within a test but varied from day to day. The authors recommended that drift transects should be taken several times during the survey to compensate for any drift, or the re-zeroing of the EM38 on a frequent basis during the course of the survey (at a minimum once every hour). Inphase (I/P) readings of the EM38 measures the sensitivity of the receiver electronics to the primary signal induced by the transmitter. For optimum accuracy, the I/P readings should be maintained at zero. Initial inphase nulling is done before a survey to cancel the large primary signal from the EM38-MK2 so it does not overload the electronic circuitry. Instrument zero is done to make sure the EM38-MK2 would actually read zero (it no longer responds to terrain conductivity) when taken to a height of more than 1.5 m above the soil surface. Final inphase nulling deals with the additional signal picked up by the receiver coil of the EM38-MK2, caused by the magnetic susceptibility of soils. Soil temperature can also have a profound effect on EMI EC_a readings; up to a 1.9% increase with a 1°C increase in temperature throughout the entire soil profile (Corwin and Scudiero, 2016). EC_a readings should ideally be referenced to 25°C, with a temperature correction factor, as explained for example, in Sheets and Hendrickx (1995). Unfortunately, no soil temperature measurements were taken and hence no temperature correction factor was applied to the EC_a readings at the various fields.

Apart from the instrument drift runs, four additional tests were done to evaluate the reliability of EC_a readings, as recommended by Corwin and Scudiero (2016). The first test considers the magnitude of EC_a readings, which were highest at Fields 1, 6 and 7, i.e. $EC_{a\ deep}$ readings (> 50 mS m^{-1}) during the first survey. EC_a readings smaller than 50 mS m^{-1} are generally associated with medium to coarse textured soils with low levels of soil salinity and water content (Corwin and Scudiero, 2016), which was the case at Fields 2 to 5 (Figures 3.5 to 3.9). The second test involves calculating the correlation coefficient (r) between $EC_{a\ deep}$ and $EC_{a\ shallow}$. If r is low ($0.5 < r < 0.8$) then there might by problems with the EC_a readings due to the upper portion of the soil profile being to dry, or the lower portion of the profile having a textural discontinuity, a shallow groundwater table or bed rock (Corwin and Scudiero, 2016). At Fields 4, 6 and 7 the r values were below 0.7 during the first survey. Problems in EC_a readings at Field 4 might be attributed to the presence of a calcareous layer below 1 m. According to Figures 3.5 and 3.8, the clay content and θ_g at Field 4 remained relatively constant with an increase in depth, hence no textural discontinuity or shallow groundwater table is present. The low correlation between $EC_{a\ deep}$ and $EC_{a\ shallow}$ at Field 6 and 7 (EC_a readings were taken in the horizontal dipole orientation) during the first survey could have been caused by the textural discontinuity as shown in Figure 5.6. Test three involves calculating the ratio $EC_{a\ shallow}$ / $EC_{a\ deep}$. A ratio smaller than 1 suggest a regular profile where the target property (EC_e, clay or soil water content) increases with depth. Section 5.3.1 showed that in general EC_e, clay content and θ_g at Field 1, 2, 3 and 5 increased with an increase in depth, which corresponds to the measured EC_a ratio of less than 1 at these fields during the first survey. If the depth profile of the measured target soil property (EC_e, clay or soil water content) does not correspond to the ratio, then the $EC_{a\ deep}$ and/or $EC_{a\ shallow}$ readings may be devious.

The most useful test is the DPPC correlation analysis as described in Sections 5.2.1 and 5.3.5. Results for the DPPC analysis of the data obtained from the first survey at each field are shown in Table 5.4. In the analysis it was decided to use only $EC_{a\ deep}$ readings, which were more stable during the survey at each field, as discussed above. Furthermore, measured data of EC_e, clay content, θ_g and BD were used as composite depths of 0-0.3, 0-0.6, 0-0.9, 0-1.2 and 0-1.5 m to determine EC_{ac} of 0-1.5 m. The correlation between $EC_{a\ deep}$ readings taken during the first survey and mean EC_{ac} over a depth of 1.5 m were 0.015, 0.994, 0.522, 0.506, 0.498, 0.548 and 0.405 for Fields 1 to 7, respectively. If an accurate DPPC model is employed and the errors associated with $EC_{a\ deep}$ readings minimal, then a value close to 1 should occur, as was found at Field 2. Also each $EC_{a\ deep}$--soil property correlation should agree quite well with $EC_{a\ prd}$--

soil property correlation, which are shown in Table 5.4 and Figure 5.11a for data from the first survey. Signal deterioration at Fields 3, 4, 6 and 7 were extreme (> 50%) indicating a high variability of clay content, and bulk density across the field and poor correlation with EC_e.

Table 5.4 Dual-Pathway Parallel Conductance (DPPC) correlation analysis results of apparent deep electrical conductivity readings ($EC_{a\ deep}$) and soil property data (measured at the 12 EC_a-directed sampling sites) obtained during the first survey (June 2016) at Fields 1 to 7. All data were log transformed before performing the correlation analysis

Field (correlation EC_{ac}--$EC_{a\ deep}$) (mean signal deterioration)	Soil property	EC_{ac}	$EC_{a\ prd}$	95% confidence		$EC_{a\ deep}$
1 (0.015) (1.4%)	EC_e	0.993	0.014	-0.057	0.085	-0.014
	Clay	-0.073	-0.001	-0.601	0.599	0.421
	θ_v	0.469	0.007	-0.525	0.538	-0.359
	BD	0.645	0.009	-0.451	0.469	-0.012
2 (0.994) (7%)	EC_e	0.964	0.958	0.933	0.984	0.965
	Clay	0.452	0.449	0.362	0.536	0.391
	θ_v	0.722	0.717	0.649	0.785	0.702
	BD	0.194	0.193	0.097	0.289	0.215
3 (0.522) (100%)	EC_e	0.011	0.006	-0.507	0.519	0.337
	Clay	0.521	0.272	-0.166	0.710	0.102
	θ_v	0.982	0.513	0.417	0.609	0.458
	BD	0.253	0.132	-0.364	0.629	0.341
4 (0.506) (99%)	EC_e	0.104	0.053	-0.464	0.569	0.073
	Clay	0.541	0.274	-0.163	0.711	0.108
	θ_v	0.837	0.424	0.139	0.708	0.334
	BD	-0.055	-0.028	-0.546	0.491	-0.030
5 (0.498) (12.4%)	EC_e	0.936	0.466	0.282	0.65	0.510
	Clay	0.321	0.16	-0.334	0.654	-0.118
	θ_v	0.673	0.335	-0.051	0.721	0.218
	BD	-0.210	-0.104	-0.615	0.406	-0.250
6 (0.548) (83%)	EC_e	0.410	0.225	-0.234	0.684	0.337
	Clay	-0.155	-0.085	-0.582	0.413	0.056
	θ_v	0.929	0.509	0.322	0.696	0.399
	BD	0.162	0.089	-0.408	0.586	-0.060
7 (0.405) (39%)	EC_e	0.778	0.315	-0.031	0.661	0.113
	Clay	0.630	0.255	-0.172	0.683	0.586
	θ_v	0.431	0.175	-0.322	0.671	-0.057
	BD	-0.617	-0.25	-0.683	0.183	-0.569

EC_{ac} = calculated apparent soil electrical conductivity; EC_e = electrical conductivity of a saturation extract; θ_v = volumetric soil water content; BD = bulk density; $EC_{a\ deep}$ = apparent soil electrical conductivity obtained with the EM38-MK2 (Section 5.3.2); $EC_{a\ prd}$ = predicted apparent soil electrical conductivity correlation structure (Section 5.3.5)

The results in Figure 5.11a show that in general there is a reasonable association between $EC_{a\ deep}$-soil property correlations and $EC_{a\ prd}$--soil property correlations (most of the data points fall within the 1:1 line) for data obtained during the first survey. At Field 1 and 7 problems exist, however, with either $EC_{a\ deep}$ readings or soil property data from the first survey because the data points that fall outside the 10% deviation line correspond to these fields. Correlations between $EC_{a\ deep}$ readings taken during the second survey and mean EC_{ac} over a depth of 1.5 m were much better, namely 0.64, 0.96, 0.60 and 0.90 at Field 1, 2, 3 and 5, respectively. Compared to the first survey at these fields, Figure 5.11b also shows a higher degree of association between $EC_{a\ deep}$--soil property correlations and $EC_{a\ prd}$--soil property correlations. Fields 4 and 6 were excluded from the DPPC analysis of data in the second survey because of problems in $EC_{a\ deep}$ readings, as explained by the results in Figure 5.10.

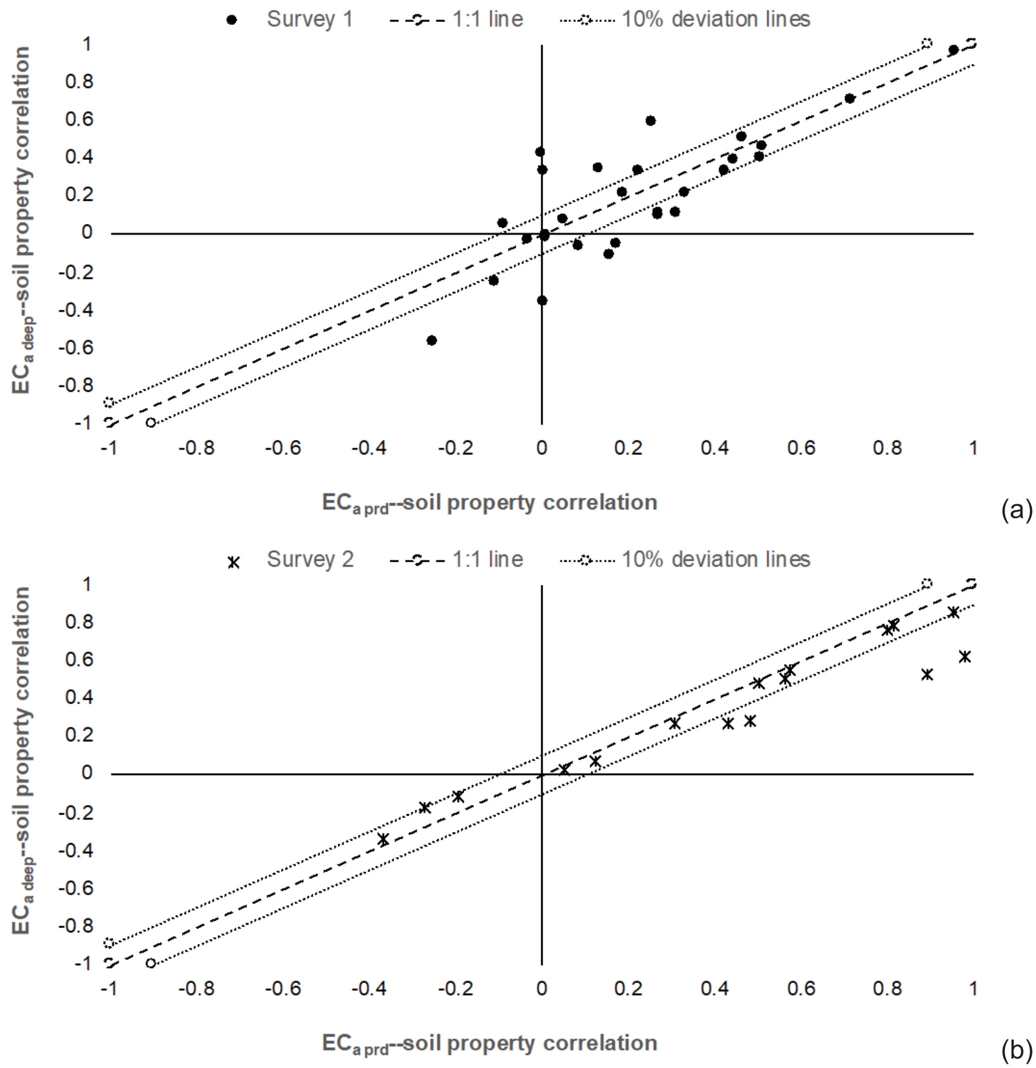


Figure 5.11 The 1:1 association between $EC_{a\ deep}$--soil property correlations and $EC_{a\ prd}$--soil property correlations of data obtained during the first survey at Fields 1 to 7 (a) and during the second survey at Fields 1, 2, 3 and 5 (b). An explanation of the correlations can be found in Sections 5.2.1 and 5.3.5.

Unfortunately, the DPPC correlation analysis can only indicate that there is a problem with either $EC_{a\ deep}$ readings or soil property data. It does not indicate where the problems lies. If it is assumed that $EC_{a\ deep}$ readings and soil property data are reliable at these fields, then the validity of the DPPC model when applied to the soils located at the various fields can be questioned. Rhoades et al. (1989, 1990) have shown that the DPPC model is generally applicable to arid-land mineral soils of the Southwestern United States. Rhoades et al. (1999) mentions that there is "no reason to believe that it is equally applicable to similar arid-land soils found elsewhere". The authors however, do caution against using the model on soils containing high contents of gypsum, which have not been tested as gypsum particles may be more conductive than silicate particles. $EC_{a\ deep}$--soil property correlations shown in Table 5.4 and Figure 5.11 represent actual "worst-case" scenarios for the $EC_{a\ deep}$ survey and soil property data set. A multiple linear regression model can produce better correlations because additional trend surface parameters can be incorporated when these parameters improve prediction accuracy. This will be illustrated in the next section.

5.4.3 Stochastic calibration of EC_a to a target soil property and graphical display

At all the fields the $EC_{a\ deep}$ readings were used to model the target soil property (EC_e, clay content, $\boldsymbol{\theta_v}$ and BD) variability according to Equation 3.17 with the $\beta_2\ ln(EC_{a\ shallow})$ term removed. This was decided because $EC_{a\ deep}$ readings proved to be the most reliable as discussed previously. The automatic model identification and analysis of all possible model algorithms of ECAP-Calibrate also indicated the $EC_{a\ deep}$ would provide the best modelling results. If the $\beta_2\ ln(EC_{a\ shallow})$ term in Equation 3.17 is not disregarded, the multicollinear signal effect between $EC_{a\ deep}$ and $EC_{a\ shallow}$ readings that might excise should be addressed. Fortunately, the ESAP software attempts to address the issue by using decorrelated readings and scaled location coordinates.

Final parameter combination ($EC_{a\ deep}$ and trend surface parameters) for the spatial MLR models to estimate spatial variability of a target soil property, developed from the June 2016 survey, are shown in Table 5.5. The models were developed with the automatic model identification and analysis of all possible model algorithm in ESAP-Calibrate, as explained in Section 5.2.3, for all composite depth ranges (0-0.3, 0-0.6, 0-0.9, 0-1.2 and 0-1.5 m). The composite depth range that gave the highest correlation (R^2) between a final parameter combination ($EC_{a\ deep}$ and trend surface parameters) and the target soil property were selected. This depth range represents the approximate depth that the EM38-MK2 instrument (Corwin and Scudiero, 2016) measures at the specific field, i.e. the soil depth that primarily influences the $EC_{a\ deep}$ reading.

Table 5.5 Final parameter combination for the spatial multiple linear regression calibration models between the apparent soil electrical conductivity reading (with the EM38-MK2) and a target soil property for the June 2016 survey

Property	Field	Depth (m)	Model
EC_e	1	0-1.5	ln (EC_e) = b0 + b1(z1) + b2(x)
	2	0-0.9	ln (EC_e) = b0 + b1(z1)
	3	0-1.5	ln (EC_e) = b0 + b1(z1) + b2(y) + b3(y^2)
	4	0-0.9	ln (EC_e) = b0 + b1(z1) + b2(z1^2) + b3(y)
	5	0-0.9	ln (EC_e) = b0 + b1(z1) + b2(x) + b3(x^2)
	6	0-0.3	ln (EC_e) = b0 + b1(z1) + b2(z1^2) + b3(x)
	7	0-0.6	ln (EC_e) = b0 + b1(z1) + b2(y) + b3(y^2)
Clay	1	0-1.2	ln (Clay) = b0 + b1(z1)
	2	0-1.2	ln (Clay) = b0 + b1(z1) + b2(x)
	3	0-0.3	ln (Clay) = b0 + b1(z1) + b2(z1^2)
	4	0-0.9	ln (Clay) = b0 + b1(z1)
	5	0-0.6	ln (Clay) = b0 + b1(z1)
	6	0-0.6	ln (Clay) = b0 + b1(z1)
	7	0-0.6	ln (Clay) = b0 + b1(z1) + b2(z1^2) + b3(x) + b4(y) + b5(x^2)
(1-5) (6, 7)	1	0-1.5	ln (θ_v) = b0 + b1(z1) + b2(x) + b3(x^2)
	2	0-0.9	ln (θ_v) = b0 + b1(z1) + b2(y)
	3	0-1.5	ln (θ_v) = b0 + b1(z1) + b2(z1^2) + b3(x) + b4(x^2)
	4	0-0.9	ln (θ_v) = b0 + b1(z1) + b2(x)
	5	0-0.3	ln (θ_v) = b0 + b1(z1)
	6	0-0.6	ln (θ_v) = b0 + b1(z1) + b2(z1^2) + b3(y)
	7	0-0.6	ln (θ_v) = b0 + b1(z1) + b2(x) + b3(y)
BD	1	0-0.6	ln (BD) = b0 + b1(z1) + b2(x) + b3(y) + b4(xy) + b5(x^2) + b6(y^2)
	2	0-1.2	ln (BD) = b0 + b1(z1)
	3	0-1.5	ln (BD) = b0 + b1(z1)
	4	0-0.3	ln (BD) = b0 + b1(z1)
	5	0-0.3	ln (BD) = b0 + b1(z1) + b2(x)

z1 = decorrelated $EC_{a\ deep}$ reading; x and y = scaled coordinates; EC_e = electrical conductivity of a saturation extract; θ_v = volumetric soil water content; θ_g = gravimetric soil water content; BD = bulk density

Table 5.6 provides the statistical analysis of the various spatial MLR models developed with data from the first survey. A F-test was done to determine if a specific calibration model significantly represents the target soil property given the specific parameter combination. In addition, each parameter in the MLR model was tested for significance with a t-test.

Table 5.6 Statistical analysis of the spatial multiple linear regression models and parameter combinations listed in Table 5.5

Property	Field	1	2	3	4	5	6	7
EC_e	**Depth (m)**	0-1.5	**0-0.9**	**0-1.5**	0-0.9	**0-0.9**	0-0.3	0-0.6
	Model	*	*	*	ns	*	*	*
	R^2	0.5348	**0.9528**	**0.8549**	0.5474	**0.7383**	0.6329	0.7427
	RMSE	0.5821	**0.1393**	**0.1173**	0.1466	**0.3573**	0.1038	0.0596
	Intercept	7.7887 *	**4.5164 ***	**5.1776 ***	4.1696 *	**5.1509 ***	4.6339 *	4.2053 *
	b1	0.0973 ^{ns}	**0.3903 ***	**0.2329 ***	0.0169 ^{ns}	**0.2196 ***	0.0453 ^{ns}	-0.0143 ^{ns}
	b2	-1.9748 *	-	**-2.2548 ***	-0.0584 ^{ns}	**-4.4622 ***	0.0174 ^{ns}	1.1939 *
	b3	-	-	**2.3507 ***	0.2921 ^{ns}	**4.8475 ***	-0.2737 *	-1.1638 *
Clay	**Depth (m)**	0-1.2	0-1.2	0-0.3	0-0.9	0-0.6	0-0.6	0-0.6
	Model	ns	ns	*	ns	ns	ns	*
	R^2	0.2977	0.6868	**0.6818**	0.0129	0.0579	0.0655	0.9277
	RMSE	0.1089	0.1386	**0.1268**	0.2359	0.2480	0.1888	0.1187
	Intercept	3.3865 *	2.1230 *	**2.7081 ***	2.2711 *	2.1727 *	3.4672 *	3.3043 *
	b1	0.0521 ^{ns}	-0.0160 ^{ns}	**0.0806 ***	0.0199 ^{ns}	-0.0452 ^{ns}	0.0336 ^{ns}	-0.0481 ns
	b2	-	0.5626 ^{ns}	**-0.0985 ***	-	-	-	0.0299 ns
	b3	-	-	-	-	-	-	-2.2356 *
	b4	-	-	-	-	-	-	1.1233 *
	b5	-	-	-	-	-	-	1.9066 *
θ_v (1-5) θ_g (6, 7)	**Depth (m)**	0-1.5	0-0.9	0-1.5	**0-0.9**	0-0.3	0-0.6	0-0.6
	Model	*	ns	*	*	ns	ns	*
	R^2	0.9197	0.7537	0.8871	**0.5180**	0.1449	0.4353	0.6968
	RMSE	0.0317	0.1303	0.2060	**0.1629**	0.1644	0.3571	0.2351
	Intercept	-1.1871 *	-2.3555 *	-1.9620 *	**-2.4780 ***	-2.2845 *	2.7804 *	3.0774 *
	b1	0.0146 ^{ns}	0.1052 ^{ns}	0.0311 ^{ns}	**0.1183 ***	-0.0497 ^{ns}	0.0638 ^{ns}	0.0177 ^{ns}
	b2	-0.9894 *	0.2747 ^{ns}	-0.0403 ^{ns}	**0.6685 ***	-	-0.0850 ^{ns}	-0.7138 *
	b3	0.7343 *	-	1.2403 ^{ns}	-	-	-0.6997 ^{ns}	-0.5897 ^{ns}
	b4	-	-	-2.8187 *	-	-	-	-
BD	**Depth (m)**	0-0.6	0-1.2	0-1.5	0-0.3	0-0.3	-	-
	Model	*	ns	ns	ns	*	-	-
	R^2	0.8895	0.5939	0.2302	0.0109	0.7878	-	-
	RMSE	0.0145	0.0136	0.0304	0.0360	0.0228	-	-
	Intercept	0.4869 *	0.4950 *	0.4431 *	0.4501 *	0.3660 *	-	-
	b1	-0.0093 ^{ns}	0.0103 ^{ns}	0.0128 ^{ns}	-0.0028 ^{ns}	0.0030 ^{ns}	-	-
	b2	-0.3381 *	-	-	-	0.1290 *	-	-
	b3	-0.2537 *	-	-	-	-	-	-
	b4	0.0077 ^{ns}	-	-	-	-	-	-
	b5	0.2924 *	-	-	-	-	-	-
	b6	0.2829 *	-	-	-	-	-	-

* = significant at 5%; ns = non-significant; z1 = decorrelated $EC_{a\ deep}$ readings; x and y = scaled coordinates

All the models developed at the various fields for estimating EC_e during the first survey were significant, except at Field 4. The proportion of variation in EC_e (dependent variable) that was explained by the different parameter combinations (independent variable) at these fields was high (R^2 > 0.6), except Field 1. The primary depth of influence varied from field to field, i.e. 0-1.5 m for Fields 1 and 3, 0-0.9 m for Fields 2 and 5 and 0-0.3 and 0-0.6 for Field 6 and 7, respectively (Table 5.6). However, only at Fields 2, 3 and 5 $EC_{a\ deep}$

readings were significant (parameter b1 in Table 5.6 is significant) in the MLR models of EC_e, i.e. EC_e across the field is significantly influencing the $EC_{a\ deep}$ readings. In addition to $EC_{a\ deep}$ readings, at Field 2 no x and y coordinates were included in the MLR model, while the y-coordinate was significant at Field 3 and the x-coordinate at Field 5 (Table 5.6). At Field 3 clay content in combination with EC_e significantly influenced the $EC_{a\ deep}$ reading, while at Field 4 only θ_v significantly influenced the $EC_{a\ deep}$ readings. The parameter combination at Field 4 however, explained a low proportion of the variation in θ_v ($R^2 < 0.6$). Figure 5.12 shows interpolated maps of EC_e across Field 2, 3 and 5, estimated with the specific MLR model using the ESAP-SaltMapper software.

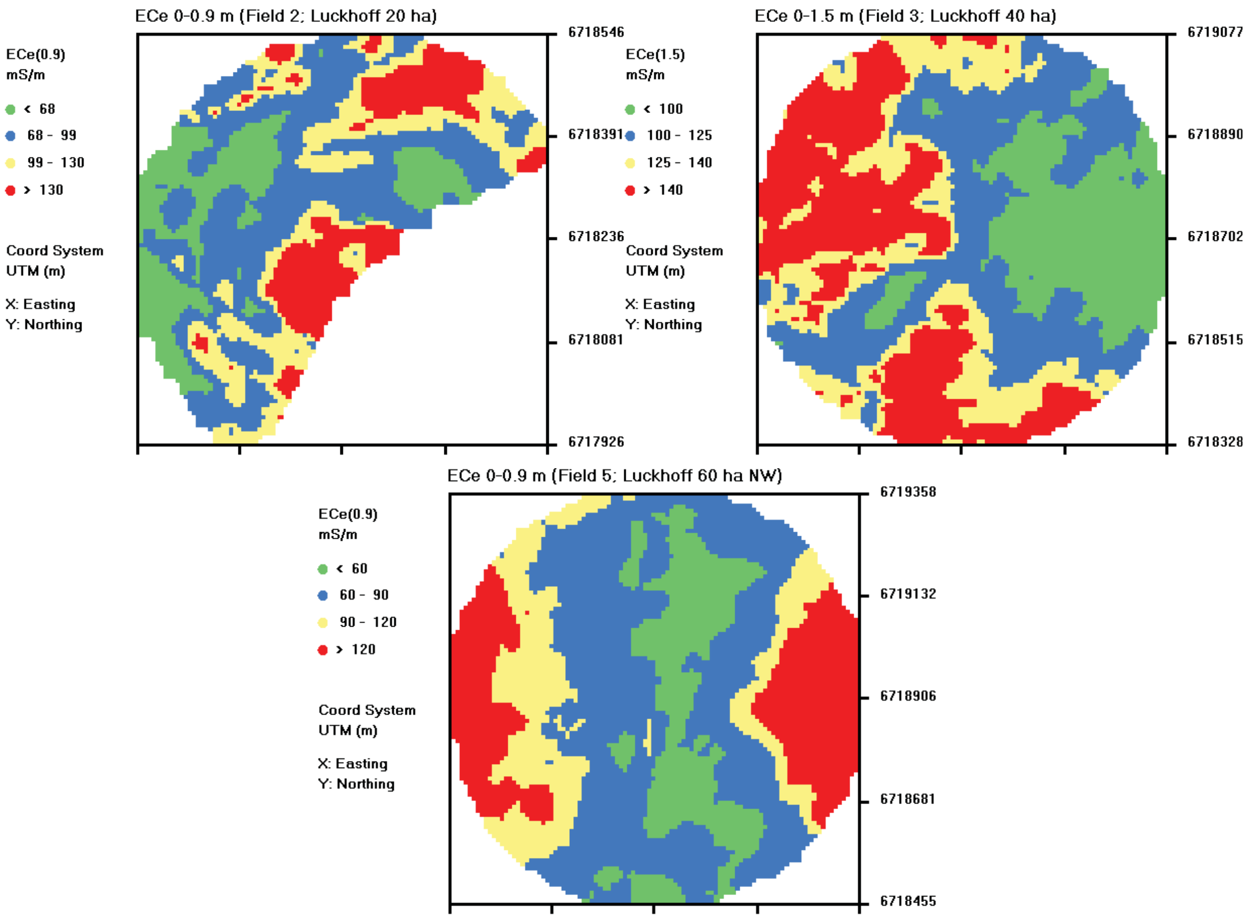


Figure 5.12 Interpolated maps (using the ESAP-SaltMapper software) of estimated soil salinity (EC_e) where deep apparent soil electrical conductivity ($EC_{a\ deep}$) readings taken during the first survey were a significant parameter in the spatial multiple linear regression (MLR) model (Table 5.5 and 3.6).

Biased spatial MLR models can be developed if the random nature of the ε component (constant variance of the residuals) in Equation 3.17 and the assumption of normality for ε is not confirmed. Spatial autocorrelation of the residuals will also cause devious results. The first two assumptions were graphically confirmed with the residual plots provided by ESAP-Calibrate, while the Moran residual spatial autocorrelation test was calculated (Cliff and Ord, 1981), which showed non-significant spatial structure at these fields. At Field 1, 6 and 7 $EC_{a\ deep}$ readings did not significantly (parameter b1 in Table 5.6 is non-significant) influence EC_e estimations during the first survey, or EC_e across the field are not driving the $EC_{a\ deep}$ reading. The intercept of the spatial MLR models at these fields were, however, significant (Table 5.6) as well as the scaled x coordinate at Field 1 and 6 and y coordinate at Field 7. This effectively signifies that the mean estimated EC_e, represented by the intercept of the MLR models, changes across the field as the x or y coordinate changes, and not as $EC_{a\ deep}$ changes, as shown in Figure 5.13. For example, at Field 1 the measured EC_e values at sampling sites corresponding to more or less the same x-coordinate (same side of the field, for example left hand side) have more or less the same value (mean). On the other side (right hand side) of the field the EC_e values at those sampling sites have more or less the same value.

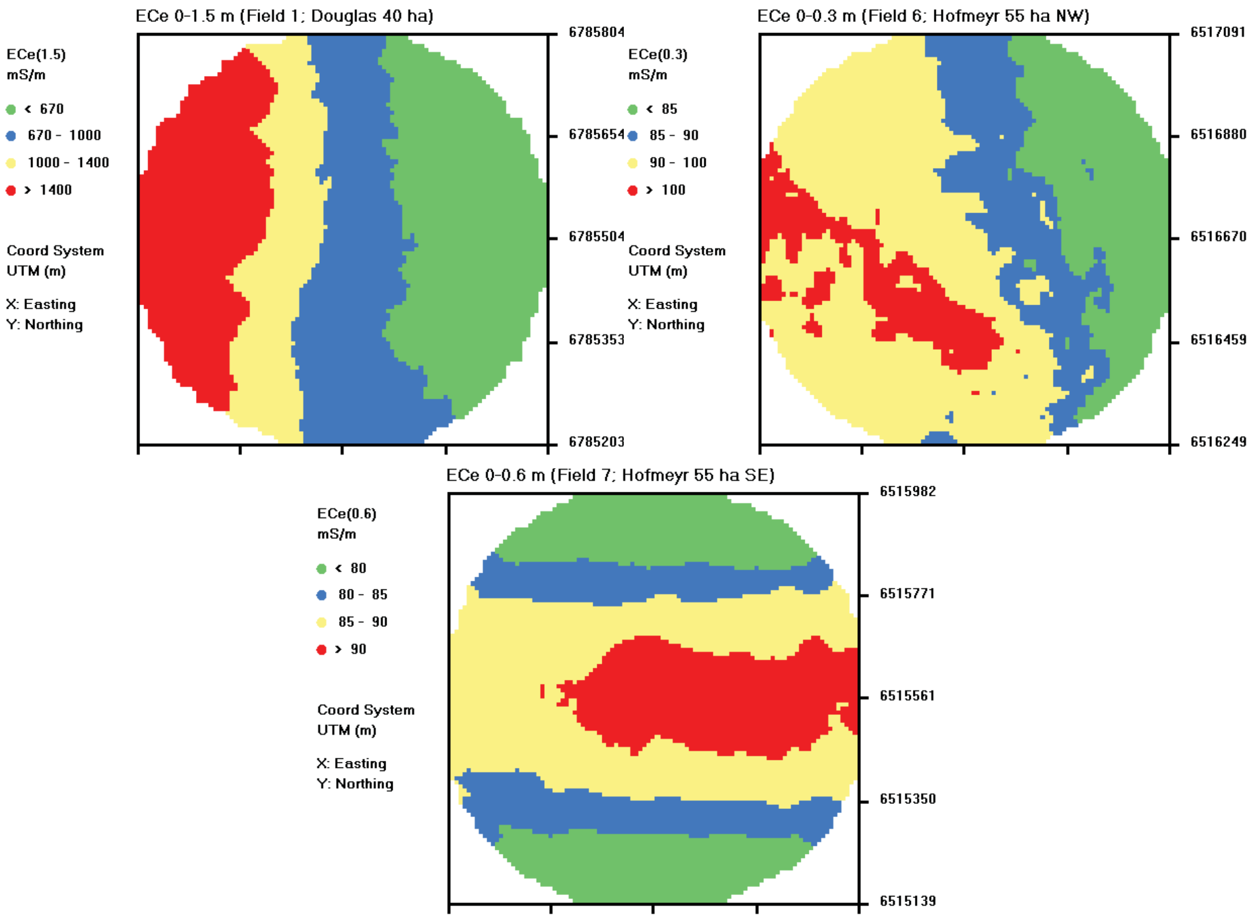


Figure 5.13 Interpolated maps (using the ESAP-SaltMapper software) of estimated soil salinity (EC_e) where deep apparent soil electrical conductivity ($EC_{a\ deep}$) readings taken during the first survey were not a significant parameter in the spatial multiple linear regression (MLR) model (Table 5.5 and 3.6).

Table 5.7 shows the final parameter combination for the spatial MLR models developed from the December 2016 (Fields 2, 3 and 5) and June 2017 (Field 1) surveys, while Table 5.8 provides the statistical results. The results are provided only for Field 1, 2, 3 and 5 because of devious $EC_{a\ deep}$ readings at Field 4 and 6 as shown in Figure 5.10. During the survey $EC_{a\ deep}$ readings at Field 1, 2, 3 and 5 were not significantly influenced by EC_e across the field. A high proportion of the variation in EC_e ($R^2 > 0.7$) at Fields 1 and 3 are explained by the parameter combination, primarily by the x-coordinate which was significant in the spatial MLR models. $EC_{a\ deep}$ readings during the surveys were significantly influenced by clay content at Field 1, clay content and θ_v at Field 2 and θ_v at Field 5. Figure 5.14 shows interpolated maps of these target soil properties (which significantly influenced $EC_{a\ deep}$ readings) across Fields 1, 2 and 5, estimated with the specific MLR model using the ESAP-SaltMapper software.

Table 5.7 Final parameter combination for the spatial multiple linear regression calibration models between the apparent soil electrical conductivity reading (with the EM38-MK2) and a target soil property for the December 2016 (Fields 2, 3 and 5) and June 2017 (Field 1) surveys

Property	Field	Depth (m)	Model
EC_e	1	0-0.6	ln (EC_e) = b0 + b1(z1) + b2(x) + b3(y)
	2	0-1.5	ln (EC_e) = b0 + b1(z1)
	3	0-0.3	ln (EC_e) = b0 + b1(z1) + b2(x) + b3(y) + b4(x^2)
	5	0-1.5	ln (EC_e) = b0 + b1(z1)
Clay	1	0-1.2	ln (Clay) = b0 + b1(z1)
	2	0-1.2	ln (Clay) = b0 + b1(z1) + b2(y)
	3	0-1.5	ln (Clay) = b0 + b1(z1)
	5	0-1.2	ln (Clay) = b0 + b1(z1) + b2(y)
θ_v (1-5) θ_g (6, 7)	1	0-1.5	ln () = b0 + b1(z1)
	2	0-1.5	ln () = b0 + b1(z1)
	3	0-1.5	ln () = b0 + b1(z1) + b2(x) + b3(y) + b4(xy) + b5(x^2) + b6(y^2)
	5	0-1.5	ln () = b0 + b1(z1) + b2(y)
BD	1	0-1.5	ln (BD) = b0 + b1(z1) + b2(x)
	2	0-1.2	ln (BD) = b0 + b1(z1)
	3	0-1.5	ln (BD) = b0 + b1(z1)
	5	0-1.2	ln (BD) = b0 + b1(z1)

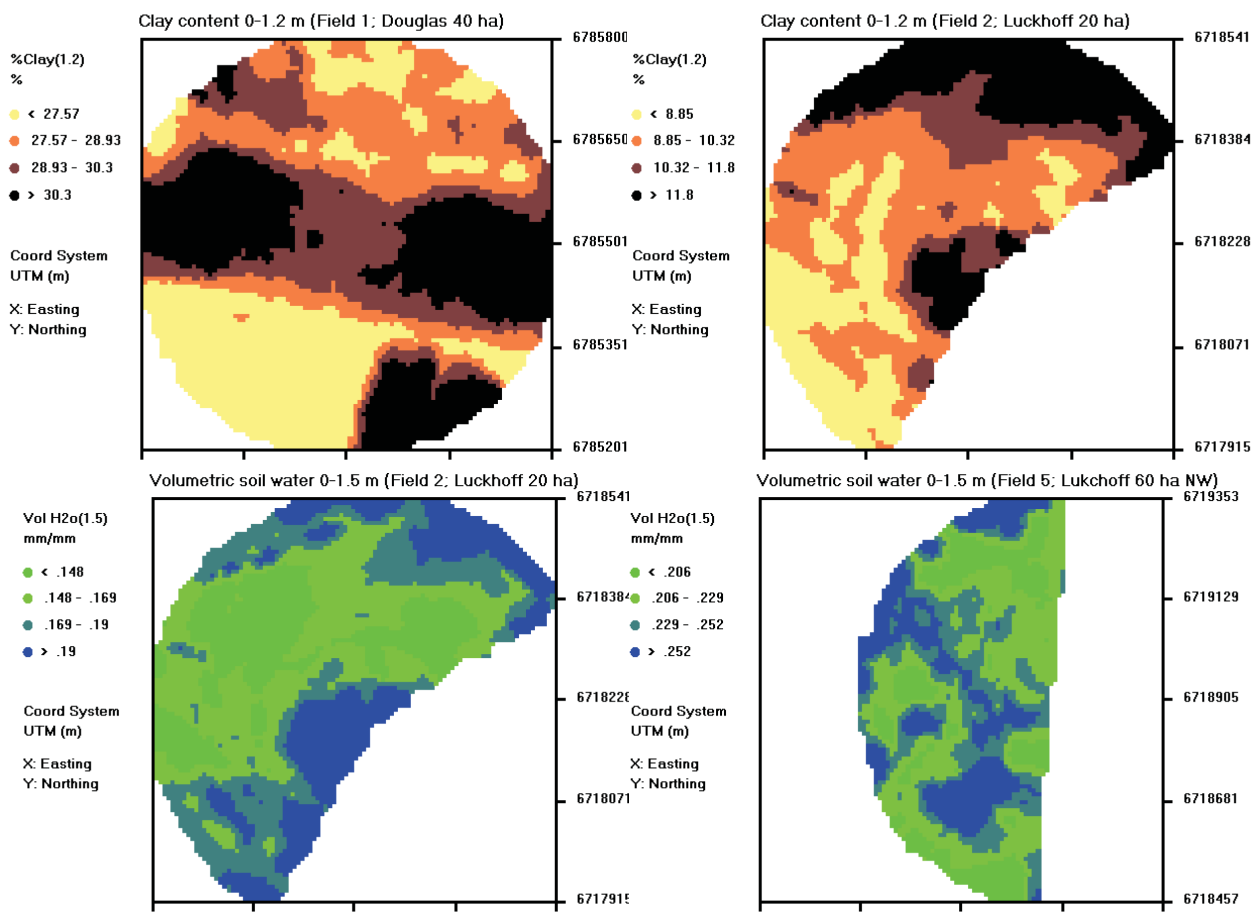


Figure 5.14 Interpolated maps (using the ESAP-SaltMapper software) of estimated clay content and volumetric soil-water content where deep apparent soil electrical conductivity ($EC_{a\ deep}$) readings taken during the second (Fields 2 and 5) and final (Field 1) surveys were a significant parameter in the spatial multiple linear regression (MLR) model (Table 5.7 and 3.8).

Table 5.8 Statistical analysis of the spatial multiple linear regression models and parameter combinations listed in Table 5.7

Property	Field	1	2	3	5
EC_e	**Depth (m)**	0-0.6 m	Mean	0-0.3 m	0-1.5 m
	Model	*	ns	*	ns
	R^2	0.7605	0.5298	0.7419	0.4418
	RMSE	0.2120	0.2211	0.1807	0.2324
	Intercept	4.6523 *	5.0306 *	4.5607 *	4.6899 *
	b1	0.0681 ^{ns}	0.2582 ^{ns}	-0.0014 ^{ns}	0.1319 ^{ns}
	b2	0.9088 *	-	-2.1776 *	-
	b3	-0.3473 ^{ns}	-	-0.1575 ^{ns}	-
	b4	-	-	2.8825 *	-
Clay	**Depth (m)**	**0-1.2 m**	**0-1.2 m**	0-1.5 m	0-1.2 m
	Model	*****	*****	ns	ns
	R^2	**0.5413**	**0.9325**	0.0937	0.8487
	RMSE	**0.0892**	**0.0657**	0.0896	0.0628
	Intercept	**3.3626 ***	**1.9555 ***	2.6039 *	2.5131 *
	b1	**0.0695 ***	**0.1566 ***	-0.0221 ^{ns}	-0.0489 ^{ns}
	b2	**-**	**0.6018 ***	-	-0.6440 *
θ_v (1-5) θ_g (6, 7)	**Depth (m)**	0-1.5 m	**0-1.5 m**	0-1.5 m	**0-1.5 m**
	Model	ns	*****	*	*****
	R^2	0.2670	**0.8809**	0.9729	**0.9384**
	RMSE	0.0757	**0.0563**	0.0462	**0.0637**
	Intercept	-1.7536 *	**-1.7948 ***	-1.6017 *	**-1.5397 ***
	b1	0.0328 ^{ns}	**0.1685 ***	-0.0254 ^{ns}	**0.1483 ***
	b2	-	-	-0.1029 ^{ns}	**0.1075 ^{ns}**
	b3	-	-	0.9325 *	**-**
	b4	-	-	0.1406 ^{ns}	**-**
	b5	-	-	-0.5754 *	**-**
	b6	-	-	-1.2808 *	**-**
BD	**Depth (m)**	0-1.5 m	0-1.2 m	0-1.5 m	0-1.2 m
	Model	ns	ns	ns	ns
	R^2	0.2876	0.4681	0.1559	0.3856
	RMSE	0.0315	0.0156	0.0318	0.0110
	Intercept	0.3839 *	0.4868 *	0.4413 *	0.4975 *
	b1	0.0059 ^{ns}	0.0161 ^{ns}	0.0105 ^{ns}	-0.0056 ^{ns}
	b2	-0.0662 ^{ns}	-	-	-

5.5 Discussion

It was shown by the DPPC correlation analysis (done according to Corwin and Lesch, 2003) of grid soil sampling data (dataset 1 = EC_e, clay content and θ_g) taken during June 2017 that soil salinity will potentially dominate EC_a measurements at these irrigated fields (r > 0.9 between EC_{ac} and EC_e at Fields 1 to 7) located near Douglas, Luckhoff and Hofmeyr in central South Africa. The feasibility of doing an EC_a survey to spatially characterise clay content and BD at all the fields, except Fields 6 and 7, were low. At these two fields the clay content is generally above 25% with evidence of textural discontinuity, while sandy to sandy loam soils ($\pm$ 10% clay) dominate at Fields 2 to 5. Only at Field 3 did it seem that an EC_a survey could potentially be feasible to spatially characterise θ_v. The authors acknowledge that the analysis was done with data collected after the EC_a surveys were done, i.e. June 2016 and December 2016. Ideally, the analysis should be done before an EC_a survey to determine the feasibility of doing an EC_a survey. It is expected however, that this did not influence the results obtained from these fields, primarily because the correlation between the static soil property of clay content and the dynamic soil properties of EC_e and θ_v at all the fields were poor. Hence, terrain and external natural drainage (artificial drainage only at Field 4) conditions played a considerable role in the spatial pattern of EC_e and θ_v at these fields. Even if the spatial pattern and/or magnitude of EC_e and θ_v changes over time, a good idea, as to whether these measurements influence EC_a readings at these fields was obtained. It is acknowledged that the distribution efficiency of the irrigation system and management of irrigation scheduling can also influence the magnitude and spatial pattern of EC_e and θ_v at these fields.

The general importance of understanding primary soil property effects and minimising secondary influences when using EC_a readings to spatially characterise a target soil property was emphasised once more with local data (dataset 2 = EC_a-directed sampling of EC_e, clay content, θ_v and BD). It was shown that for these soils care should be taken when interpreting $EC_{a\ shallow}$ readings as obtained with the EM38-MK2 in the vertical or horizontal dipole orientation due to instrument drift and/or soil temperature effects, especially when EC_a surveys are done over two days. In general, $EC_{a\ deep}$ readings obtained with the EM38-MK2 remained relatively stable during a survey even when done over multiple days. A DPPC correlation analysis (done according to Corwin and Lesch, 2003) of $EC_{a\ deep}$ readings and soil property data collected during the June 2016 survey revealed that in general the data were reliable, except at Fields 1 and 7. The December 2016 survey at Fields 2, 3 and 5 as well as the June 2017 survey at Field 1 did however show better results in terms of reliability of EC_a readings and soil property data.

It should be noted that the findings of both DPPC correlation analysis assumes that the DPPC model of Rhoades et al. (1989) is applicable to these soils. No evidence could be found regarding the applicability of the DPPC model to irrigated soils in South Africa, especially calcareous soils found in the major irrigated regions of central South Africa.

During the June 2016 EC_a survey at three of the seven fields (Fields 2, 3 and 5), the spatial MLR models revealed that EC_e significantly (at 5%) influenced $EC_{a\ deep}$ readings, which confirmed the earlier DPPC correlation analysis of grid sampling data at these fields. The best spatially MLR models were obtained for composite depth ranges of 0-0.9 m, 0-1.5 m and 0-0.9 m at these fields, respectively. More than 70% of the variation in EC_e (R^2 values) was explained by the parameter combinations of $EC_{a\ deep}$ at Field 2, $EC_{a\ deep}$ and the y-coordinate at Field 3 and $EC_{a\ deep}$ and the x-coordinate at Field 5. At Field 4 the spatial MLR model showed that θ_v of the 0-0.9 m composite depth significantly influenced $EC_{a\ deep}$ readings. Only 52% of the variation in θ_v was however explained by $EC_{a\ deep}$ readings at this Field.

During the second survey at Fields 2, 3 and 5, EC_e did not significantly (at 5%) influence $EC_{a\ deep}$ readings. At Fields 2 and 5 θ_v were instead the dominant (significant) influence on $EC_{a\ deep}$ readings, with more than 80% of the variation in θ_v explained by $EC_{a\ deep}$ readings at Field 2 and a combination of $EC_{a\ deep}$ readings and y-coordinate at Field 5. Soil data from the 12 EC_a-directed sampling sites at Field 2 showed that during the December 2016 survey, the soil was in general wetter with a lower spatial range (difference between maximum and minimum value) compared to the June 2016 survey. The mean θ_v over a depth of 1.5 m across the 6 sampling sites at Field 2 increased by 37% from June to December 2016, while the range decreased by 29%. During the same time period the mean EC_e across the field over the same depth increased by 42%, while the range decreased by 15%. The dominant influence of θ_v during the December 2016 survey as opposed to EC_e at Field 2 can therefore be explained. This was also true for the western side of Field 5. Only this side of the field was surveyed in December 2016 and is therefore used in the discussion. The mean EC_e over a 1.5 m depth across the 6 sampling sites on this side of the field decreased by 5% and the range by 7%. By contrast the mean θ_v over the same depth across the field increased by 48% and the range by 64% during the same time period. At Field 3 neither EC_e nor θ_v significantly influenced $EC_{a\ deep}$ readings during the December 2016 survey. From June to December 2016, the mean EC_e over a depth of 1.5 m across the 12 sampling sites decreased by 40%, and the range by 12%, while the mean θ_v increased by 60%. The range decreased by 31%. Hence, the θ_v across the field during the December 2016 survey is more uniform.

Literature (comprehensively summarised by Corwin and Scudiero, 2016) has shown that in semi-arid and arid environments soil salinity generally dominates the EC_a measurement. Furthermore, for EC_a readings less than 100 mS m^{-1}, other conductive soil properties can have an increased influence on EC_a readings. These results however showed (June 2016 survey) that for sandy to sandy loam soils in central South Africa generally uniform in depth and spatially across the field in terms of clay content, relatively low EC_e values (< 150 mS m^{-1}) can dominate relatively low EC_a readings ($\pm$ 50 mS m^{-1}). It was also found that the influence of θ_v on EC_a readings at these soils increased considerably with an increase in θ_v across the field (December 2016 survey). It is important to remember that when the water content drops below 50 to 70% of field capacity, the conductance pathways in the solution phase are broken (Corwin and Lesch, 2013) causing spurious results. A general rule is not to do an EC_a survey with EMI or ER when the water content in the soil profile of interest is not more than 70% of field capacity (Corwin and Scudiero, 2016). Field capacity generally refers to a soil-water content at a matric potential of -33 kPa, or the soil-water content in the field at which free drainage stops (generally between 2 to 4 days following rainfall and/or irrigation). The mean θ_v at a matric potential of about -30 kPa across Fields 1 to 5 over a depth of 1.5 m amounted to 0.249, 0.197, 0.190, 0.194 and 0.185 mm mm^{-1}, respectively. These values were calculated with locally developed pedotransfer functions (RETEN, Streuderst, 1985) from mean silt-plus-clay measurements at Fields 1 to 5. During the June 2016 survey the mean θ_v over a depth of 1.5 m across Fields 2, 3 and 5 was about 70, 60 and 80% of these field capacity values. During the December survey, the mean θ_v over a depth of 1.5 m across these fields was more than 90% of field capacity, while the minimum θ_v was 75, 66 and 85% of field capacity. Clearly, the wetter conditions during the December 2016 survey dominated the $EC_{a\ deep}$ readings at these fields as discussed earlier. At Field 1 during the June 2016 survey, the mean θ_v over a depth of 1.5 m across the field was about 96% of field capacity, decreasing to about 71% during the June 2017 survey. Hence, during the second survey, clay content significantly dominated the $EC_{a\ deep}$ reading at this field. However, less than 55% of the variation in clay content (R^2 values) was explained by the $EC_{a\ deep}$ readings. Corwin and Scudiero (2016) highlight that in cases where soil texture is highly variable (like at Field 1) it may be difficult to characterise the variability with only spatial EC_a readings. Better results have been obtained, for example by Heil and Schmidhalter (2012) when terrain attributes as well as boundary and quaternary sediments were included in a MLR model to estimate texture (sand, silt and clay).

When a good spatial MLR model is obtained from EC_a readings and soil property data collected from EC_a-directed sampling sites, the target soil property can be estimated at all EC_a readings taken across the field. Figure 5.12 provides an example where EC_e was estimated across Fields, 2, 3 and 5 with the spatial MLR models developed during the June 2016 survey and then interpolated with ESAP-SaltMapper to create a continuous raster map. The ESAP software also provides a useful option of projecting relative yield (with the threshold and slope concept) at the EC_a readings taken across the field under the current soil salinity pattern (estimated EC_e values). As an example, the relative yield of wheat, maize and beans were projected at Fields 2, 3 and 5 under EC_e estimations made with the MLR models developed during the June 2016 survey. For wheat, maize and beans a threshold of 600, 170 and 100 mS m^{-1} was used and a slope 7.10, 12 and 19%, respectively. An equal depth weighting factor of 0.2 per 0.3 m depth interval was also used. Figure 5.15 shows the interpolated maps (using the ESAP-SaltMapper software) of these projected relative yields.

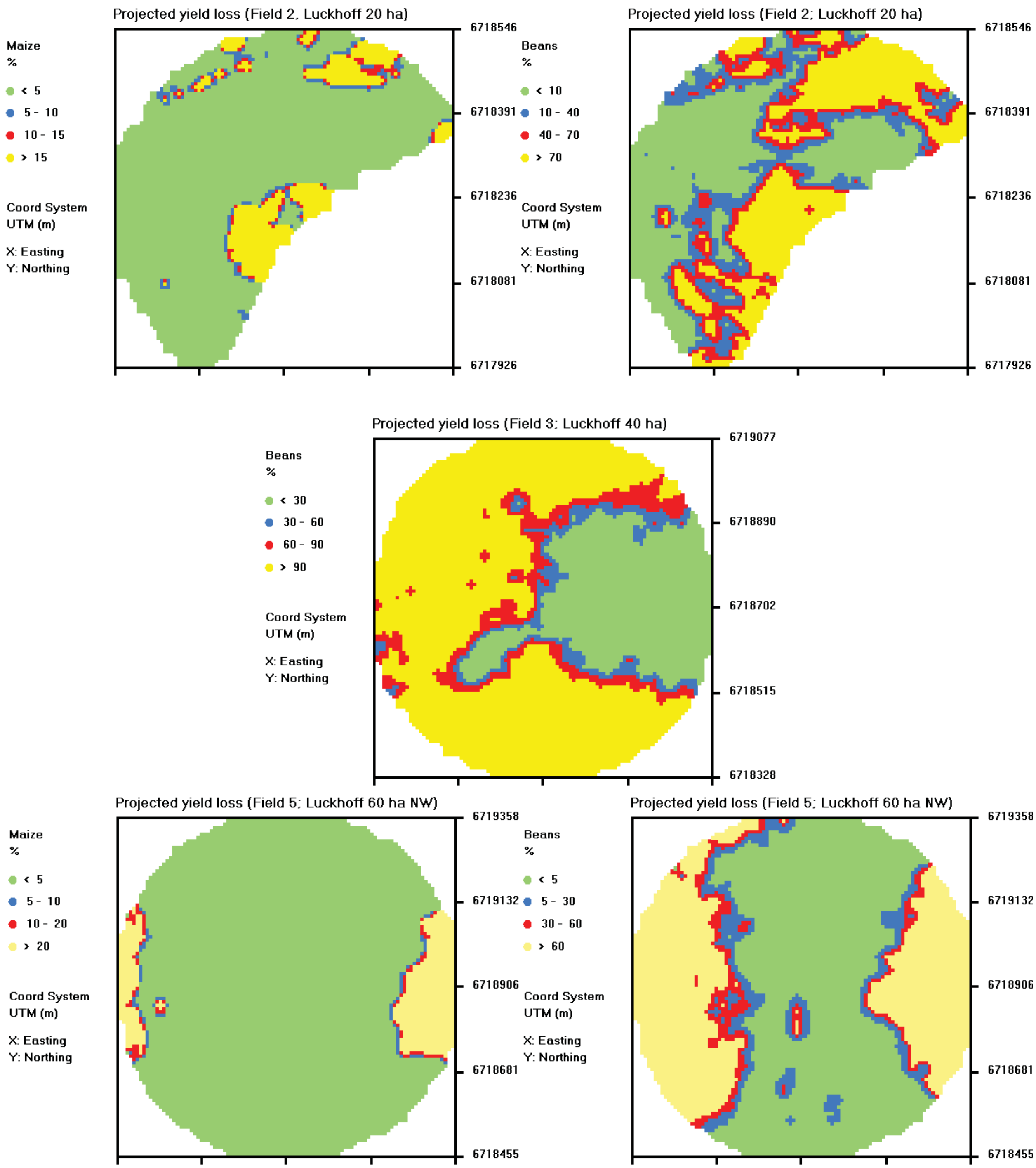


Figure 5.15 Interpolated maps (using the ESAP-SaltMapper software) of projected relative yields for maize and beans under EC_e estimations made with the multiple linear regression models developed during the June 2016 survey (Figure 5.12).

At none of the fields a reduction in relative yield is projected for wheat under the June 2016 EC_e estimations because the values were lower than the threshold of 600 mS m^{-1}. For maize grown at Fields 2 and 5 a mean field loss of 6 and 5% was projected, respectively, while for bean grown at Field 2, 3 and 5 a mean field loss of 40, 67 and 33% was projected, respectively.

5.6 Conclusions

Apparent soil electrical conductivity (EC_a) surveys aimed at spatially characterising a target soil property through EC_a-directed sampling and stochastic spatial multiple linear regression (MLR) play an important role as a first step in adopting precision agriculture. Especially in terms of managing the salt load associated with irrigation because relevant soil properties like EC_e, clay content, θ_v and BD are the primary soil properties influencing EC_a readings. The objective of Chapter 5 was to investigate the feasibility and effectiveness of EC_a surveys (with EMI; EM38-MK2) done on sandy to sandy loam (Fields 2 to 5) and clay (Fields 1, 6 and 7) irrigated soils, cultivated with fields crops in semi-arid central South Africa, to spatially characterise these four soil properties.

The ESAP-95 Version 2.01R software package (developed by researchers at the USDA-ARS US Salinity Laboratory) was used to analyse two different datasets. Dataset 1 consisted of EC_e, clay content and measurements determined from samples collected (June 2017) at several depths from 277 sampling sites across 330 ha (7 fields). Dataset 2 contained about 354 EC_a readings per hectare from multiple surveys (Table 5.1) together with measurements of EC_e, clay content, θ_v, and BD determined from samples collected at several depths from 12 EC_a-directed sampling sites per field (Section 5.3.3).

From the DPPC (Dual Pathway Parallel Conductance) correlation analysis of dataset 1, the following conclusions can be drawn:

- For $\pm$ 10% clay (Fields 2 to 5) soils EC_e values below $\pm$ 150 mS m^{-1} tend to dominate EC_a calculated with the DPPC model (EC_{ac}, Table 5.2). This was also true for the $\pm$ 25% clay soils (Fields 1, 6 and 7) when the EC_e was relatively low (< 100 mS m^{-1} at Fields 6 and 7) or high (250 mS m^{-1} at Field 1).
- Increasing clay content (Fields 6 and 7) will have an increasing influence on bulk soil conductance (EC_{ac}). The range in spatial variability of clay content, however, must not be excessive (20% clay content), which was the case at Field 1 (at Field 1 EC_{ac}--Clay content correlation = 0.15).
- Evidence that θ_v significantly (r = 0.75) influenced EC_{ac} was found only at one field. This was also the only field which showed a reasonable correlation (r = 0.59) between EC_e and θ_v.

An analysis of dataset 2 revealed the following.

- Ambient temperature (instrument drift) and/or soil temperature can affect EC_a readings, which confirmed most of the literature. Care should be taken when interpreting $EC_{a\ shallow}$ readings taken with the EM38-MK2 instrument in the vertical or horizontal dipole orientation. However, it seems that $EC_{a\ deep}$ readings were not considerably influenced by instrument drift during the day or when a survey is done over multiple days (provided that the instrument is properly setup before use, i.e. initial inphase nulling, instrument zero and final inphase nulling).
- $EC_{a\ deep}$ readings and soil property data from the June and December 2016 surveys at Fields 2, 3 and 5 were the most reliable according to the DPPC correlation analysis. At these fields, correlations between $EC_{a\ deep}$ readings and mean EC_{ac} were more than 0.5, while the association between $EC_{a\ deep}$-soil property correlations and $EC_{a\ prd}$-soil property correlations were high (within 10% of 1:1 line). Problems were detected at the other fields during any of the first, second or final surveys with either EC_a readings or soil property data. This conclusion assumes that the DPPC

model is applicable to soils found in semi-arid South Africa. Further research however regarding this is required.

- For sandy to sandy loam soils uniform in depth and spatially across the field in terms of clay content (Fields 2, 3 and 5), relatively low EC_e values (< 150 mS m^{-1}) significantly influenced relatively low EC_a readings ($\pm$ 50 mS m^{-1}). This was according to the spatial multiple linear regression (MLR) models that were developed with data from the June 2016 survey. At the same fields however, during the December 2016 survey EC_e did not significantly influence $EC_{a\ deep}$ readings because of wetter soil conditions which dominated the $EC_{a\ deep}$ readings.
- During the final survey at Field 1, evidence of clay content significantly influencing $EC_{a\ deep\ readings}$ was found. However, less than 55% of the variation in clay content was explained by the $EC_{a\ deep}$ readings. At none of the fields with clay soils did EC_e significantly influence $EC_{a\ deep}$ readings according to the spatial MLR models.

During the survey period, at only Field 1 was EC_e high enough across the field to cause significant yield reductions, due to osmotic stress of a moderately salt tolerant crop like maize (if a threshold of 170 mS m^{-1} is assumed) and salt tolerant crop like wheat (if a threshold of 600 mS m^{-1} is assumed). Unfortunately, EC_e at this field did not significantly influence EC_a readings. The value of EC_a surveys, EC_a-directed sampling and stochastic MLR to spatially characterise EC_e and subsequent yield reductions due to osmotic stress of a salt sensitive crop like beans were illustrated at Fields 2, 3 and 5 (Figure 5.12 and 3.15).

CHAPTER 6. DECISION SUPPORT WITH THE SOIL WATER MANAGEMENT PROGRAM, SWAMP

6.1 Introduction

After spatial soil, crop and terrain measurements and mapping an information system that supports decision-making (decision support system, DSS) will be vital, towards water and salt management with precision agriculture. In terms of water and salt management at field level, the DSS will have to combine spatial and temporal soil, crop and atmospheric information (measurements) as well as information about possible management options, in the form of best on-farm practices (Chapter 4), to formulate differential actions.

The soil water sensor technology is a popular decision support system comprising continuous measuring probes, telemetry and web-based irrigation software, also termed e-agronomy. The software programmes are advanced and support farmers daily in scheduling decisions. A common water management strategy is to deplete the profile to a pre-determined level and then refill the profile to the drained upper limit. One of the drawbacks of the technology is that most of the commercial soil-water probes do not measure osmotic potential of soils. In practice, this implies that salt management is somewhat in the background and is not integrated with soil-water management. Water management models, like SWB and SWAMP, are important decision support systems utilised to analyse water management decisions or to show gaps in knowledge.

Chapter 6 will briefly provide a description of the VBA source code version 2020.1 for SWAMP to simulate the soil water and salt balance and consequent matric and osmotic stress effects on water uptake and yield of field crops. Lastly, data from a case study will be used for a biophysical-economic optimisation of a popular irrigation strategy. This was done to demonstrate that the SWAMP model is able to simulate the dynamic interactions between water and salt management necessary for precision decision support.

6.2 Background

Chapter 4 highlighted the fact that there is a multitude of transient-state soil-crop-water mathematical models with varying complexities that can aid in decisions regarding possible management options. Complexities refer to the amount of information required by the specific model in order to simulate processes involved in the soil-crop-atmosphere system which is affected by the salt load associated with irrigation. Hence, more practical models would require less information and make use of default parameters for the various algorithms describing the processes involved. Typically these models would allow only for the essential time-dependent variables (rainfall, irrigation, evaporation, transpiration, water table uptake and drainage) encountered in the field that determine the accumulation and distribution of salt within a soil profile and the response of crops to matric and osmotic stress. More advanced models require much more information for the algorithms and aim to account for, additional to the previous variables, also artificial drainage, preferential flow and the chemistry of major dissolved ions in soil water. These models can account for cation exchange, mineral dissolution, precipitation and the subsequent effect on hydraulic conductivity and soil water flow. In most cases the more complex models not only allow for the growth limiting factors of matric and osmotic stress but also growth defining factors of radiation intensity, atmospheric carbon dioxide concentration, atmospheric temperature and crop characteristics.

In the late 80s and 90s, the Water Research Commission (WRC) invested in the development of two soil-crop-water models, namely BEWAB (Bennie et al. 1988) and SWAMP (Bennie et al., 1998). Staff led by

Proff. Bennie and Du Preez at the Department of Soil, Crop and Climate Sciences of the University of the Free State were responsible for the development, training and technology exchange of the models. BEWAB (short for "Besproeiingswaterbestuur") is a practical irrigation scheduling tool developed with the purpose of guiding farmers in their decisions about when and how much water to apply at field level. In a national survey on the impact of various types of models in the irrigation sector of South Africa, Stevens and van Heerden (2013) showed that the investment by the WRC in BEWAB was justified. Respondents (118) in the survey comprised advisors (27.9%), engineers (22.9%), academics (19.5%), researchers (16.1%), farmers (5.1%), water control officers (5.1%) and water administrators (3.4%). The authors noted that in addition to the model's initial purpose, BEWAB is also used by professionals in the field of designing and planning of water management strategies at catchment and scheme level. Promotion and use of BEWAB was mainly channelled through formal training of soil science and agronomy students at the University of the Free State (Singels et al., 2010). Hence, it was no surprise that training was highly ranked as one of the additional reasons why BEWAB was used amongst the respondents in the study. The Soil WAter Management Program SWAMP was initially developed for water management in rain-fed cropping systems (Bennie et al., 1998). Subsequently SWAMP was widely adopted by the dryland agricultural advisor community to support field observations of water management in semi-arid central South Africa (Bennie and Hensley, 2001; Hensley et al., 2011).

Maintaining the two models (BEWAB and SWAMP) is hard from a human and financial resources viewpoint. A weakness of BEWAB is the fact that after its initial development no adaptations and/or improvements to the algorithms have been made, while the software has not been updated for nearly 30 years. The model's key features however remain its user friendliness and efficacy of its proposed irrigation schedules provided from limited inputs of a target seed yield, total soil depth (mm), silt-plus-clay content (%) of each 300 mm soil interval and a selection of a desired irrigation interval. SWAMP, although also regarded as a pragmatic model, was used more by researchers and agricultural advisors as a science tool for describing or discovering new ideas regarding water management in dryland cropping systems. In 2003 SWAMP was adapted to allow for capillary rise from constant or falling shallow groundwater tables within or just below a depth of 2 m (Ehlers et al., 2003). Barnard et al. (2013) then illustrated that the model can be used successfully to assess current on-farm water management practices by irrigation farmers (that grow field crops in sandy to sandy loam shallow groundwater table soils in a semi-arid region) with easily obtainable input variables, while maximizing the use of in situ field observations. In 2015, subroutines were added to SWAMP and some algorithms were adapted to allow for salt accumulation and distribution within a soil profile (soil salinity) and the subsequent osmotic effect on water uptake and crop yield (Barnard et al., 2015).

At the heart of both models, despite their different design aims, lies the concept of the water supply rate of a rooted soil layer. The algorithm encapsulates basically the fact that the daily soil water supply rate of all rooted layers must be adequate to provide the crop daily with enough water to prevent soil-induced crop-water stress due to decreasing matric and/or osmotic potentials. Hence, the soil layer water supply rate is a function of the soil-root conductance, relative soil water content, rooting density and the soil-root hydraulic gradient. Singels et al. (2010) showed that the algorithm outperformed various others in simulating water uptake from a rooted soil layer under matric stress conditions.

Due to the fact that both models use this algorithm, a decision was made not to update BEWAB to modern computer capabilities after so many years. The decision is motivated by the fact that BEWAB essentially does not simulate the complete soil water balance (only components essential for determining an irrigation schedule) and the fact that SWAMP has been enhanced as explained above. SWAMP therefore basically replaces BEWAB and can be tailored according to the user's specific needs, i.e. the information supplied by the user to the software and the outputs received from the software. For example, SWAMP can be designed to provide irrigation schedules developed from popular irrigation strategies and limited inputs, similar to BEWAB. In addition, when applied to rain-fed cropping systems these irrigation strategies and scheduling capabilities can be deactivated or when management of the salt load associated with irrigation is required, the salt subroutines can be activated. This is all possible because the source code of SWAMP was adapted and translated into the Visual Basic for Applications (VBA) programming language. Hence, with this code SWAMP can run as part of Excel, a popular spreadsheet application developed by Microsoft. With the VBA code, variables and algorithms were adapted to accommodate five dimensional arrays, i.e. different simulation years (y), a maximum of two crop growing seasons per year (g), different soils per crop growing season (s), days within a crop growing season (d) and different soil layers for each soil (k). Therefore, in one simulation (run or loop) of multiple years' predefined crop-rotations, predefined multiple different soils per rotation with varying depths per soil can be simulated on a daily basis. This saves considerably on computing time. The VBA code provides the user with an option to use SWAMP for temporal and spatial support regarding soil, crop and water-related decisions in irrigated and rain-fed crop production systems. More important is the fact that SWAMP can now be integrated with an economic model and/or various optimisation algorithms, significantly enhancing the model's capabilities. It is important to note that SWAMP remains a one-dimensional soil-water-flow model with no lateral flow capabilities as yet.

6.3 Description of VBA source code version 2020.1 for SWAMP

Details regarding development of the various algorithms to simulate the components of the soil-water balance on a daily basis can be found in Bennie et al. (1998). The report also contains default parameters and equations to calculate default parameters for field crops like wheat, barley, peas, maize, groundnuts and cotton grown in arid to semi-arid regions on sandy to sandy loam soils. Barnard et al. (2013) provide a summary of the various algorithms and Barnard et al. (2015) provide adaptations to simulate the salt balance and consequent osmotic effect on water uptake and yield.

To initialise the VBA source code for a simulation of a defined number of years, crop rotation per year and different soils per crop growing season the atmospheric, crop, soil and water information (which does not require calibration) listed in Table 6.1 must be provided. Separate Excel spreadsheets have been designed where this information can be easily entered. From this information default crop and soil parameters as well as the soil-crop interacting parameters are determined and shown in separate spreadsheets. The user is provided with an option to change these values (i.e., calibrate the model). Table 6.2 provides a list of the model parameters and the simulated process for which the specific parameter is used.

First in the initialise subroutine, after importing the inputs and model parameters, seasonal potential transpiration (refers to non-limiting water supply from soil, hence determined by climatic conditions and plant characteristics) of the given crops is determined with the approach of De Wit (1958) (according to Hanks and Rasmussen, 1982). With this approach, seasonal potential transpiration is related to maximum biomass production (Y_m) with a crop-specific parameter (m) and the mean atmospheric evaporative demand (ET_0) over the growing season. If the VBA source code for SWAMP is used under rain-fed conditions the seasonal transpiration requirement to obtain a specific target biomass production is determined instead of seasonal potential transpiration. The target biomass production is calculated from an input target seed yield and harvest index. Daily potential transpiration or transpiration requirement (for rain-fed conditions) values are then determined with a generated four-growth-phase equation. These daily values thus represent the upper limit for transpiration during a specific growing season. Next the root density over the growing season and the drained upper limit (DUL) of each soil layer are initialised. The DUL of each soil layer is determined by weighing the DUL of the root zone according to the thickness and silt-plus-clay of each layer. DUL of the root zone are determined by the a and b' parameters in Table 6.2, i.e. the slope and intercept of drainage curves as suggested by Ratliff et al. (1983), which have been expanded in the original source code for a bare or cropped soil (Bennie et al. 1998). Lastly, as part of initialisation an iteration subroutine is run to determine the soil-root conductance coefficient (F_{sr}) for the given input soil-root conditions. If available measured values can also be entered. The subroutine is explained in Bennie et al. (1998) and Barnard et al. (2015).

When the VBA source code is run, the daily change in soil-water content (mm) of a defined multi-layer soil is determined from values of rainfall, irrigation, evaporation, root water uptake (actual transpiration) and percolation; the equivalent volumetric soil-water content of the layer is also calculated.

Table 6.1 Atmospheric, crop and soil information required by SWAMP for a simulation of a defined number of years, crop rotation per year and different soils per crop growing season

Atmosphere information
• Number of years (y)
• Daily ET_0 (mm)
• Daily rainfall
Crop information
• Type of crop for each year (maximum of 2 per year)
• Planting month for each year
• Planting day for each year
• Growing season length (if default is not used)
Soil information
• Number of soils (s)
• Number of 0.3 m deep layers for each soil
• SC (%) of each layer for each soil
• θ_v (mm mm^{-1}) of each layer for each soil at start of simulation
• EC_e (mS m^{-1}) of each layer for each soil at start of simulation
Simulation layers are 0.1 m deep, except the first and second layer
Water information
• EC of the irrigation water (mS m^{-1})

SC = silt-plus-clay; ET_0 = reference evapotranspiration of a clipped cool-season grass; θ_v = volumetric soil water content; EC_e = electrical conductivity of a saturation extract.

The current VBA source code does not include the contribution of a shallow groundwater table to evapotranspiration through capillary rise. This subroutine is available in an earlier source code (Ehlers et al., 2003) and will be included in future versions. In addition, the current VBA source code does not account for run-off or run-on of water, while only two irrigation strategies can be simulated. Firstly, where the user specifies the number of days between irrigations and the fixed volume of water to be applied during each event. Secondly, where the user specifies the percentage of critical depletion in soil water content that is allowed before irrigation is initiated to refill the soil to field capacity. Daily changes in salt content of the multi-layer soil (kg ha^{-1}) is determined from salt added and lost from a specific layer due to redistribution of water.

Rainfall and irrigation (mm) are infiltrated in a single event on a daily basis. Salts added through irrigation (kg ha^{-1}) to the first layer are determined by multiplying the volume of irrigation (mm), corresponding input EC (mS m^{-1}) and c1 parameter (that convert EC to salt content, kg salt ha^{-1} mm^{-1}). Infiltrated water is then redistributed in the soil profile on a daily basis in a single event with the macroscopic cascading principle, i.e. the mass transport of water through soil pores according to convection. For this the DUL of each layer is used, which have been determined during model initialisation as explained in the previous paragraph.

Daily drainage from the defined soil profile is simulated more mechanistically over time. The first (highest) drainage event happens the day after rainfall and/or irrigation and continues during subsequent days (excess redistributed water will remain temporarily in the soil profile), decreasing over time, according to the drainage curve parameters (a and b') and soil water content of the previous day. The soil-water content for determining the volume of water for first drainage event includes rainfall and/or irrigation of the previous day.

Table 6.2 Crop, soil and water parameters as well as the soil-crop interacting parameters required by SWAMP for a simulation of a defined number of years, crop rotation per year and different soils per crop growing season

Parameter	Abbreviation	Description	Process
Crop	A' (days)	Days until end of establishment	Potential transpiration
	B' (days)	Days until end of vegetative growth	
	C' (days)	Days until end of reproductive development	
	GSL (days)	Days until physiological maturity	
	a' (days)	Relative crop water requirement at end of A'	
	d' (days)	Relative crop water requirement at end of D'	
	Y_m (kg ha^{-1})	Maximum biomass production	
	m	Crop specific parameter (WP)	
	HI	Reference harvest index	Transpiration requirement for input target yield
	Target SY (kg/ha)	Target seed yield	
	Ψ_P (kPa)	Critical leaf water potential	Actual transpiration
Soil	DC	Empirical soil parameter	Salt redistribution and leaching
	a	Empirical soil parameter	Water redistribution and drainage
	b'	Empirical soil parameter	
	θ_s (mm mm^{-1}) *	Volumetric soil water content at saturation	
	θ_a (mm mm^{-1}) *	Air dry volumetric soil water content	Evaporation
	θ_{10} (mm mm^{-1}) *	Volumetric soil water content at -10 kPa	Actual transpiration
	θ_{1500} (mm mm^{-1}) *	Volumetric soil water content at -1500 kPa	
Soil-crop	L_m (mm mm^{-2})	Maximum root length index	Root density
	RPR (mm day^{-1})	Root penetration rate	
	RootMax (mm)	Maximum rooting depth	
	F_{sr}	Soil-root-conductance coefficient	Actual transpiration
	FB_{max}	Maximum fractional cover	Evaporation
	FB_1	Parameter to estimate FB_{max}	
	FB_2	Parameter to estimate FB_{max}	
	FB_3	Parameter to estimate FB_{max}	
Water	c1	Converts EC to salt content (kg salt ha^{-1} mm^{-1})	Salt balance
	c2	Converts EC to total dissolvable salts (mg ℓ^{-1})	
	c3	Converts soluble salt concentration to osmotic potential (kPa)	

* = for each layer; SY = seed yield

Empirical leaching curves (DC parameter) that determine the fraction of excess salt removed per mm of percolation per mm soil depth is used in the process of salt redistribution through miscible displacement (the soil solution is mixed by a combination of dispersion and diffusion, Barnard et al., 2010). The salt content (kg ha^{-1}) of each layer is expressed as a saturated soil-water content, hence representing soil salinity as EC_e, i.e. electrical conductivity of a saturation extract.

Matric potential from each soil layer on a daily basis is determined from volumetric soil-water content values with a water retention function described by the θ_{10} and θ_{1500} parameters. The relationship between soluble salt concentration and osmotic potential (c3) as proposed by Borg (1989) are used to determine the osmotic potential from EC_e values. The required c2 parameter is the same as c1 now used to convert EC to total dissolvable salts (TDS, mg ℓ$^{-1}$). Osmotic potential is, however, expressed for the actual simulated soil-water content experienced by plant roots, and not when the soil layer is saturated.

Actual transpiration from a soil layer or water uptake by plant roots are done according to Philip (1966), i.e. a dynamic physical continuum that is divided into a demand and supply component. The demand component is represented by potential transpiration (or transpiration requirement for rain-fed production systems) that was determined during initialisation of the model. The supply component is determined according to Bennie et al. (1988) with the soil layer water supply rate algorithm. When the model is run, the profile water supply rate (sum of all soil layers water supply rate) determines if the demand component can be supplied on a daily basis given the specific relative soil-water content, rooting density, soil-root hydraulic gradient (matric and osmotic potential) and the soil-root conductance coefficient. Hence, actual daily transpiration is equal to the daily potential transpiration under no matric and/or osmotic stress, conditions and equal to the profile water supply rate when these stresses reduce the supply of water.

Finally, the VBA source code also adopts the popular approach of not simulating plant growth per se. Actual transpiration or root-water uptake is simulated, and the seasonal uptake related to seasonal potential uptake, in order to calculate the actual biomass production, which is converted to grain yield with the harvest index. Unlike the popular model AquaCrop (Steduto et al., 2012), the current version does not include the effect of water stress on harvest index.

6.4 SWAMP application case study

6.4.1 Soil-water-based irrigation strategies

Irrigation strategies are considered good if they use as much information as possible to devise the strategy. Irrigation strategies that are based on the soil-water content measurements or estimations are considered good because soil water content is the result of all the processes governing water transport in the soil-crop-atmosphere system. A typical strategy based on soil water content is to deplete the soil water to a specific threshold before irrigating. The timing of irrigation events is therefore variable as the processes governing soil-water content determine the timing of irrigation events. Common practice is to refill the soil profile to field capacity or to a slightly lower level, to allow for rainfall to be stored in the soil profile. Irrigation scheduling modellers typically add the total amount of irrigation water necessary to refill the soil profile to the desired level. In many instances, the required irrigation amount is greater than the irrigation system capacity. In such cases it may take two or more days to refill the soil profile to the desired soil-water content which has a significant impact on soil evaporation and drainage calculations.

Two soil-water-based irrigation strategies were evaluated with SWAMP. Strategy 1 allows a 50% depletion before irrigating a net irrigation amount of 14 mm, while Strategy 2 depletes the soil water with 30% before applying a net irrigation of 14 mm.

6.4.2 Optimal irrigation schedule

The two-soil water-based strategies were compared with an optimal irrigation strategy (Strategy 3). Choosing an optimal irrigation schedule is complex because it is impossible to formulate the SWAMP simulation within a mathematical programming framework. The complexity of the SWAMP model therefore renders the application of standard mathematical programming algorithms to optimise the salt and water management unfeasible. The Differential Evolution (DE) algorithm that is developed as part of the WRC project on the “Economic management of water and salt stress for irrigated agriculture: a precision agriculture case study” (Water Research Commission, 2017) the DE algorithm was adjusted and combined with the VBA source code of SWAMP to determine an optimal irrigation schedule.

DE is a stochastic search algorithm inspired by biological evolution. The search steps consist of an initialisation step where the appropriateness of a population of random irrigation schedules are evaluated and an iterative step where mutation, crossover and selection are repeated over subsequent generations to generate new irrigation schedules. Figure 6.1 provides a flow chart of the different steps and operations necessary to optimise irrigation and salt management using DE. What follows is a chronological description of the steps and operations. The first step is to initialise a population of NP vectors of irrigation schedules (individuals) that consist of D irrigation decisions. Each schedule represents a candidate solution to the optimisation problem. Let's symbolise each individual in a generation by $X_i^g = \left[x_{i,1}^g,\ x_{i,2}^g\ \cdots\ x_{i,D}^g\right]$, for i = 1, 2, … NP irrigation schedules, where g = 0, 1, … G is the current generation with G representing the maximum number of generations and D representing the maximum number of irrigation decisions an irrigator needs to make. Large heterogeneity in the initial population (g = 0) is key to ensure that as much as possible of the search space is covered. A uniform distribution is used to generate the initial search space. An irrigation decision (d) is defined by the timing of the irrigation event and the amount of irrigation that is applied where all the irrigation decisions within a growing season across different years defines an irrigation schedule (i). The assumption is that an irrigator allocates the necessary pumping hours over two consecutive days to make maximum use of the available off-peak hours when the electricity tariff is lowest. Consequently, D = 75 for a wheat growing season length of 150 days. For each d, the irrigator has to decide whether to irrigate or not. Once the decision is made to irrigate, the next step is to decide the magnitude of the irrigation. The irrigation amount for the d^{th} irrigation decision within the i^{th} irrigation schedule can be generated with Equation 6.1.

Where $U(0,1)$ represents a uniformly distributed random number in the range [0,1], $x_{i,d,min}^0$ and $x_{i,d,max}^0$ are the minimum and maximum irrigation amounts as constrained by the irrigation system design. The initial population of irrigation schedules evolves through a process of mutation and crossover. For each target vector, a mutant vector is created with Equation 6.2, where r_1, r_2 and r_3 are randomly chosen indices from which need to be different from the current generation index i and F is a constant scaling factor.

$$V_i^g = X_{r1}^g + F \cdot \left(X_{r2}^g - X_{r3}^g\right) \tag{6.2}$$

The exploration capability of mutant generation strategy employed is strong since both base and the difference vectors are randomly generated. Crossover increases the diversity of the population combining the mutant vector with the target vector to create a trail vector $\mathrm{U}_\mathrm{i}^\mathrm{g} = \left[\mathrm{u}_{\mathrm{i},1}^\mathrm{g},\ \mathrm{u}_{\mathrm{i},2}^\mathrm{g}\ \cdots\ \mathrm{u}_{\mathrm{i},\mathrm{D}}^\mathrm{g}\right]$ where

$$\mathrm{u}_{\mathrm{i,d}}^\mathrm{g} = \begin{vmatrix} \mathrm{v}_{\mathrm{i,d}}^\mathrm{g} & \text{if } U(0,1) \le CR \\ \mathrm{x}_{\mathrm{i,d}}^\mathrm{g} & \text{otherwise} \end{vmatrix} \tag{6.3}$$

In standard applications of DE, the crossover rate (CR) is a constant. However, in our application CR is assumed a normal distribution with mean of 0.5 and a standard deviation of 0.15. The concept of "fitness" is used in DE to evaluate the appropriateness of a specific irrigation schedule. In our case a "more fit" irrigation schedule is defined as one with a higher margin above specified costs where the margin is calculated as the gross income generated with the schedule minus yield-dependant fertiliser and harvesting costs as well as irrigation costs. During evolution an irrigation schedule in the population is replaced by a trial irrigation schedule if the margin above specified costs of the trial irrigation schedule is higher. The DE algorithm completed 1500 iterations to determine the optimal irrigation schedule.

$$x_{i,d}^{0} = \begin{cases} 0 & \text{if } U(0,1) \leq 0.5 \\ x_{i,d,min}^{0} + \left(x_{i,d,max}^{0} - x_{i,d,min}^{0} \right) \left(U(0,1) - 0.5 \right) / 0.5 & \text{otherwise} \end{cases} \quad (6.1)$$

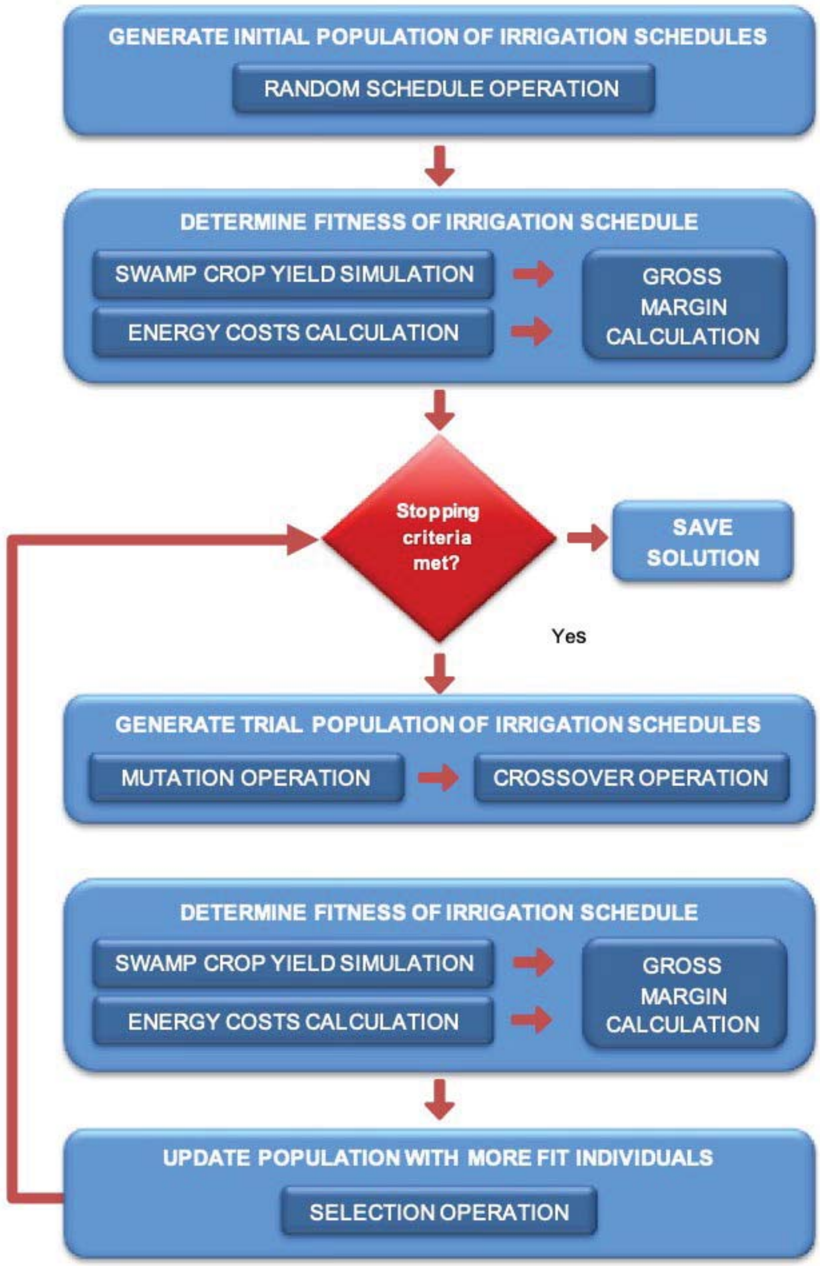


Figure 6.1 Flow chart of differential evolution optimisation procedure.

6.4.3 Model inputs and parameters

The SWAMP VBA source code was first run for irrigation Strategy 1 and 2 (Section 6.3.1). Next, the irrigation schedule optimisation (Strategy 3) was done with the combined SWAMP VBA source code and the DE optimisation algorithm (explained in Section 6.3.2). All simulations and optimisation iterations were done in Microsoft Excel 2013.

A 40 ha field (Field 3 as described in Chapter 5) located in the Orange-Riet Irrigation Scheme was used as the representative case study. It was decided to apply Strategy 1 and 2 as well as optimise the irrigation schedule over 3 growing seasons of wheat and maize. This time period was chosen because farmers tend to replace wheat or maize after three years with another crop due to the disease take-all. In some cases farmers use a fallow period during the wheat or maize growing season every three or so years (Van Rensburg et al., 2012) to combat take-all. Daily rainfall and ET_0 data ("Rietrivier: Sandpersele" (Nu: 19892, Lat: -29.07, Long: 24.62 and Alt: 1140) obtained from the Agricultural Research Council's Institute for Soil, Climate and Water (ARC-ISCW) in Pretoria for a 3-year period was used. The weather station is located within the Orange-Riet Irrigation Scheme. Planting dates of 16 June for wheat and 10 December for maize during the three year-period were used. Chapter 5 showed that in general the soil is uniform in clay content across the 40 ha field. Hence, it was assumed that the crops were cultivated on a 1.8 m deep sandy loam soil with a mean silt-plus-clay content of 15% and a volumetric soil water content of 0.176 mm mm^{-1} at the start of the three year period. The initial EC_e at the start of the three-year period was 250 mS m^{-1}, which represents the maximum measured soil salinity levels across the field as shown in Figure 5.12. Hence, the optimal irrigation schedule for the double cropping wheat-maize rotation over three years at this field were done for a worst-case soil-salinity scenario. This optimal determined irrigation schedule was also applied to lower values of soil salinity (EC_e) at the start of the three-year period, namely 80 and 160 mS m^{-1}. The EC of the irrigation water was set at 120 mS m^{-1} over the three years, which represent a case where drainage water is used for irrigation (Section 5.3.1 indicated that this farmer uses his drainage water for irrigation). Table 6.3 provides the model parameters that were used.

Table 6.3 Crop, soil and water parameters as well as the soil-crop interacting parameters used in the simulation of a double cropping wheat-maize rotation over three years, grown on a sandy loam soil in a semi-arid region

Parameter		Wheat	Maize
Crop	A' (days)	65	20
	B' (days)	110	60
	C' (days)	130	70
	GSL (days)	150	135
	a' (days)	0.20	0.10
	d' (days)	0.50	0.05
	Y_m (kg ha^{-1})	16500	26300
	m	150	337
	HI	0.52	0.60
	Ψ_P (kPa)	2400	1800
Soil	DC	10.15	
	a	26.12	
	b'	217.07	
	θ_s (mm mm^{-1}) *	0.3595	
	θ_a (mm mm^{-1}) *	0.0240	
	θ_{10} (mm mm^{-1}) *	0.1805	
	θ_{1500} (mm mm^{-1}) *	0.0708	
Soil-crop	L_m (mm mm^{-2})	9.80	9.40
	RPR (mm day^{-1})	19	23.53
	RootMax (mm)	2000	2000
	F_{sr}	subroutine	
	FB_{max}	100	100
Water	c1	0.075	
	c2	7.5	
	c3	0.072	

6.5 Results and discussion

6.5.1 Seasonal results for three years

Table 6.4 shows the results for the three alternative irrigation strategies applied to the continuous wheat-maize crop rotation over the 3 year period where the initial EC_e of the soil is 250 mS m^{-1} and the irrigation water quality is 120 mS m^{-1}. The results for Strategy 1 show that the change in salt content of the soil is positive which means that no salts are lost thorough leaching. Consequently, salt buildup occurs over the six-year period as is evident from the increase in EC_e (from 250 mS m^{-1} in year one to 723 mS m^{-1}at the end of the simulation). The salt buildup in the soil is the direct result of the effectiveness of irrigation Strategy 1 to use rainfall as a water source for transpiration. However, the strategy is not very effective to manage soil salinity since the salt buildup results in crop yields that are lower than the potential crop yields of wheat and maize. The potential crop yields of wheat and maize under no osmotic and matric stress are respectively 8580 kg ha^{-1} and 15780 kg ha^{-1}.

Table 6.4 Three-year seasonal SWAMP simulation output for alternative irrigation schedules on a wheat-maize rotation with a starting soil water EC_e of 250 mS m^{-1} and irrigation water quality of 120 mS m^{-1}

Crop	Transpiration deficit	Rainfall	Irrigation	Change in salt content	Soil profile EC_e Start	Soil profile EC_e End	Crop yield
	mm			kg ha^{-1}	mS m^{-1}		kg ha^{-1}
Irrigation strategy 1							
Wheat	-54	52	405	3653	250	325	7658
Maize	-42	160	459	4155	325	411	14424
Wheat	-63	115	392	3541	411	484	7550
Maize	-31	128	378	3421	484	554	14697
Wheat	-118	86	554	4994	554	657	6716
Maize	-82	81	351	3171	657	723	13049
Irrigation strategy 2							
Wheat	-36	52	540	4868	250	350	7976
Maize	-20	160	486	4398	350	441	15141
Wheat	-43	115	473	4270	441	529	7883
Maize	-9	128	486	-4809	529	430	15474
Wheat	-67	86	594	5359	430	540	7524
Maize	-38	81	527	4751	540	638	14514
Irrigation strategy 3							
Wheat	-6	52	572	-2710	250	194	8483
Maize	-1	160	473	-1406	194	165	15759
Wheat	-6	115	443	4000	165	248	8477
Maize	-1	128	428	3875	248	327	15759
Wheat	-6	86	570	-3742	327	250	8481
Maize	-1	81	407	3676	250	326	15759

Irrigation Strategy 2 triggers more frequent irrigation events because the depletion level that triggers an irrigation event is lower compared with irrigation Strategy 1. The expectation is that the soil profile will be wetter with Strategy 2 compared to Strategy 1, which will result in some salt losses through leaching. The results for Strategy 2 show that more salts accumulate in the soil during each crop growth season with the exception of the second maize crop season, where salts were leached from the soil profile. The salt buildup in each crop growth season is the direct result of increased seasonal irrigation amounts without any drainage. An interesting observation is that the crop yields of Strategy 2 are consistently higher when compared to Strategy 1 even though the EC_e levels of each for the first three crop growing seasons were higher when compared to Strategy 1. Although the crop yields of Strategy 2 are higher than Strategy 1, transpiration deficits still occur in each season which show that potential crop yields are not realised.

Strategy 3 is based on optimal irrigation decisions. The results for Strategy 3 show that it is optimal to leach salts from the soil profile to increase crop yields. Salt losses through leaching occur if over irrigation takes place or when the timing of an irrigation event is altered to increase the probability that rainfall will cause drainage. When considering the first maize crop, Strategy 2 applies 486 mm of irrigation with salt buildup of 4398 kg ha^{-1} while Strategy 3 applies 13 mm less water, resulting in a decrease of 1406 kg ha^{-1} salts due to leaching. The only way to cause leaching of salts with less irrigation is to change the timing of irrigation events to increase the probability that rainfall will drain from the soil profile. The results further show that Strategy 3 manages irrigation decisions dynamically over the three-year period in such a way that salt buildup that might occur in a specific season does not impact significantly on crop yields. Consequently, the simulated crop yields over the three years are close to the potential yield of each crop.

Next, the daily changes in key output parameters for the first year are discussed to highlight the dynamic interactions between water and salinity stress management.

6.5.2 Daily results for the first year

Figure 6.2 shows how the timing of irrigation and rainfall influences the matric and osmotic potentials in the soil profile for the first wheat and maize crop seasons. The timing of irrigation events for Strategy 1 and Strategy 2 are based on a soil water depletion level. Results show that irrigation is initiated late in the season with Strategy 1, which results in the soil profile being much drier when compared to Strategy 2 which initialises irrigation much earlier with corresponding matric potential that is much higher than Strategy 1. During the last part of the wheat growing season both soil water-based irrigation strategies dry out the soil profile, thereby causing matric potential to decrease. An important difference between the two-soil water-based irrigation strategies and Strategy 3 is the fact that more irrigation is applied during the latter part of the growing season with Strategy 3. Consequently, the soil is much wetter with a corresponding high matric potential during the last part of the season.

The osmotic potential in the soil profile resulting from irrigation Strategy 1 shows a decrease in potential until irrigation is initialised. Once irrigation is started the osmotic potential hoovers sideways until the last part of the season where the potential decreases as the soil profile is becomes drier. The osmotic potential resulting from applying irrigation Strategy 2 follows that of Strategy 1 until irrigation is initialised. Since irrigation is initialised earlier with Strategy 2, the osmotic potential of the soil is higher because the soil profile is wetter. However, the increase in salt load due to higher irrigation volumes causes osmotic potential to be slightly higher than that of Strategy 1 from day 105 to the end of the wheat growing season. Interestingly, the wheat yield of Strategy 2 is higher than Strategy 1 even though the osmotic potential is consistently marginally higher than that of Strategy 1 during the last part of the growing season. Osmotic potential is, however, not the only factor affecting crop yield. The matric potential of Strategy 2 is higher than that of Strategy 1 over the total wheat growing season. Furthermore, the increase in matric potential due to a wetter soil caused the osmotic potential of Strategy 2 to be higher than that of Strategy 1 between day 35 and 105. The combined effects of osmotic and matric potential (total soil water potential) causes wheat yield of Strategy 2 to be higher than that of Strategy 1. The osmotic potential of Strategy 3 closely follows the osmotic potential of Strategy 1. The potential is, however, slightly lower at the beginning of the season due to an irrigation event at the start of the season. Since regular irrigation starts earlier in the season when compared to Strategy 1, the osmotic potential of Strategy 3 starts to hoover sideways at a higher osmotic potential from day 58. Strategy 3 leaches salt from the profile near the end of the season causing a sharp increase in the osmotic potential of the soil.

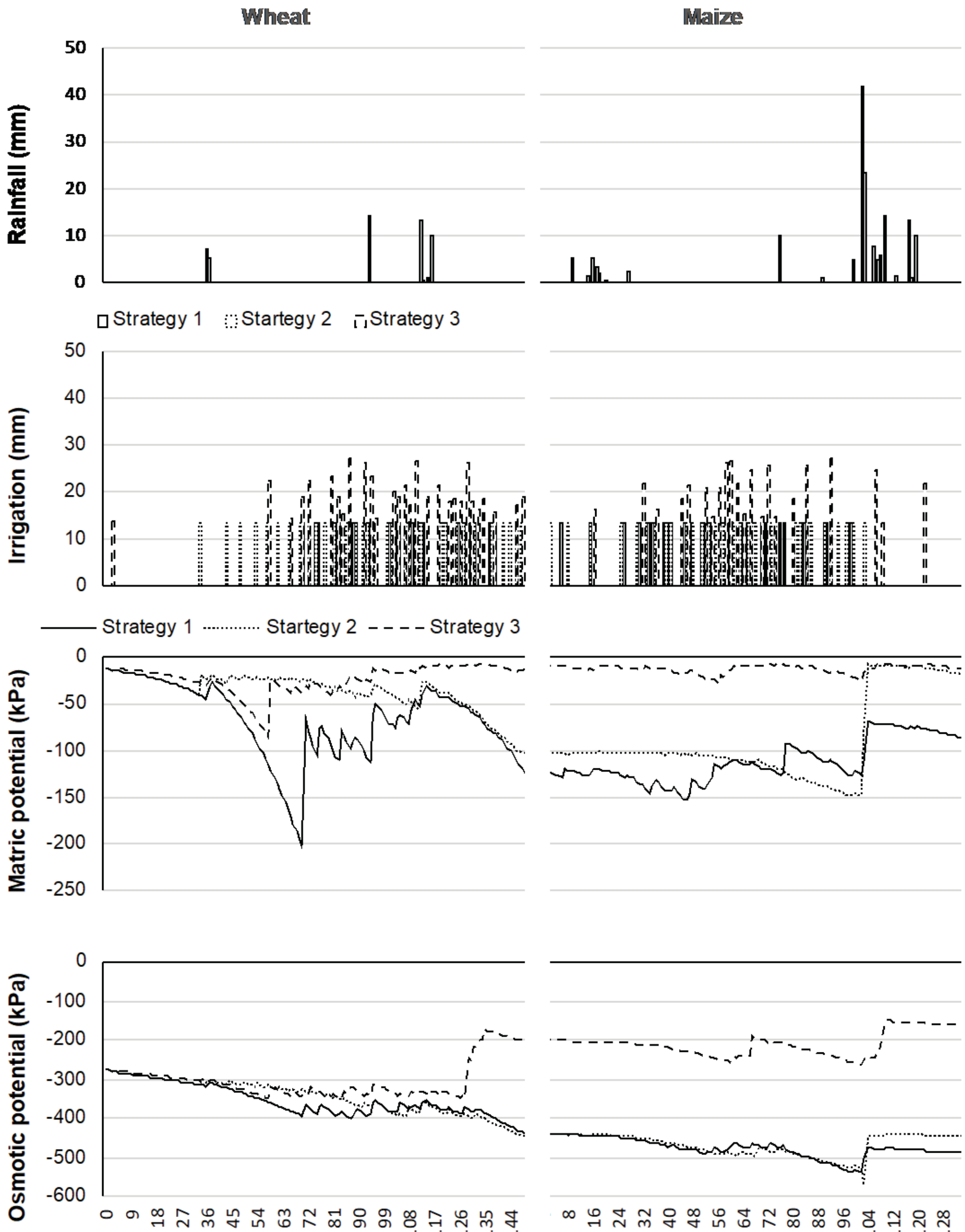


Figure 6.2 Daily simulated results of alternative irrigation schedules (Strategy 1 to 3) for year one of the three-year wheat-maize rotation, grown on a sandy loam soil with a starting soil salinity (EC_e) of 250 mS m^{-1} in a semi-arid region and irrigated with water having an EC of 120 mS m^{-1}.

The soil-water status at the beginning of the maize growing season is the direct result of the way irrigation water was managed during the wheat growing season. Irrigation was managed with both the soil-water-based irrigation strategies such that the soil became much drier with corresponding lower matric potentials. The osmotic potentials of these strategies were also lower because no salts were leached from the soil and the soil was drier. Conversely, Strategy 3 managed irrigation such that the soil is much wetter with corresponding higher matric potential. The osmotic potential was also higher since some salts were leached from the soil profile, and the soil is wetter.

Higher matric and osmotic potentials are beneficial for maize production because maize is more sensitive to salinity (osmotic) stress when compared to wheat. Strategy 3 keeps the soil profile near field capacity with corresponding high matric potentials when producing maize. The osmotic potential tends to follow matric potential. The osmotic potential increased to above starting osmotic potential values due to salt leaching near the end of the growing season. In general, the osmotic potential of the soil-based irrigation strategies tends to decrease over time since no leaching takes place and salts are added to the soil profile, takes while the soil-water content is kept fairly constant with corresponding matric potentials between -100 kPa to -150 kPa. The only exception occurs at the end of the growing season where rainfall causes matric potential to increase with corresponding increases in osmotic potential. With Strategy 2, these increases were more in comparison to Strategy 1 since the rainfall event of 42 mm coincides with an irrigation event. The inflow of water into the profile was, however, just enough to fill the profile to field capacity without any drainage. Consequently, the osmotic potential of Strategy 2 only increases slightly above that of Strategy 1 because of a higher matric potential.

6.5.3 Applying the optimal strategy to other soil salinities

Applying precision irrigation in “cake slices” provides a practical alternative to variable rate irrigation technology which can change the application rate of each nozzle to better match irrigation applications to soil-crop conditions. The implication is that each cake slice might consist of different soil-crop conditions, while irrigation application is uniformly applied across all the different soil-crop conditions. Table 6.5 shows the results of applying Strategy 3 to a starting soil EC_e level of respectively 80 and 160 mS m^{-1} on key output variables while keeping irrigation water quality at 120 mS m^{-1}.

Table 6.5 Three-year seasonal SWAMP simulation output for irrigation Strategy 3 of a wheat-maize rotation grown on a sandy loam soil with a starting soil salinity (EC_e) of 80 and 160 mS m^{-1} in a semi-arid region and irrigated with an EC of 120 mS m^{-1}

Crop	Transpiration deficit	Rainfall	Irrigation	Change in salt content	Soil profile EC_e Start	Soil profile EC_e End	Crop yield
	mm			kg/ha	mS m^{-1}		kg/ha
Start of simulation EC_e = 80 mS m^{-1}							
Wheat	-6	52	572	-446	80	71	8483
Maize	-1	160	473	-589	71	59	15759
Wheat	-6	115	443	4000	59	141	8483
Maize	-1	128	428	3875	141	221	15759
Wheat	-6	86	570	613	221	234	8483
Maize	-1	81	407	3676	234	309	15759
Start of simulation EC_e = 160 mS m^{-1}							
Wheat	-6	52	572	-1357	160	132	8483
Maize	-1	160	473	-494	132	122	15759
Wheat	-6	115	443	4000	122	204	8483
Maize	-1	128	428	3875	204	284	15759
Wheat	-6	86	570	-1055	284	262	8483
Maize	-1	81	407	3676	262	338	15759

The results show that the water budgets of the different scenarios will be the same since the soil and the crops grown did not change. The salt balances are, however, different. In comparison with the results for a starting EC_e level of 250mS m^{-1} (Table 6.4), the salt balances directional changes are the same, while the magnitude of the changes are either the same or less. The exception is the third wheat crop where the change in salt content was positive. The crop yields are unaffected because less salt is present in the soil at the start of the 3-year rotation system.

6.6 Conclusions

The results showed that SWAMP can simulate the impact of management decisions on changes in matric and osmotic potentials that are highly dynamic. Furthermore, the results showed that irrigation strategy choice has a significant influence on these potentials as well as the resulting crop yields. Care should therefore be taken to apply steady-state concepts to provide decision support regarding salinity management. The optimal irrigation strategy clearly showed the importance of taking a longer-term view when managing salinity because decisions made in one season have an impact on the feasibility of crop production in the following season. Applying the optimal irrigation strategy for the worst-case scenario to less-worse case scenarios showed that management principles applied to the worst case will be applicable to less-worse case scenarios. The optimal irrigation strategy assumes complete knowledge of production conditions over the season, which should be challenged. The potential for use of the optimisation algorithm the optimisation algorithm to devise management zones for applying precision irrigation is vast. The research done as part of this project-provide the basis for research on the economic management of water and salt stress within a precision agriculture setting (Water Research Commission, 2017).

CHAPTER 7. SUMMARY AND RECOMMENDATIONS

7.1 Introduction

True to its primary objective, i.e. to increase national and household food security and to improve the livelihoods of people in a farming, community and on a regional level, through efficient and sustainable utilisation and development of water resources in agriculture, the Water Research Commission (WRC) played a significant role in directing research and application of water and salt management at farm-level in South Africa over the past four decades. They have empowered many young scientists in developing research niches regarding the salt load associated with irrigation and efficient use of irrigation water. Proof of this can be found in Table 4.3 of this project where the themes, focal areas and contributing authors have been highlighted. Themes relevant to our project, are irrigation systems, irrigation scheduling, drainage management, crop-salt tolerance, rootzone salinity/sodicity management, on-farm interception, and drainage re-use. Recommendations and guidelines in these projects and international literature were consulted, distilled and reformulated into practical guidelines taken up in three volumes, which are summarised in this chapter.

7.2 Summary

The aim of the WRC-project was to compile guidelines for technology exchange to manage the salt load associated with irrigation at farm and field level with precision agriculture. The following general objectives were formulated at the start of the project.

1. Compile water and salt management guidelines and elicit from stakeholders the acceptability thereof.
2. Evaluate on a case study basis the methods/procedures employed by advisors for delineating site-specific-water and salt management units.
3. Develop a software-based decision support system for recommendations to improve site-specific water and salt management.

To meet the objectives of the project, various tasks were initiated and completed in no chronological order. Firstly, WRC funded projects and international research related to water and salt management of irrigated fields were reviewed. The review is available in the first part of Chapter 4 (Volume 3), but was also used as science basis for the water and soil science orientated chapters in Volume 1, namely Chapters 3 – fundamentals of water management, Chapter 4 – fundamentals of applied salt management and Chapter 5 – solutions. Secondly, general principles of adopting precision agriculture or site-specific-crop management were reviewed and the core is captured in the second part of Chapter 4 (Volume 3). Aspects of precision agriculture that were reviewed were: measuring and monitoring of relevant attributes, attribute mapping, decision support with transient soil-crop-water salinity models and apparent soil electrical conductivity (EC_a), as measured through electromagnetic induction (EMI), for spatial characterising soil variability. As an extension of the review, a section on the theoretical and operational considerations of ESAP-95 Version 2.01R (Electrical conductivity Sampling Assessment and Prediction, Lesch et al., 2000) was also presented in Chapter 5 (Volume 3), as well as a description of Visual Basic for Application (VBA) source code version 2020.1 for SWAMP in Chapter 6 (Volume 3). Thirdly, five research case studies were identified to investigate these principles of water and salt management with precision agriculture and EC_a-directed field-scale characterising of soil variability as part of the upscaling of EMI research. The case studies were conducted in the Douglas district (Northern Cape province), near Luckhoff in the Free State province, near Hofmeyr in the Eastern Cape and two sites in KwaZulu-Natal near Mkuze and Empangeni. The results of the case studies were discussed in Chapters 3, 5 and 6 of Volume 3. Fourthly, farmers and agricultural advisors in these provinces were engaged regarding current and best on-farm water and salt management practices as well as water and salt management with precision agriculture throughout the duration of the project. This was done through questionnaires and ad hoc on-farm in situ spatial assessments of water and salt management. Results of the socio-economic survey to benchmark variables to guide the development of content and processes to improve adoption and uptake of salt management practices were discussed in Chapter 2 (Volume 3). An additional eight ad hoc case studies were presented in Volume 2 as part of the initiative to create examples as material for the scaling out of EMI information to crop-specific associations and their members.

7.2.1 Volume 1: On-farm water and salt management guidelines for irrigated crops: Level one decision support

Problem statement: Excess soil salt is a huge problem worldwide. Estimations show that about six percent of the world's total land surface is salt affected. The latest predictions indicate that at least 90 000 ha of South Africa's irrigation soil is salt affected, and this impacts negatively on the livelihoods of farmers across all scales, i.e. subsistence-, smallholder scale-, commercial- and mega-farmers. Hence, there is a need for guidelines to protect our soils and to improve crop yields for all types of farmers who have different resources.

Context: Not all farmers have the ability or resources to extract and utilise information from scientific documents. Therefore, DSS for Level one users is specifically compiled for the extension officers, also known as Behaviour Change Officers (BCOs), who are equipped to facilitate the exchange of information to resource-deficient farmers. A resource-deficient farmer represents a group of farmers who cannot afford detailed soil salinity surveys and private consultants. These farmers rely on classic science information to control soil salts.

Objectives: The aim of this report was to compile a water and salt management guideline for BCOs serving the irrigation sector. To achieve this, four objectives were set.

i. Summarise the main findings from the socio-economic survey on knowledge about salt management of irrigators from the commercial sector in the Breede River, Vaalharts and Douglas irrigation schemes, and the northern KwaZulu-Natal district (Chapter 2).
ii. Extract from literature the art and science of irrigation scheduling, and the packaging of information as a guideline, using two best-scheduling practices as examples, *viz.* crop coefficients and continuous measuring probe technology (Chapter 3).
iii. Distil from literature the fundamental principles required for salt management of crop fields, and package the information as a salt management guide (Chapter 4)
iv. Compile a solution-management guideline on the treatment of root zone salts in a proactive and active manner (Chapter 5).

Knowing your farmers: The aim of the socio-economic survey was to capture data about the existing knowledge levels, management practices as well as the beliefs and perceptions about salt management on irrigated farms. Farmers who participated in the survey represent the Western Cape (Breede River), Central region (Vaalharts and Douglas irrigation schemes as a unit), and northern KwaZulu-Natal (KZN) (sugarcane farmers in the Felixton, Umfolozi and Pongola mill supply areas). Results pertaining to the demographics suggest that the majority of the farmers are well positioned to receive Level One information.

Younger farmers, with higher levels of education and higher income or larger farm operations, are good indicators of where Level Two interventions could possibly be appropriate. The base line information study succeeded in showing that there are high-risk farms that are inherently susceptible or already being impacted by salinity or sodicity. Efforts should focus on these farms, especially when the situation is compounded by low levels of knowledge about the soil and its inherent susceptibility and/or need for skilful management interventions. Purposeful and deliberate effort is required to establish examples of implementation, and to gather and make accessible the relevant economic and practical information to larger farmer groups.

Fundamentals of water management: Farmers are encouraged to make use of objective scheduling methods as surveys have shown that the uptake thereof is low. The aim of this chapter was to revisit some fundamentals in irrigation scheduling as a guide to improve water management. Three aspects were highlighted, *viz.* (i) the soil water balance and the water management borders, (ii) the application of crop coefficient as an atmospheric based irrigation scheduling method with SAPWAT4 as a working tool, and (iii) the application of soil-water sensor technologies for irrigation scheduling with SWAMP as the working tool.

Fundamentals in salt management: In summary, this chapter provides nine fundamental pointers that will guide BCOs in facilitating salt management of irrigated fields, viz. soil sampling, suitability of soils for irrigation, sources of salts, salt threshold for soils, salt threshold for crops, irrigation systems, drainage systems, quality of irrigation water and leaching.

Solutions for salt-related problems: The focus of this chapter was to summarise practical solutions on water and salt management. Two approaches for solving salt-related problems were proposed as guidelines, namely a proactive and active approach. The proactive approach is based on the root-zone salinity assessment procedure described by Ehlers et al. (2007). The assessment is based on drainage conditions in the soil profile, whether be restricted or freely drained. Two procedures (A and B) are available under restricted drainage conditions, i.e. where the EC_e is smaller than the crop's salinity threshold (Procedure A) and where the EC_e is greater than the threshold (Procedure B). Another two procedures (C and D) are available for freely drained soils. These procedures discriminate between a lower crop threshold (Procedure C) and a higher threshold (Procedure D) compared to the soil EC_e. An example for each of the procedures (A-D) were included as a guideline to assess field situations. Under the active solution approach, guidelines to reclaim saline and sodic soils were also summarised.

7.2.2 Volume 2: On-farm water and salt-management guidelines for irrigated crops: Level two decision support

Problem statement: The trend of land-use change to perennial crops is evident in almost all the large irrigation schemes in South Africa. Transforming crop fields from field crops to perennial crops will, according to Thayalakumaran et al. (2007) and co-workers, lead to a new salt equilibrium in the next decade. This change in land use demands intensive monitoring and assessment of water and salts in soils to optimise production of every cubic meter of land, hence, the demand for precision agriculture, or site-specific management.

Context: The Second Volume of the three WRC-reports, was aimed at encouraging and supporting those farmers who want to change towards site-specific management, i.e. precision management of water and salts. The latest technology in site-specific management involves EMI surveys and ground truthing of soil properties related to soil salts. It is also envisaged that the BCOs will play an important role in the process of scaling out the EMI technology. It should be stated that the training of BCOs is beyond the scope of the project.

Objectives: The aim of the Volume 2 report was to apply EMI technology in crop fields as a method for site-specific assessment of soil salts in the rootzone. The specific objectives for the level two decision support were:

i. to illustrate a logical framework, using EMI derived soil properties, for supporting scientific sound decisions regarding the site-specific assessment of soil salts in the rootzone. The specific objectives of the framework were: (a) to show where the salts are in the crop field, (b) how they impact on the hydro-physical properties, such as bulk density, saturated hydraulic conductivity, water storage in the profile, and (c) to couple site-specific procedures to rectify problematic areas. A case study on a vineyard was used to establish the concept. (Chapter 3).
ii. to create case studies on site-specific assessment of water and salts in perennial crops to broaden the base and support for out-scaling of EMI technology. Crops used as case studies, were lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries (Chapter 4).

A logic framework for guiding site-specific assessment of soil salts: A case study on a vineyard was used to demonstrate the use of the logical framework in site-specific assessment of water and salt management. Results on EC_a, terrain analysis, soil forms, soil properties measured and derived from EC_a of the top-, sub- and deep subsoil as well as the profile available water were presented. Soil properties of interest were drainage (infiltration, internal drainage and external drainage reflected by K_{sat}), particle size distribution, compaction, salinity, sodicity, water storage (saturation point and drained upper limit) and aeration, not to mention the surface properties derived from the terrain analysis and the micro-morphological properties observed during the soil classification exercise. A logical framework was developed, and its use was demonstrated through this case study. With respect to the vineyard case study, the framework was convenient during the discussion of the hydro-physical report with the farmer and his managers.

Scaling out of EMI technology (Chapter 4): The main problem in the dissemination of EMI information, however, is the scaling out of the technology. It was argued that perennial crops will be the best platform to launch such an initiative as these farmers are in the best financial position to afford such surveys. Hence, the second objective of the project was to target leading farmers in the industry and convince them to apply the EMI technology on their farms. Consequently, seven case studies on site-specific assessment of water and salts in perennial crops were conducted and presented in Chapter 4. It can be concluded that the framework assisted us in establishing examples for lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries. This will broaden the base and support for out-scaling of EMI technology to crop-specific associations in the near future. Without exception, the case studies were successful in a) showing where the salts are in the crop field, b) how they impact on the hydro-physical properties, such as bulk density and water storage in the profile, and c) to couple site-specific procedures to rectify problematic areas. Lastly, it can be concluded from our experience that the framework serves as a template for guiding the hydro-physical report, saving time and resulting in a more efficient service. The framework also contributes towards guiding discussions on water and salt management, saving precious time during consultations with farmers.

7.2.3 Volume 3: On-farm water and salt-management guidelines for irrigated crops: Level three decision support

The third volume on salinity management reflects on EMI research (upscaling) conducted on selected irrigation farms in the Northern Cape, Free State, Eastern Cape and KwaZulu-Natal. This is to achieve a deeper understanding of salt-related problems and their medium-to-long-term management. This type of decision support is on a research level and is aimed at serving the science community, although mega-farmers, corporations, and companies can also benefit from it in the medium to long-term. In this case, salinity models like SWAMP were used to make medium-to-long-term estimations of salts on land productivity. Volume 3 consists of five content chapters with specific objectives.

Chapter 2: Socio-economic study: The main reasons for adoption success and/or failure, generally, are well documented in the literature, but little is published on the adoption of salinity management practices. It seems that there are virtually no case studies found that benchmark the actual knowledge levels, perceptions and attitudes of farmers with respect to farm practices addressing salinity in South Africa. The scale of the problem, therefore, extends beyond the classification and mapping of areas with salinity problems. Farmers' knowledge levels, perceptions, attitudes and capability to deal with salinity are even less known. Several research questions were defined, and, based on these questions; the following hypotheses were tested:

i. Farmers do not perceive salinity as a threat to the future of irrigation farming (H1).
ii. Farmers do not understand causes of salinity (H2).
iii. Farmers do not have knowledge of preventative and corrective measures (H3).
iv. Benefits of preventative and corrective measures do not outweigh the costs (H4).
v. Benefits of preventative and corrective measures do not outweigh the implementation effort (H5).

The null hypothesis of H1 to H4 was rejected, while H5 was accepted, because only the Breede River area agreed that it would be easy to adjust irrigation scheduling as a management practice. Overall, it can be concluded that the acceptability of farmers' knowledge (or lack thereof) about the salt status of their soils, irrigation water and diagnostic parameters is debatable. On-farm testing, demonstration plots, hands-on training interventions or allowing farmers to learn from fellow farmers via farm visits and technical tours are higher leverage pathways to stimulate uptake and adoption. Purposeful and deliberate effort is also required to establish examples of implementation and to gather and make accessible the relevant economic and practical information to larger farmer groups.

Chapter 3: Sugarcane case studies on soil salt distribution and yields: The sugarcane case studies were selected from data obtained from routine measurements at the Fertiliser Advisory Service laboratory at SASRI, showing the presence of saline-sodic and sodic soil conditions. Case study 1 was in the Mkhuze district in the northern parts of KwaZulu-Natal (KZN) at an altitude between 180 and 211 masl. Case study 2 was near Empangeni in the Heatonville irrigation scheme at an altitude between 70 and 95 masl. EMI and topographical surveys were conducted during July 2016 and June 2017 (Case study 1) and during October 2016 and 2017 (Case study 2).

Far-reaching results were obtained from the two case studies and can be used to create awareness amongst farmers on the need to improve their water and salt management. The EC_e maps indicated that salinity is not a problem at both the sites. The real problem is the high Na levels that generally increase with depth and vary over the field. Large areas in both sites were above the threshold ESP value of 7% which resulted in significant stalk yield losses; 10.2 t ha^{-1} for every 1% increase in ESP at Case study 1 and 1.9 t ha^{-1} per unit in Case study 2. The accumulation of Na in the subsoil is attributed to the poor drainage of the sites due to the high clay content and dispersion, inherent high Na content of the parent material, Na content of irrigation and rainwater as well as the inherent natrophobic property of sugarcane. Workshops are recommended to create awareness of water and salt management, which includes monitoring of irrigation water quality, monitoring and identification of salt affected areas within fields, promoting the installation of artificial drains, and leaching of salts.

Chapter 4: Literature synopsis: The chapter focuses on three important aspects. Firstly, best on-farm water and salt management practices distilled from international and regional literature. From the research contributions principles for proactive management of water and salt were derived, viz. i) to minimise salt mobilisation and additions through irrigation water, ii) to prevent decreases in crop yield due to excessive dissolvable salt accumulation in the root zone, iii) to prevent degradation of soil permeability due to excessive sodium concentrations and iv) to minimise irrigation-induced drainage and leaching. Guidelines to achieve this will not only address onsite problems, but also offsite issues of water conservation and degradation of groundwater and river water sources, as well as leaching of essential nutrients.

The second aspect of the literature review focuses on precision farming principles and practices. With the ever-increasing availability and affordability of technology to support decisions within a field, the need also exists for spatial water and salt management. The literature synopsis provided a discussion on how to accomplish this. This discussion is based on the published general framework for precision agriculture or rather site-specific-crop management, namely i) spatial in situ direct or indirect soil, crop and terrain measurements and monitoring ii) mapping of these attributes iii) decision support and iv) deferential action. Each of these components were briefly discussed in a general site-specific-crop-management context, and how this context relates to spatial salinity management.

The last aspect of the literature revolved around decision support, which is of utmost importance in solving complex problems associated with water and salt management. In terms of decision support for salinity management, differences in the approaches adopted by popular transient state soil-crop-water salinity models were briefly highlighted. The aim of this section was not to provide a comprehensive review of all transient-state models, but rather to discuss some of the general approaches adopted by popular models, and to highlight differences between them. Against this background, approaches in soil-water flow, crop growth and yield, potential evaporation and transpiration, actual transpiration and root water uptake and salt transport are briefly discussed.

Chapter 5: Wheat and maize case studies: Spatial characterisation of soil properties related to water and salt management: The objective of this chapter was to spatially characterise soil properties of crop fields under wheat and maize production, using EMI technology and the software package ESAP. Soil properties of interest were soil salt load, water content, clay content and bulk density. These properties were investigated across centre pivot irrigated fields, located in three provinces, to highlight two important aspects, namely the feasibility and effectiveness of EC_a surveys done on irrigated soils to map all four properties. Data sets of the seven crop fields were organised per soil layer with thickness of 0.3 m depth up to 1.5 m intervals, where possible.

From dataset 1 the following main findings were derived: i) For sandy to sandy loam soils of the central irrigation areas of South Africa, EC_e values below $\pm$ 150 mS m^{-1} tend to dominate EC_{ac} readings. This was also true for the sandy clay loam soils with low EC_e values (< 100 mS m^{-1}) or high ($\pm$ 250 mS m^{-1}); ii) As expected, an increasing clay content has an increasing influence on bulk soil conductance, provided that the range in spatial variability is within the $\pm$ 20% clay content limit. iii) In this study it seems that water content did not influence EC_{ac}. Only one field showed a reasonable correlation (r = 0.59) between EC_e and volumetric soil water content (θ_v).

Data set 2 revealed the following main findings: i) It seems that shallow EC_a-readings and to a lesser extent, the deep readings of the EM38-MK2 instrument are influenced by the ambient temperature during the day. Hence, care should be taken when interpreting shallow EC_a readings; ii) In some fields, $EC_{a\ deep}$ readings and soil property data correlated well while other readings did not. Hence, further research is needed as we are not sure whether the DPPC model is applicable to soils found in semi-arid parts of South Africa. iii) For sandy to sandy loam soils uniform in depth and spatially across the field in terms of clay content, low EC_e values (< 150 mS m^{-1}) significantly influenced low EC_a readings (± 50 mS m^{-1}). iv) Only one field showed evidence that clay content significantly influenced $EC_{a\ deep}$ readings. According to the spatial MLR models in none of the fields with clay soils did EC_e significantly influence $EC_{a\ deep}$ readings.

Chapter 6: Decision support with the soil water management program, SWAMP: Irrigation software programmes are advanced and support farmers daily in scheduling decisions. A common water-management strategy is to deplete the profile to a pre-determined level and then refill the profile to the drained upper limit. One of the drawbacks of the technology is that most of the commercial soil-water probes do not measure osmotic potential of soils. In practice this implies that salt management is somewhat in the background and is not integrated with soil water management. Other important decision support tools are crop models, like SWB and SWAMP. Recently, the source code of SWAMP was adapted and translated into the Visual Basic for Applications (VBA) programming language. The VBA code now provides the user with an option to use SWAMP for temporal and spatial support regarding soil, crop and water and salt-related decisions in irrigated and rain-fed crop production systems.

The objectives of this chapter were: (i) to briefly describe the newly developed source code of SWAMP to simulate the soil-water and salt balance and consequent matric and osmotic stress effects on water uptake and yield of field crops. (ii) to apply the model in assessing the importance of integrating water and salt management. (iii) to assess the potential for applying the optimised irrigation schedule in precision farming as a future decision support option.

One of the case studies of the project was used to test three irrigation strategies: Strategy 1 was based on soil-water sensor technology that allows a 50% depletion before irrigating a net irrigation amount of 14 mm. Strategy 2 depletes the soil water with 30% before applying a net irrigation of 14 mm and strategy 3-optimal irrigation schedule. Simulations were run daily over three years, for a consecutive wheat-maize crop rotation.

The results showed that SWAMP can simulate the impact of management decisions on changes in matric and osmotic potentials that are highly dynamic. Furthermore, the results showed that irrigation strategy choice has a significant influence on these potentials as well as the resulting crop yields. Care should therefore be taken to apply steady-state concepts to provide decision support regarding salinity management. The optimal irrigation strategy clearly showed the importance of taking a longer-term view when managing salinity because decisions made in one season have an impact on the feasibility of crop production in the following season. Applying the optimal irrigation strategy for the worst-case scenario to less worse-case scenarios showed that management principles applied to the worst case will be applicable to less worse-case scenarios. The optimal irrigation strategy assumes complete knowledge of production conditions over the season, which should be challenged. The potential for using the optimisation algorithm in order to devise management zones for applying precision irrigation is vast.

7.3 Recommendations

It is important for national food security that areas in crop fields subjected to waterlogging and salinity be addressed. Our own situation is that, conservatively estimated, about 90 000 ha of South Africa's irrigation soil is salt affected, and this impacts negatively on the livelihoods of farmers across all scales. The EMI-technology in conjunction with remote sensing technology provide solutions to identify these areas and to make specific recommendations. The technology is in line with the World Bank's vision and protocol on which funding of projects that aim to secure and protect irrigated land with the objective to increase land productivity and livelihoods, enjoy preference in their funding strategy (Kijne, 2011). The following recommendations were made:

i) Training of Behaviour Change Officers

Application of guidelines in Volume 1: One of the pre-requisites for using the guidelines summarised in Volume 1 is that potential users should have a basic knowledge of irrigation sciences related to climate, soil, and crop sciences. Thus, there is a need to train or retrain extension officers and advisors in the technical aspects (BCOs) of water and salt management.

Application of guidelines in Volume 2: The scaling out of the EMI-technology to farmers is a problem. Here it is recommended that training should be provided to BCOs. The motivation is that BCOs play a decisive role in dissemination of information. Relationships between scientists on the one side (scientist), farmers on the other side (applicator) and behaviour change officers (BCO) at the base side, forming an equilateral triangle, are imperative in advancing the initiative. Important here, is the principle of equilateral: the partnership in this relationship is equal and should not be skewed towards isosceles or scalene triangle shapes where one side or partner dominates the other. This partnership advocates a more sustainable irrigation sector attempt to empower farmers and encourage them to continually evaluate and improve on-farm water and salt management through learning how to test and adapt (Kijne, 2011).

ii) Organising of crop-specific workshops on the outscaling of EMI technology

The main problem, however, is the scaling out of the EMI-technology to leading farmers, which is often recognised as an essential platform to introduce new technology to co-farmers. Nine case studies on site-specific assessment of water and salts in perennial crops were conducted, viz, grapes, lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries. These case studies provide the opportunity for outscaling of EMI application through crop specific workshops. Without exception, the case studies were successful in (a) showing where the salts are in the crop field, (b) how these salts impact on the hydro-physical properties, such as bulk density and water storage in the profile, and (c) to apply site-specific procedures to rectify problematic areas.

iii) Demonstration of salt removal experiments

The socio-economic survey revealed that the benefits of salinity management outweigh the costs. However, farmers are also of the opinion that the effort to implement salt-management interventions can hinder or reduce the benefit gained. Clever work is required to bridge the mindset of applicators and to package EMI-information. It is recommended that demonstration trials on land reclamation with artificial drainage be conducted at leading farmers' fields. A good example is the macadamia case study where the farmer insisted that demonstration trials be conducted in some of the affected areas to show the efficiency of the latest subsurface drain technology.

iv) On-farm water and salt management policies

The opportunity is there to develop policies that will guide land owners/users of irrigation land towards a higher level of responsibility and accountability in protecting natural resources against water and salt accumulation. EMI-technology provides the means to monitor such impacts as demonstrated in the case studies. It is recommended that EMI should be used to monitor and assess water and salt management at least once in 10 years, preferably once every 5 years. In the case of small scale farmers, it is recommended that Government should subsidise the monitoring of salt-affected soils.

v) Developing and testing of underground drainage/irrigation system

Water table soils are in great demand amongst dryland farmers and are regarded as a Class 1 dryland soil. A problem with the soils is the potential build-up of salts via long-term use of fertilisers and the mobilisation of salt from parent material. Another problem relating to these soils is that during high-rainfall periods, which we experienced in 2019/20 season, there is a danger that the water table can rise uncontrollably, causing waterlogging that results in severe crop losses. A potential solution to the two problems is the installation of an underground system that can be used to control the water table heights through drainage and irrigation. Thus, it is important that the water table heights and salinity level be monitored. EMI technology can be used to identify such soils. It is recommended that research should be conducted on the development and testing of a dual underground drainage/irrigation system together with sensors that can monitor water table heights cost effectively.

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APPENDICES

Appendix 4.1: Chemical analyses of soil samples collected on 14 July 2016 and physical analyses on samples collected on 1 Jul 2017 (Case study 1)

Depth: 0-300 mm

Plot	1	2	3	4	5	6	7	8	9	10	11	12	Mean
pH (1:5)	6.87	8.10	7.74	7.77	7.96	8.03	7.24	7.95	7.89	7.68	7.19	6.98	7.62
K mg/L	323	336	290	296	229	364	294	257	301	336	281	387	308
Ca mg/L	4024	4523	4389	4084	4290	4301	3880	4288	4218	4727	4196	4211	4261
Mg mg/L	924	1123	809	809	819	1240	930	794	975	900	788	864	915
Na mg/L	884	1001	604	605	749	1183	876	689	740	681	522	670	767
EC (1:5, mS/m)	57	66	60	58	51	65	57	51	54	49	51	51	56
EC mS/m	67	68	58	67	58	69	72	50	58	53	63	73	63
SAR	5.35	6.18	3.90	3.15	4.91	6.50	6.71	3.42	3.88	3.95	3.03	4.57	4.63
ESP %	10.7	8.2	5.5	6.9	8.1	8.3	9.3	5.8	6.6	6.1	5.3	8.1	7.4
Clay %	62	49	56	51	68	59	62	60	62	62	55	52	58
BD g/cm^3	1.59	1.49	1.43	1.47	1.52	1.42	1.54	1.49	1.30	1.26	1.21	1.33	1.42
KSat mm/hr	4.9	14.0	22.7	31.5	15.3	24.3	9.5	21.8	11.9	14.7	6.9	5.0	15.2

Depth: 300-600 mm

Plot	1	2	3	4	5	6	7	8	9	10	11	12	Mean
pH (1:5)	7.24	8.51	8.45	8.09	8.51	8.42	8.20	8.39	8.55	8.25	7.73	7.57	8.16
K mg/L	314	227	182	247	187	221	179	211	277	225	157	303	228
Ca mg/L	4214	4333	3783	3982	3766	4416	3746	4283	4945	4493	3995	4564	4210
Mg mg/L	1235	1426	1124	846	1039	1394	1103	1107	1634	1142	887	1056	1166
Na mg/L	1373	2026	1264	901	1041	2147	1289	1387	2097	1408	562	1338	1403
EC (1:5, mS/m)	66	74	60	58	52	68	60	52	68	49	52	58	60
EC mS/m	99	72	52	71	60	69	68	50	57	54	51	86	66
SAR	9.20	9.85	9.00	4.73	7.83	16.28	8.98	9.24	10.68	8.00	3.23	10.65	8.97
ESP %	11	18	10	9	11	25	12	12	25	11	7	14	13.6
Clay %	34.2	58.0	53.0	72.2	62.0	54.0	66.8	70.2	68.2	75.0	45.6	54.8	59
BD g/cm^3	1.557	1.543	1.497	1.624	1.431	1.477	1.616	1.596	1.441	1.409	1.369	1.367	1.49
KSat mm/hr	3.9	6.9	3.5	7.1	6.7	2.6	13.3	8.8	14.8	1.4	9.6	3.2	6.8

Depth: 600-900 mm

Plot	1	2	3	4	5	6	7	8	9	10	11	12	Mean
pH (1:5)	8.72	8.84	9.03	8.68	8.83	8.82	8.63	8.75	8.94	8.71	8.88	8.74	8.80
K mg/L	209	188	136	261	163	201	168	170	203	189	120	251	188
Ca mg/L	3523	3852	3094	5348	3549	4308	3272	3776	4071	4065	2970	4244	3839
Mg mg/L	1245	1506	1586	1829	1343	1710	892	1225	1395	1160	976	1301	1347
Na mg/L	2542	2664	2028	2839	1691	3608	1090	2053	2694	2086	739	2312	2196
EC (1:5, mS/m)	79	76	61	65	57	68	52	60	70	63	38	57	62
EC mS/m	111	64	60	63	56	52	66	49	55	59	51	76	64
SAR	16.33	13.02	16.88	14.46	15.84	6.09	10.91	10.41	12.79	12.48	5.34	15.51	12.51
ESP %	24	28	29	31	23	27	14	27	34	28	8	30	25.2
Clay %	48.8	44.6	32.8	72.2	51.0	52.4	-	61.0	64.2	77.0	55.4	59.0	56
BD g/cm^3	-	1.698	1.572	1.573	1.605	1.514	-	1.555	1.431	1.438	1.416	1.424	1.52
KSat mm/hr	-	17.8	0.5	6.5	0.3	1.0	-	4.8	1.8	0.9	7.6	0.6	4.2

EC = Electrical Conductivity; SAR = Sodium Adsorption Ratio; ESP = Exchangeable Sodium Percentage; BD = Bulk Density; KSat = Saturated hydraulic conductivity

Appendix 4.2: Sugarcane nutrient content at the age of 10.6 months for three biomass parts per plot (Case study 1)

Plot number	1	2	3	4	5	6	7	8	9	10	11	12	Mean
N (kg/ha)													
Brown leaves	45.0	29.1	35.1	35.1	38.5	20.4	82.0	37.3	30.4	42.0	41.7	37.2	39.5
Green leaves	72.3	67.5	67.2	67.9	46.8	42.2	93.4	47.8	59.1	70.0	69.3	52.3	63.0
Stalks	143.2	157.7	118.9	164.6	107.8	106.4	137.1	172.3	123.5	182.2	118.3	170.3	141.9
Total	260.6	254.3	221.2	267.6	193.1	169.0	312.5	257.5	213.0	294.3	229.4	259.7	244.3
P (kg/ha)													
Brown leaves	4.4	2.8	2.8	3.3	3.7	1.8	5.5	2.9	3.0	3.4	4.0	3.3	3.4
Green leaves	9.3	8.7	8.4	9.1	6.3	6.3	11.3	6.1	7.7	9.2	8.3	7.1	8.1
Stalks	21.0	27.6	20.5	32.9	18.0	23.0	25.7	30.2	22.4	40.5	25.4	35.1	26.8
Total	34.6	39.1	31.7	45.3	27.9	31.1	42.4	39.2	33.2	53.1	37.6	45.4	38.4
K (kg/ha)													
Brown leaves	40.7	7.1	14.2	19.6	23.8	11.8	25.5	11.8	19.8	18.2	17.9	19.0	19.1
Green leaves	139.6	108.2	117.6	114.2	94.1	81.8	158.7	74.0	101.5	117.5	118.9	112.3	111.5
Stalks	202.6	165.6	192.7	279.8	140.8	149.5	222.8	168.0	204.8	273.4	185.9	275.4	205.1
Total	382.9	280.8	324.5	413.6	258.7	243.1	407.1	253.8	326.2	409.0	322.7	406.7	335.8
Ca (kg/ha)													
Brown leaves	37.0	56.2	68.4	58.0	46.7	29.5	162.1	61.9	51.0	64.8	59.6	46.3	61.8
Green leaves	19.3	32.0	23.7	26.5	12.5	15.8	42.8	17.2	23.1	25.0	20.6	16.2	22.9
Stalks	17.5	35.5	24.6	38.4	18.0	20.1	34.3	34.5	19.6	35.4	21.1	25.0	27.0
Total	73.8	123.6	116.6	122.9	77.2	65.5	239.2	113.6	93.7	125.2	101.3	87.6	111.7
Mg (kg/ha)													
Brown leaves	16.7	17.1	28.5	18.8	19.2	11.8	40.1	25.5	19.8	27.3	28.8	19.9	22.8
Green leaves	17.7	20.8	17.6	15.7	10.3	10.0	23.6	12.2	14.8	15.0	17.3	12.0	15.6
Stalks	45.4	55.2	45.1	60.3	35.9	31.6	51.4	51.7	36.5	60.7	46.5	50.1	47.5
Total	79.8	93.0	91.1	94.9	65.4	53.5	115.1	89.5	71.0	103.0	92.6	81.9	85.9
S (kg/ha)													
Brown leaves	7.3	6.4	8.5	8.2	7.3	5.0	16.4	9.8	7.6	11.4	11.9	8.3	9.0
Green leaves	19.3	32.0	23.7	26.5	12.5	15.8	42.8	17.2	23.1	25.0	20.6	16.2	22.9
Stalks	34.9	51.2	41.0	82.3	33.0	31.6	68.6	47.4	36.5	55.7	50.7	50.1	48.6
Total	61.5	89.7	73.2	117.0	52.8	52.4	127.7	74.5	67.2	92.0	83.3	74.6	80.5
Si (kg/ha)													
Brown leaves	278.7	263.7	272.5	308.9	250.1	181.2	1069.2	267.2	298.2	472.6	318.8	384.0	363.8
Green leaves	138.8	166.1	97.0	158.1	75.3	89.1	283.7	77.9	108.6	168.3	134.5	155.3	137.7
Stalks	45.4	74.9	61.5	175.6	59.9	51.7	124.3	99.1	89.8	126.6	93.0	140.2	95.2
Total	462.9	504.7	430.9	642.5	385.3	322.1	1477.2	444.2	496.6	767.4	546.3	679.6	596.6
Na (kg/ha)													
Brown leaves	2.4	1.9	3.0	2.9	2.1	1.3	5.7	2.2	2.3	2.5	3.1	3.1	2.7
Green leaves	1.7	2.4	2.1	2.2	1.0	1.2	1.8	1.3	1.6	2.3	1.9	1.5	1.8
Stalks	3.0	11.9	4.8	5.0	3.7	5.9	4.3	6.2	3.9	3.4	4.1	4.2	5.0
Total	7.1	16.2	9.9	10.1	6.9	8.5	11.9	9.7	7.8	8.2	9.2	8.7	9.5

Appendix 4.3: Chemical analyses of soil samples collected on 11 October 2016 and physical analyses on samples collected on 3 October 2017 (Case study 2)

Depth 0-300 mm

Plot	1	2	3	4	5	6	7	8	9	10	11	12	Mean
pH(water)	6.88	5.95	7.18	5.63	7.03	7.31	6.59	5.08	6.67	4.64	4.75	6.40	6.17
K mg/L	120	98	103	40	89	122	113	54	683	55	51	42	131
Ca mg/L	940	1061	1784	460	787	2563	1445	826	1935	426	402	665	1108
Mg mg/L	774	488	1007	204	755	966	866	419	757	189	127	331	574
Na mg/L	672	257	612	90	1028	589	556	183	233	95	69	127	376
EC mS/m	165	130	174	90	221	78	155	135	98	99	85	82	126
SAR	13.1	3.6	7.2	2.0	16.4	6.2	6.8	2.3	1.8	2.1	2.0	3.1	5.5
ESP %	20.4	10.3	13.3	8.8	27.5	10.2	13.3	9.2	5.5	10.0	8.6	8.3	12.1
CEC cmol/L	9.4	7.7	14.5	3.0	9.6	17.7	11.8	5.7	15.5	2.6	2.4	4.7	8.7
Clay%	28.3	66.7	27.2	44.6	26.0	42.5	33.3	31.5	44.6	29.4	24.9	20.1	34.9
BD g/cm^3	1.63	1.63	1.64	1.57	1.61	1.58	1.51	1.66	1.37	1.66	1.70	1.70	1.60
KSat mm/hr	1.79	15.50	4.91	26.27	1.81	0.03	2.77	1.91	0.96	14.66	6.63	4.64	6.82

Depth 300-600 mm

Plot	1	2	3	4	5	6	7	8	9	10	11	12	Mean
pH(water)	8.01	7.70	8.37	6.12	7.97	8.36	8.30	5.60	7.46	5.88	6.08	6.93	7.23
K mg/L	135	108	113	66	116	133	124	38	687	66	52	47	140
Ca mg/L	967	1339	1316	1034	604	2164	1447	697	1559	853	898	708	1132
Mg mg/L	1324	946	1806	616	942	1419	1167	542	1031	643	401	669	959
Na mg/L	1680	742	2912	257	1724	1339	937	210	614	327	251	535	961
EC mS/m	193	95	192	51	234	91	145	61	108	43	60	81	113
SAR	21.9	11.5	21.3	4.1	30.7	12.9	10.9	3.4	5.6	5.3	5.7	10.5	12.0
ESP %	30.7	17.8	35.8	9.5	40.1	19.4	19.5	10.0	12.9	13.0	12.1	20.2	20.1
CEC cmol/L	15.6	12.6	25.3	8.5	11.9	21.6	14.8	6.4	18.3	8.6	6.2	8.8	13.2
Clay%	32.1	23.3	73.9	25.8	28.6	42.6	39.0	33.0	33.4	29.3	15.1	26.8	33.6
BD g/cm^3	1.63	1.59	1.60	1.60	1.62	1.58	1.55	1.65	1.39	1.66	1.76	1.75	1.62
KSat mm/hr	1.81	0.56	0.01	0.60	0.35	0.29	1.90	0.90	3.88	4.58	2.99	2.68	1.71

Depth 600-900 mm

Plot	1	2	3	4	5	6	7	8	9	10	11	12	Mean
pH(water)	8.69	8.85	9.07	6.83	8.32	9.08	8.71	6.45	8.37	7.06	6.81	7.67	7.99
K mg/L	209	127	81	84	131	148	140	41	774	86	77	60	163
Ca mg/L	1606	961	1049	1698	546	1804	1483	526	1770	884	1188	584	1175
Mg mg/L	1573	1212	1407	958	1148	1839	1329	722	967	954	944	803	1155
Na mg/L	3524	1292	2572	438	2885	2916	1379	265	921	546	385	993	1510
EC mS/m	249	127	231	45	268	109	164	35	194	68	45	107	137
SAR	25.9	22.4	23.9	5.7	30.5	19.9	15.9	3.9	10.3	7.8	5.9	14.4	15.5
ESP %	41.2	27.1	38.7	10.3	50.4	34.3	25.2	12.0	18.0	16.3	10.7	30.5	26.2
CEC cmol/L	24.3	15.2	21.6	14.5	16.5	29.4	17.0	7.2	19.1	11.4	12.0	10.1	16.5
Clay%	55.7	32.9	52.1	31.0	43.7	57.5	33.6	36.1	41.1	34.7	12.3	39.4	39.2
BD g/cm^3	1.69	1.68	1.65	1.62	1.65	1.61	1.55	1.71	1.44	1.68	1.73	1.74	1.64
KSat mm/hr	0.15	-	0.00	-	0.07	0.10	4.81	0.32	4.84	0.07	-	0.94	1.26

EC = Electrical Conductivity; SAR = Sodium Adsorption Ratio; ESP = Exchangeable Sodium Percentage; BD = Bulk Density; KSat = Saturated hydraulic conductivity

Appendix 4.4: Sugarcane nutrient content at the age of 10.7 months for three biomass parts per plot (Case study 2)

Plot number	1	2	3	4	5	6	7	8	9	10	11	12	Mean
Average of N (kg/ha)													
Brown	34.3	41.8	16.2	26.0	20.1	17.9	21.7	19.4	43.0	21.7	26.2	18.2	25.5
Green leaf	56.5	50.0	25.2	44.9	21.8	32.2	32.5	39.6	62.0	47.3	35.2	30.9	39.8
Stalks	223.9	179.9	94.7	158.9	45.6	74.8	152.4	83.0	367.0	104.4	82.1	177.8	145.4
Total	314.7	271.8	136.0	229.8	87.5	124.9	206.5	142.0	471.9	173.4	143.4	226.9	210.7
Average of P (kg/ha)													
Brown	2.2	2.8	0.9	1.1	1.6	2.1	1.4	1.7	3.5	1.2	1.7	0.9	1.8
Green leaf	7.5	7.6	3.6	5.7	3.0	6.4	4.9	6.9	9.5	6.7	5.1	4.7	6.0
Stalks	34.8	38.6	22.8	25.8	10.3	45.7	28.6	39.3	61.2	25.3	28.4	61.6	35.2
Total	44.6	49.0	27.3	32.6	14.9	54.2	34.9	47.9	74.2	33.2	35.3	67.1	42.9
Average of K (kg/ha)													
Brown	5.2	13.9	4.3	8.5	7.1	6.8	7.2	8.8	26.8	7.0	6.3	6.5	9.0
Green leaf	82.1	93.9	46.2	75.5	36.1	66.4	61.6	72.6	152.6	87.4	70.8	58.7	75.3
Stalks	273.7	308.4	238.3	369.4	83.8	265.8	300.0	279.7	1257.3	170.8	249.3	342.0	344.9
Total	361.0	416.2	288.7	453.4	127.0	339.0	368.8	361.1	1436.6	265.2	326.4	407.1	429.2
Average of Ca (kg/ha)													
Brown	33.5	47.4	20.9	32.8	21.2	28.5	26.0	23.1	25.3	31.1	38.1	21.2	29.1
Green leaf	10.6	11.9	7.1	9.8	5.4	9.3	8.2	10.1	13.1	14.5	13.3	10.9	10.4
Stalks	14.9	19.3	13.1	17.2	5.9	16.6	19.0	17.5	27.2	22.1	22.1	41.0	19.7
Total	59.1	78.6	41.0	59.8	32.5	54.3	53.3	50.8	65.6	67.7	73.5	73.2	59.1
Average of Mg (kg/ha)													
Brown	20.9	24.2	10.6	13.0	11.0	11.1	11.1	9.7	9.9	6.5	8.0	4.8	11.7
Green leaf	12.4	12.4	6.7	8.3	4.5	6.7	6.7	7.8	7.7	8.3	6.4	7.0	7.9
Stalks	69.7	83.5	45.7	51.5	20.6	49.8	57.1	52.4	40.8	34.8	31.6	75.2	51.1
Total	102.9	120.1	63.0	72.8	36.1	67.6	74.9	70.0	58.4	49.6	46.0	87.0	70.7
Average of S (kg/ha)													
Brown	33.5	47.4	20.9	32.8	21.2	28.5	4.3	4.6	6.3	5.9	6.3	3.9	18.0
Green leaf	10.6	11.9	7.1	9.8	5.4	9.3	8.2	10.1	13.1	14.5	13.3	10.9	10.4
Stalks	64.7	83.5	49.0	55.8	20.6	66.4	61.9	74.3	135.9	53.8	56.8	116.3	69.9
Total	108.8	142.9	77.0	98.4	47.2	104.2	74.4	89.1	155.4	74.1	76.4	131.1	98.2
Average of Si (kg/ha)													
Brown	126.0	162.7	77.0	82.0	57.0	184.4	89.2	104.8	395.7	100.9	149.1	56.3	132.1
Green leaf	50.8	56.2	31.2	41.9	19.9	66.0	31.6	48.1	186.5	72.9	48.5	51.2	58.7
Stalks	84.6	109.2	71.8	60.1	27.9	145.4	100.0	131.1	380.6	63.3	47.3	157.3	114.9
Total	261.4	328.2	180.0	184.0	104.8	395.8	220.7	283.9	962.8	237.1	244.9	264.9	305.7
Average of Na (kg/ha)													
Brown	0.7	1.2	0.5	1.2	0.5	0.7	0.6	0.6	1.1	0.7	0.6	0.8	0.8
Green leaf	1.0	0.9	0.5	0.9	0.3	0.5	0.4	0.4	0.6	0.6	0.4	0.3	0.6
Stalks	6.1	2.5	2.2	3.7	0.7	5.3	1.4	2.5	3.2	1.3	1.4	2.7	2.8
Total	7.8	4.5	3.2	5.8	1.5	6.5	2.4	3.6	4.9	2.7	2.3	3.8	4.1