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

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WATER RESEARCH COMMISSION

TT 847/1/21

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

Report to the

Water Research Commission

by

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WRC Report No. TT 847/1/21

July 2021

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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)

ISBN No 978-0-6392-0248-8
Printed in the Republic of South Africa

EXECUTIVE SUMMARY

1. Problem statement

Irrespective of the location in the world, the opening of a tap to irrigate a crop field opens opportunities for increasing crop yields and land productivity. Intensification of agriculture, however, poses risks to crops and soils that demand management. One of the major risks of irrigation is accumulation of salts in the soil. Soil salts originate mainly from dissolved salts in irrigation water, fertiliser application, as well as mobilisation of salts in soils and parent material. Uncontrolled build-up of salts carries two threats to farmers, i.e. salinity and sodicity. Salinity affects crop growth and yield directly through osmotic pressure that reduces the availability of soil water, resulting in early plant-water stress and loss of yield. Sodicity, a condition where sodium is the dominant salt in the soil solution or adsorbed on clay and organic particles, affects soil directly and the crop indirectly. Like salinity, it causes early plant-water stress, but via a totally different mechanism, and is much more harmful than salinity to the agro-ecosystem. In such cases, clay particles disperse (come into suspension) and move into pore spaces where it blocks the natural flow paths of water. This happens at the surface of the soil to form a hard crust, or deeper in the profile forming clay layers.

Excess soil salt is a huge problem worldwide. Estimations show that approximately 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 soils are salt affected, and this impacts negatively on the livelihoods of farmers across all scales, i.e. subsistence farmers, smallholders, commercial- and mega-farmers. Hence, there is a need for guidelines to protect our soils and to improve crop yields for a broad spectrum of farmers with varying resources.

2. Contextualisation

The goal of the current report was to develop a water and salt management guideline that can serve as a level one Decision Support System (DSS). Information in a level one DSS is in the domain of the public, therefore accessible to all types of farmers, irrespective of socio-economic environment. 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 extension officers, also called Behaviour Change Officers (BCOs), whom are equipped to facilitate the exchange of information to resource-deficient farmers. A resource-deficient farmer represents a group of farmers that cannot afford detail soil salinity surveys and private consultants. These farmers rely on classic science information to control soil salts.

Resourceful farmers have options to utilise private consultants and laboratories that render field services. Guidelines for conducting such services and expected outcomes are presented as a level two Decision Support System (Volume 2 in this series of three WRC reports). Generally, level two DSS deals with high-income crops such as pecans, walnuts, blue berries and lucerne. The aim of such an investigation is to show distribution of salts in the field, determine their impact on hydro-physical properties, and to provide procedures for solving salt related problems.

For a deeper understanding of salt-related problems and their medium to long-term management, a level three decision support system was introduced (Volume 3). This DSS is on a research level and is aimed at serving the science community, although mega-farmers, agricultural cooperatives and companies may also benefit from it. In this case, salinity models, such as SWAMP, are used to make medium to long-term estimations of salt impact on land productivity.

3. Objectives

The goal of this report was to compile a water and salt management guideline for BCOs serving the irrigation sector. In order to achieve this main goal, four objectives were set:

i. Summarise the main findings of a socio-economic survey among irrigators from the commercial sector in the Breede River, Vaalharts and Douglas irrigation schemes, as well the northern KwaZulu-Natal district, on their knowledge about salt management (Chapter 2).

ii. Extract information on the art and science of irrigation scheduling from literature and presenting it as a guideline using two of the best scheduling practices as examples, i.e. crop coefficients and continuous measuring probe technology (Chapter 3).

iii. Obtain the fundamental principles from literature 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).

4. Knowing the farmers

The aim of the socio-economic survey was to capture data regarding the existing knowledge levels, management practices, as well as beliefs and perceptions around 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). Demographic results suggested that the majority of these 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 baseline information study indicated that there are high-risk farms that are inherently susceptible or already being impacted by salinity or sodicity. Behaviour-change 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. Five hypotheses were formulated to test beliefs and perceptions regarding salt management in irrigation. These results suggested that the farmers adequately perceive the threat of salinity and also apparently have sufficient knowledge about the causes, as well as the preventative and corrective measures for salinity management. The farmers further indicated that the benefits of salinity management do outweigh the costs, but that the effort to implement salt management interventions is not justified by the benefit gained. In conclusion, in alignment with literature, the survey suggested 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, or allowing farmers to learn from fellow farmers via farm visits and technical tours are possible pathways. 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.

5. Fundamentals of water management

Over- and under-irrigation of crop fields have a direct impact on land productivity and indirect effect on soil salts. Therefore, farmers are encouraged to make use of objective scheduling methods as surveys have shown that the uptake of such methods is low, not just in South Africa, but world-wide. The aim of this chapter was to revisit some fundamentals in irrigation scheduling as a guide to improve water management. Three aspects were highlighted, i.e. (i) the soil water balance and water management boundaries, (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.

As background for the scheduling approaches, the soil water balance was summarised and contextualised within the soil water management boundaries. To achieve this, empiric equations were extracted from different sources for estimating saturation point, drained upper limit (DUL) and permanent wilting point (PWP). The guideline provides information on methods for estimating the allowable depletion point. This is a point between DUL and PWP that reflects on the water storage capacity of a soil. Management of soil water within these two boundaries poses a low risk in crop water stress, if any.

Crop coefficient is an irrigation scheduling method widely used in the industry. Application of this method entails a sound understanding of concepts such as reference evaporation, actual evapotranspiration and the characteristics of crop coefficients. The guideline provides information on these aspects as well as the application thereof to determine how much water to apply during an irrigation event in order to satisfy crop water needs in a specific soil-plant-atmosphere continuum. To further accentuate the application of crop coefficients in planning of irrigation projects, an overview on SAPWAT4 was included in the guidelines.

Advances in technology of soil water sensors for irrigation scheduling stands on three pillars, i.e. continuous logging probes, telemetry and web-based irrigation software. The guidelines give insight into the characteristics of probes that use capacitance for indirect measuring of soil water content. The review confirms that the sensors are very accurate, but practical calibration seems to be a problem in the industry. Despite the calibration problem, the industry thrived as indirect calibration techniques were mastered, assisting in decisions regarding when and how much water to apply. Advances in telemetry and web-based irrigation software makes it possible to provide quality services to farmers. BCOs are encouraged to promote at least one of these two scheduling methods.

6. Fundamentals in salt management

In summary, this chapter provides nine fundamental pointers that will guide BCOs in facilitating salt management of irrigated fields:

i. Soil sampling: A flow diagram (Figure 4.1) was introduced on the different stages of deciding how and where to sample soils. The stages can be divided into approach, method, design and sampling pattern. Two approaches in soil sampling was highlighted, namely the traditional and site-specific approach. Guidelines were developed for choosing a suitable method of soil sampling.

ii. Suitability of soils for irrigation: The selection of suitable soils for irrigation is an important task and requires specialists in the fields of agro-meteorology, pedology, crop science, engineering and economics. This section provides insight on the complex nature of soil surveys, soil indicators and norms for selecting suitable soils, and lastly to group soils into irrigation potential classes. Understanding these underlying principles will assist BCOs in their task to rectify waterlogging and salt related problems.

iii. Sources of salts: This section creates awareness on the major sources of salts in soil and discusses irrigation water, drainage water, shallow water tables, fertilisers, rain (near the coast), as well as the dissolution of inherent salts in the parent material as possible sources of salts. Eliminating or reducing the salt-source is a major objective in salt management.

iv. Salt threshold for soils: Guidelines for the classification of salt-affected soils were extracted from literature. Critical SAR values for soils in the sugar industry were also summarised. Critical SAR values indicate the point of onset of clay dispersion with the consequent degradation of soil structure, decline in infiltration rate, crust formation and a general degradation in the physical condition of the soil.

v. Salt threshold for crops: The standard guidelines for field, vegetable, forage and fruit crops were summarised.

vi. Irrigation systems: This section summarises irrigation systems under two categories using water placement and its influence on salt distribution as basis, namely point and non-point application systems. Each irrigation method has certain advantages and disadvantages and all known factors should be considered before attempting to improve salinity control by changing irrigation method.

vii. Drainage systems: Guidelines are given for placement of artificial drains according to texture classes. Studies on drainage have demonstrated that in severely salt-affected areas, crop yields increased by an average of 54% for sugarcane, 64% for cotton, 69% for rice, and 136% for wheat, within one or two seasons after installation of subsurface drainage. Yield increases were attributed to the reduction of water tables by 25% and soil salinity levels by 50% in drained fields compared to non-drained ones.

viii. Quality of irrigation water: The quality of irrigation water is mainly measured through its impact on soil and crop or the combination effect. Four indicators are extensively used over the world, including electrical conductivity, sodium content, bicarbonate content, as well as boron concentration. Norms for these indicators were summarised as guidelines.

ix. Leaching: Guidelines on leaching requirements were derived from the well-known empirical equations of Rhoades and Merril, as well as the leaching curve method of Barnard.

7. Solutions for salt-related problems

The focus of this chapter was to summarise practical solutions on water and salt management. Two approaches, i.e. a proactive and reactive approach, for solving salt-related problems were proposed as guidelines. The proactive approach is based on the root zone salinity assessment procedure described by Ehlers. The assessment is based on drainage conditions in the soil profile, whether it is restricted or freely drained. Two procedures (A and B) are available under restricted drainage conditions, i.e. where the electical conductitvity of the soil extract (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 of each procedure (A-D) was included as a guideline to assess field situations. Under the reactive approach, guidelines to reclaim saline and sodic soils were summarised.

8. Recommendations

Although this report is intended for application by extension officers or BCOs, the information of the level one DSS is accessible to all types of farmers, NGOs, project managers, consultants and engineers. However, it is recommended that potential users have a basic knowledge of irrigation sciences related to climate, soil and crop sciences. It is further recommended that BCOs that work with subsistence and smallholder farmers adapt and repackage the information in order to fit their level of communication. Resourceful farmers, especially those who are farming with high income crops, are advised to make use of the level two DSS (Volume 2). This DSS focuses on precision agriculture techniques to characterise water and salt problem areas in crop fields. Measures to improve physical and chemical soil conditions can then be directed towards affected areas. Examples of level two DSS case studies on lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries are provided. For more in-depth analysis of water- and salt-related problems, using sugarcane, wheat and maize as test crops, the level three DSS (Volume 3) is recommended for reading. This normally takes the form of a research project and is directed towards large companies and the science community.

ACKNOWLEDGEMENTS

The successful completion of this project was made possible only through the co-operation of many individuals and institutions. The authors wish to express their sincere thanks to the following:

1. Water Research Commission for advice, guidance and financial support.
2. Members of the Reference Group for valuable contributions.

Prof NS Mpandeli	: Water Research Commission (Chairman)
Dr GR Backeberg	: Water Research Commission (Former Chairman)
Dr SN Hlophe-Ginindza	: Water Research Commission
Dr Luxon Nhamo	: Water Research Commission
Dr RJ Armour	: Free State Agriculture
Dr JP Nell	: ARC-ISCW
Mr P Viljoen	: Department of Water and Sanitation
Mr Dup Haarhoff	: GWK
Prof H Jordaan	: University of the Free State
Mr HM du Plessis	: Private consultant

3. Management and administration of the University of the Free State for excellent infrastructure and facilities.
4. Messrs ZE Yokwani and TA Madito for technical assistance.
5. Ms GC Van Heerden, A Moffat and D Terblanche for their enthusiasm, competence and the cheerfulness with which they always assisted so willingly.
6. The sharing of information and advice on the irrigation scheduling component by Mr E Jordaan (HydraWize Precision Farming Solutions), F Olivier and L Hein (AquaCheck).
7. Mr D Haarhoff and his staff of Griqualand West Cooperative (GWK) for assistance, advice and informative conversations.
8. Farmers at Orange-Riet, Hofmeyr, Empangeni (Heatonville) and Mkhuzi for offering their farms for measurement purposes, and for their intuitive insights.
9. AgriPD for their effort in measuring apparent electrical conductivities of the fields and sampling of soils.
10. All staff and students involved in soil and water analyses performed at laboratories of the University of the Free State (Soil Science Section, as well as the Institute of Ground Water Studies), SASRI and Van's Lab.
11. All students who worked diligently on the WRC project, namely F Joseph, I Gura, JA Edeh, D Steenekamp, TB Motate, K Makhanya, D Mndzawe and MCN Mosiuoa.
12. Colleagues at the University of the Free State, Prof PAL le Roux and Prof CC du Preez, as well as Dr W de Clercq of the University of Stellenbosch, for valuable contributions from their fields of expertise.
13. Ms A Bothma for technical editing and proofreading of the report.

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LIST OF ABBREVIATIONS

BCO	:	behaviour change officer
CEC	:	cation exchange capacity
DSS	:	decision support system
DUL	:	drained upper limit
DWS	:	Department of Water and Sanitation
EC	:	electrical conductivity
EC_a	:	apparent electrical conductivity
EC_e	:	electrical conductivity of saturated paste extract
EC_i	:	eclectrical conductivity of irrigation water
EC_{sw}	:	electrical conductivity of soil water
EC_{wt}	:	electrical conductivity of water table
EMI	:	electromagnetic induction
E_s	:	evaporation from soil surface
ESP	:	exchangeable sodium percentage
ET	:	evapotranspiration
ET_0	:	reference evapotranspiration
ET_c	:	actual evapotranspiration of crop (crop water use)
FFU	:	fitness-for-use
K_c	:	crop coefficient
PAWC	:	profile available water capacity
PWP	:	permanent wilting point
RAW	:	readily available water
RMSE	:	root mean square error
RSSD	:	response surface sampling design
SAR	:	sodium adsorption ratio
SP	:	saturation point
T	:	transpiration
TAW	:	total available water
TEW	:	total evaporable water

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CHAPTER 1. INTRODUCTION

1.1 Problem statement

It is estimated that more than 800 million hectares of land throughout the world is salt-affected (FAO, 2005), representing more than 6% of the world's total land surface. Salinity affects approximately 20 to 50% of the world's irrigated land (Ghassemi et al., 1995; Pitman and Läuchli, 2002; Tanji and Kielen, 2002). In South Africa, approximately 6% of fields surveyed by Nell et al. (2015) in nine irrigation schemes were observed as waterlogged or salt-affected (Nell et al., 2015). The authors highlighted that this was probably an underestimation of the actual affected area, because it represented only severely affected crops. Currently, there is an estimated annual global loss in crop production in excess of US$27.3 billion due to salinity-induced degradation of irrigated lands (Qadir et al., 2014).

It is better to prevent salt accumulation in soils, than attempting to correct the problem of salinity and sodicity. Salinity is a term used to describe the build-up of dissolved salts in the soil profile resulting in an increased soil osmotic potential. If the osmotic potential of the soil water is higher than the salinity threshold of the crop, it will cause water stress and reduction in crop yield. Sodicity is a term used when sodium is the dominant salt in the soil solution or adsorbed on clay and organic particles (alkaline soils). In such a case the clay particles will disperse (come into suspension) and move into pore spaces where it blocks the natural flow paths of water. This may happen at the soil surface to form a hard crust, or deeper in the soil profile to form clay layers. The major problem with sodicity is that the soil structure is damaged to a point where irrigation becomes ineffective, ponding of water in depressions and runoff occur. Restoration cost of sodic soils is significant, sometimes close to the value of the land, as it involves intensive physical and chemical treatment.

Wherever salts have accumulated in the soil to levels approaching salinity and sodicity, it affects the livelihoods of farmers across all scales, i.e. subsistence farmers, smallholders, commercial- and mega-farmers. Socio-economic conditions over this scale vary widely. For example, subsistence farmers are associated with deep-rural areas (communal areas) where approximately 70% of South Africa's poor lives (Kundhlande et al., 2004). This group comprises of between 2 and 2.5 million farmers growing food for their families and selling their produce occasionally (Cousins, 2015). World-wide, approximately 1.4 billion subsistence farmers are located in risk-prone, marginal environments (Altieri, 2008). The education level of these farmers is generally low and production is also very low. Improving soil conditions of these farms will impact positively on agronomic productivity, household food security and hence, the reduction of poverty (Baiphethi et al., 2006). On the other end of the scale is commercial farmers, with a generally good education level to sustain high agronomic productivity (Hensley et al., 2019).

Irrespective of the scale of farming, salt affected soils in the irrigation sector is a man-made phenomenon that is, in most cases, caused unintentionally by farmers. Hence, there is a need for guidelines to protect our soils and to improve crop yields for all types of farmers with varying resource levels. The goal of this report was to develop a water and salt management guideline that can serve as a level one Decision Support System (DSS). The information in a level one DSS is in the domain of the public and therefore accessible to all types of farmers, irrespective of socio-economic environment. However, 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 extension officers whom are equipped to facilitate the exchange of information to resource-deficient farmers.

1.2 Contextualisation

As mentioned, the water and salt management guideline within the level one DSS, is specifically compiled for extension officers (hereafter termed Behaviour Change Officers, BCOs). The question arises: why BCOs? The BCOs are uniquely positioned in the middle of two types of “producers”. On the one hand are researchers that always produce new knowledge, and on the other hand, farmers who aim to produce crops at sustainable levels. The role of BCOs are to purposefully manage the innovation process between the two worlds, changing the behaviour of both scientists and farmers, facilitating the adoption of new technology. For example, in the Orange-Riet Irrigation Scheme, Botha et al. (2000) found that, at that time, farmers were of the opinion that there is little value in qualified irrigation scheduling advice and irrigation scheduling was driven by BCOs. The reason for this might have been that the farmers did not have an acceptable level of sophisticated knowledge of the subject, as there are many agronomic factors that influence the decisions on when and how much water to irrigate. From a scientific viewpoint, the information may not have been well packaged for the industry. Nevertheless, the vision of BCOs are important to bring about change in the behaviour of both these “producers”, because it is rational that accurate scheduling will conserve water and electricity, maximise yields and bring more profit to the farmer in the long-run. Innovative ideas should be simplified and carefully compiled by scientists and unpacked by agents for resource-deficient farmers, bringing change in their behaviour and attitude towards water and salts (Stevens and Van Heerden, 2013). A crucial factor that needs to be accounted for by BCOs is the packaging of information for the various farming sectors at their respective levels (Everson et al., 2011; Monde et al., 2012), which unfortunately falls beyond the scope of this report.

For resourceful farmers there is more sophisticated support to help identify and treat water and salt problems spatially in a field. This type of services is available in the private sector and can be regarded as a level two DSS. Water and salt management information that will be exchanged here is not fully in public domain, and service providers regard this information as their intellectual property. However, spatial assessment of soil water and salt status using electromagnetic induction (EMI) techniques, as well as management guidelines will be discussed in the second report of this project (Van Rensburg et al., 2020). It is expected that farmers cultivating high-income crops would make use of this type of service. In the level two DSS report, several case studies are presented, including crops such as lucerne, sugarcane, pecan, grapes and olives.

The third report in the series of on-farm water and salt management guidelines (Barnard et al., 2020) offers a level three DSS that serves the research community by generating new information and providing services to corporations and larger companies. This type of service is mainly provided by universities, research councils and private research institutions. A typical service will be to predict the impact of water and salt management on soils and crops. For this, models such as SWAMP, SWB and others can be used.

The three reports as described (Volume 1, 2 and 3) emanates from a project entitled “Management guidelines for technology transfer to reduce salinisation of irrigated land with precision agriculture”. The general aim of this project was to compile guidelines for technology exchange to manage the salt load associated with irrigation at farm and field level with precision agriculture and the specific aims to:

i. Compile water and salt management guidelines and elicit from stakeholders the acceptability thereof.

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.

To accomplish the aims of the project the following tasks were initiated and completed (not necessarily in this order). **Firstly**, Water Research Commission funded research, as well as international research related to water and salt management of irrigated fields were reviewed. **Secondly**, general principles of adopting precision agriculture or site-specific-crop management were reviewed, specifically concentrating on the extensively investigated, reliable and cost effective use of apparent electrical conductivity (EC_a) directed soil sampling (Corwin and Scudiero, 2016) to spatially characterise soil attributes related to salinity management. **Thirdly,** five case studies were identified and used to investigate the principles of water and salt management with precision agriculture and EC_a-directed field-scale characterising of soil variability. Case studies were located 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. **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, farmers' days and ad hoc, in situ spatial assessments of water and salt management problems on farms.

1.3 Objectives

The goal of Volume 1 was to compile water and salt management guidelines for BCOs serving the irrigation sector. In order to achieve the goal, four specific objectives were formulated:

i. To summarise the main findings of the socio-economic survey on knowledge about salt management among irrigators from the commercial sector in the Breede River, Vaalharts and Douglas irrigation schemes, as well as the northern KwaZulu-Natal district (Chapter 2).

ii. To extract information on the art and science of irrigation scheduling from relevant literature and presenting it a guideline using two of the best scheduling practices as examples, i.e. crop coefficients and continuous measuring probe technology (Chapter 3).

iii. To obtain the fundamental principles required for salt management of crop fields from literature, and to package the information as a salt management guide (Chapter 4).

iv. To compile a solution-management guideline on the treatment of root zone salts in a proactive and active manner (Chapter 5).

CHAPTER 2. SOCIO-ECONOMIC PERSPECTIVES TO INFORM KNOWLEDGE EXCHANGE ACTIONS

2.1 Introduction

A baseline socio-economic survey was conducted with 116 commercial irrigation farmers (family farms) from 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).

The aim of the socio-economic survey was to capture data regarding the existing knowledge levels, management practices, as well as beliefs and perceptions surounding salt management on irrigated farms. Beliefs and perceptions can override facts when influencing behaviour and adoption decisions (Leeuwis, 2004; Pannell et al*.,* 2006). For this reason, a summary of the key results is presented in this section to give behaviour change officers (BCOs) valuable insight, which could be used to plan and customise knowledge exchange and technology transfer interventions. The full complement of the study is available in Volume 3 of this WRC project (Barnard et al., 2020).

2.2 Demographics

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 socio-economic survey results in this specific study indicated that:

i. *Age:* The highest proportion of farmers were in the 31-40 and 41-50 age groups (28% and 29%, respectively). The median age was the 41-50 age group. Exceptions included that there were no farmers under 31 years of age in KZN sample, and that 13% of the respondents were in the 71 years and older group in the Breede River sample.

ii. *Land tenure:* The larger proportion of farms were owned by farmers. A relatively small proportion of the area was being leased (7% in the Breede River region, 31% in the Central region and 29% in KZN).

iii. *Size of farms:* The median area cropped under irrigation was between 100 and 200 ha, suggesting relatively good economic viability. In KZN, 86% of the respondents farmed more than 100 ha, while 67% owned more than 200 ha in the Central region sample.

iv. *Education levels:* At the time of the survey, most of the farmers had a diploma or higher qualification.

v. *Irrigation experience:* A larger proportion of the respondents (86%) had more than 10 years of experience in irrigation.

Based on the results above, the majority of farmers in the sample should be relatively well positioned to receive level one 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 two interventions could possibly be appropriate.

2.3 Baseline information

The socio-economic survey questionnaire was used to assess knowledge levels. The results presented below, therefore, reflect people's perceptions (and does not necessarily represent the soil classification/distribution in the case study regions).

Soils: In the Breede River and Central regions, 60% and 48% of the respondents respectively, indicated that soil depth was in the region of 1.1 to 2 m. In KZN, however, 47% of the respondents indicated that soil depth was between 0.1 and 0.6 m. Shallow soils indicate a higher susceptibility/risk to damage from salts and a need for more skilful management of irrigation. Most growers could report on soil texture, however, fewer could report on the soil form as per binomial soil classification system (85% in Breede River, 52% in Central and 41% in KZN did not have knowledge of the soil form(s) on their farms).

Presence and risk of salinity: Visible signs of salts was indicated by 63% of the respondents, 33% indicated having signs of a shallow groundwater table and 87% had some form of drainage installed (surface or subsurface).

Water source quantity: More than 70% of the farmers agreed that water quotas were adequate to meet both leaching and crop water requirements.

Identification of high-risk farms that are inherently susceptible or already being impacted by salinity or sodicity can help to direct behaviour change efforts, 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.

2.4 Knowledge levels/gaps

In this section, the farmers' responses were relatively consistent across the three regions. Hence, the data presented represents the average across the whole sample.

Salinity status: A large portion of farmers did not know their soil salt status. On average, 73% did not know the pH, while 85% and 87% did not know the electrical conductivity (EC) or sodium adsorption ratio (SAR) values for their soils, indicating a knowledge gap.

Critical threshold values of salt diagnostic parameters: More than 90% of the respondents across the three regions did not know the critical threshold values for EC and SAR. Similarly, more than 84% of respondents did not know the critical threshold values for calcium, magnesium and sodium.

Water source quality: Most farmers, except in KZN, agreed that water quality was monitored by water user associations, but few farmers could provide an EC value or indicate which quality class their irrigation water fell into, indicating a knowledge gap. In KZN 53% of farmers did not believe that water quality was monitored.

Considering that 63% of respondents indicated visible signs of salts on their farms, this knowledge gap should be a concern. Many farmers, however, commented that they did not need to know the exact numerical values or the critical threshold values of salt indicator/diagnostic parameters, since 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.

2.5 Practices

Leaching: A large proportion of farmers (58% in Breede River, 43% in Central and 88% in KZN) did not practice leaching.

Irrigation scheduling: On average, 9% of respondents indicated that they do not schedule irrigation, while 42% rely on experience. In addition, 60% of the respondents indicated that they did not consider salt management when making irrigation scheduling decisions.

2.6 Preferred information sources

In KZN, research stations, agricultural advisors (i.e. extension specialists) and soil laboratories were considered the most important and frequent sources of information. Farmers' days, electronic media and fertiliser company personnel also featured as important. For the Central and Breede River regions, agricultural advisors and fertiliser company personnel were considered as the most important sources of information. Soil laboratories, farmers' days and seed company personnel were also important, but more so for the Central region than in Breede River in the Western Cape.

2.7 Beliefs and perceptions

The five hypotheses listed in Table 2.1 were used to test beliefs and perceptions about salt management in irrigation. This information was considered important and relevant to the adoption decision-making process. The results highlight knowledge gaps and/or flawed perceptions and beliefs, which could inform the design of knowledge exchange and technology transfer initiatives.

Each hypothesis was tested via a set of statements or questions. Farmers were required to choose a response on a 5-point Likert scale (agree definitely, agree partially, neutral, differ partially or definitely differ) for each question/statement. These results are summarised in Table 2.1.

Table 2.1 Summary of hypothesis results

<table>
<tr><th>No</th><th>Hypothesis</th><th>Result</th></tr>
<tr><td>1</td><td>Farmers do not perceive salinity and sodicity as a threat</td><td rowspan="4">Failed to accept</td></tr>
<tr><td>2</td><td>Farmers do not understand causes of salinity and sodicity</td></tr>
<tr><td>3</td><td>Farmers do not have knowledge of preventative and corrective measures</td></tr>
<tr><td>4</td><td>The benefits of preventative and corrective measures do not outweigh the costs</td></tr>
<tr><td>5</td><td>The benefits of preventative and corrective measures do not outweigh the implementation effort</td><td>Accepted</td></tr>
</table>

These results suggest that the participating farmers adequately perceive the threat of salinity (H1) and also have sufficient knowledge regarding the causes (H2), as well as preventative and corrective measures for salinity management (H3). In addition, the sample of farmers appear to be satisfied that the benefits of salinity management outweigh the costs (H4). The only hypothesis that was accepted (H5) indicated that **farmers perceive the benefits gained does not necessarily justify the effort to implement salt management interventions**.

When testing for each hypothesis, farmers' responses to specific questions highlighted areas of uncertainty, disagreement or knowledge gaps. A summary of the responses to questions for each hypothesis is provided below (with the uncertainties and disagreements highlighted in bold):

Hypothesis 1: Farmers indicated that they perceive salinity and sodicity as a threat but **did not agree convincingly that soil infiltration will be reduced**.

Hypothesis 2: Farmers did recognise the causes of salinity and sodicity as poor irrigation management, use of poor-quality water, high soil surface evaporation, poor drainage and a rising water table.

Hypothesis 3: Farmers could adequately identify preventative and corrective measures as correct irrigation scheduling, use of salt tolerant crops and installation of artificial drainage.

Hypothesis 4: Farmers agreed that applying salt management practices will increase crop production and that managing a shallow water table was worth it, **but did not agree that salt management was inexpensive**.

Hypothesis 5: Farmers agreed that salt management practices could be tested on a small scale, that they could manage the salinity and sodicity practices on their own and that adjusting irrigation scheduling to manage salt was easy. On the other hand, farmers 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.

2.8 Discussion and conclusions

The acceptability of farmers' knowledge (or lack thereof) regarding the salt status of their soils, irrigation water and diagnostic parameters is debatable. Farmers suggested that they have advisory consultants to assist them, therefore there is less need for them to be knowledgeable on the specifics of the subject. For this reason, it is uncertain what the benefit may be of growing knowledge levels only, via behaviour change efforts. 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 farm or field level in a case study context is required to reassure or 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, or allowing farmers to learn from fellow farmers via farm visits and technical tours are possible pathways. 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.

CHAPTER 3. FUNDAMENTALS OF WATER MANAGEMENT

3.1 Introduction

Irrigation is strongly interlinked with the salt balance in the soil. Over-irrigation may cause groundwater tables to rise, bringing unwanted salts into the root zone. Use of poor-quality water for irrigation can load salts onto cropped areas. Irrigation water can also dissolve salt rich soil parent material, releasing and transporting salts and minerals. Depending on the type of irrigation system, the amount of water applied and the stage of crop canopy development, irrigation events may lead to excessive evaporation from the soil surface, resulting in capillary forces bringing salts closer to the soil surface. Conversely, good quality irrigation water and greater than normal irrigation applications can be used to leach harmful salts below the crop root zone, provided drainage is adequate.

Irrigation water is very important for increasing land productivity, but on the downside, it also carries unwanted or excess salts that will automatically be distributed in and over the field it is applied to. In order to reduce the quantity of salt coming from a specific source, it is important to reduce the amount of sub-quality irrigation water used. Reducing water quantity to the absolute minimum without harming the soil, crop and environment is embedded in the science of water management. It is important to be familiar with the principles of the soil water balance in order to understand the importance of its components, specifically the unproductive components of water losses, viz. evaporation, runoff and deep drainage. Barnard et al. (2017) reported that accurate irrigation scheduling could (i) reduce the amount of irrigation applied by utilising rainfall and shallow groundwater as supplementary water sources, (ii) minimise irrigation induced drainage, leaching and salt additions, and (iii) manage plant available water (matric and osmotic stress) to maintain optimum yields. Despite the advanced technology available to farmers and advisors, 80% of South African (Stevens et al., 2005) and 67% of Australian (Montagu and Stirzaker, 2008) irrigators do not use scientific (objective) irrigation scheduling. It remains a great challenge to change the behaviour of farmers, especially since Barnard et al. (2017) showed that farmers using subjective scheduling methods tend to over-irrigate and find it difficult to integrate water sources optimally. Barnard et al. (2017) concluded further that farmers can address some of the environmental problems associated with irrigation by adopting objective scheduling and reducing the leaching fraction.

The aim of this chapter is to provide guidance on irrigation scheduling through objective scheduling methods. Two objective scheduling methods were selected based on their world-wide practical application, i.e. crop coefficients and capacitance-based soil water technology. As background for the scheduling approaches, the soil water balance is summarised and contextualised within the soil water management boundaries. A section is also dedicated to two irrigation modelling tools, i.e. SAPWAT for planning of an irrigation project and SWAMP for practical modelling of irrigation applications for field crops.

3.2 Soil water balance

A thorough understanding of the soil water balance and the factors that influence it is essential to understand irrigation scheduling. The soil water balance for a specific soil volume (generally the depth of root zone = z) over a specific time period (t = daily, weekly or seasonally) can be mathematically described with Equation 3.1 and is diagrammatically represented in Figure 3.1 (Allen et al., 1998).

$$\Delta D_{(z)(t)} = I_{(t)} + \left(P_{(t)} - RO_{(t)}\right) - E_{(t)} - T_{(t)} + CR_{(t)} - DP_{(t)} \pm SF_{(t)} \tag{3.1}$$

Where: ΔD = change in soil water content for the root zone (z), which is soil water content at end of time period ($D_{(t+1)}$) minus soil water content at start of time period ($D_{(t)}$); I = irrigation over the specific time period; P = precipitaion over the specific time period; RO = runoff over the specific time period; E = soil surface evaporation over the specific time period; T = crop transpiration over the specific time period; CR = capillary rise over the specific time period; DP = deep percolation over the specific time period; SF = sub-surface flow over the specific time period .

Generally, the soil water balance is expressed in mm. For example if the root zone is 1.5 m deep, then the total mm of water in this soil depth at a specific time has to be be determined. This can be done using calibrated, indirect soil water content measuring equipment or by taking soil samples at 300 mm depth intervals. These samples are then weighed (representing the wet sample) and subsequently placed in an oven at 105°C, whereafter the sample is weighed again (dry sample). Equation 3.2 is then used to determine gravimetric soil water content (θ_g) at 300 mm depth intervals, which is then multiplied by the bulk density of the soil to determine the volumetric soil water content (θ_v, Equation 3.3). Volumetric water content therefore indicates the mm of water per mm soil depth (mm mm^{-1}).

$$\theta_{g(z=300)(t)} = \frac{wet\ soil\ sample_{(z=300)(t)} - dry\ soil\ sample_{(z=300)(t)}}{dry\ soil\ sample_{(z=300)(t)}} \tag{3.2}$$

$$\theta_{v(z=300)(t)} = \left(\theta_{g(z=300)(t)}\right)\left(bulk\ density_{(z=300)(t)}\right) \tag{3.3}$$

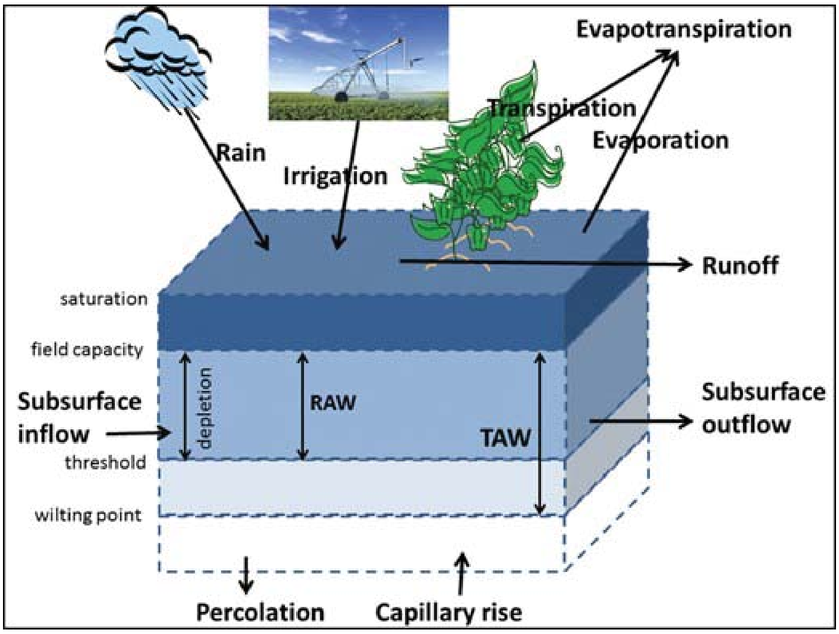

Figure 3.1 A diagrammatic representation of the soil water balance in the root zone of a crop (Allen et al., 1998).

Multiplying the volumetric soil water content with specific soil depth (in this case 300 mm) provides the total volume of water (mm) for the specific depth. Summation of all layers within the root zone then provides the total volume of water (mm) in the root zone at time t. In calculation of the remaining water balance components, 100 mm of water applied to or removed from 1 ha of soil that is for example 1.5 m deep (10 000 m^2) over time period t, is equivalent to 1000 m^3 ha^{-1} (0.5 m of water multiplied by 10 000 m^2).

Figure 3.1 shows that addition of water to a profile can be in the from rain, irrigation, lateral flow and capillary rise, while the loss of water is through evapotranspiration (transpiration and soil surface evaporation) and deep percolation. Runoff from the soil surface does not add to the soil water content in this block of soil in Figure 3.1 and is usually subtracted from rainfall. The amounts of rainfall, transpiration and soil surface evaporation are linked to the climate of the area, while capillary rise and deep percolation are mainly influenced by soil properties and water management of the irrigated and surrounding areas. For a given irigation system, unproductive losses occur through evaporation from the soil, runoff and deep drainage. Reducing these losses automatically renders more water available for transpiration, and the higher the transpiration, the higher the yield will be (Dlamini et al., 2016).

3.3 Soil water management boundaries

There are four important soil water boundaries for managing water and excess salts in soils. These boundaries can be best explained through the volumetric three phase system of soils as illustrated hypothetically in Figure 3.2.

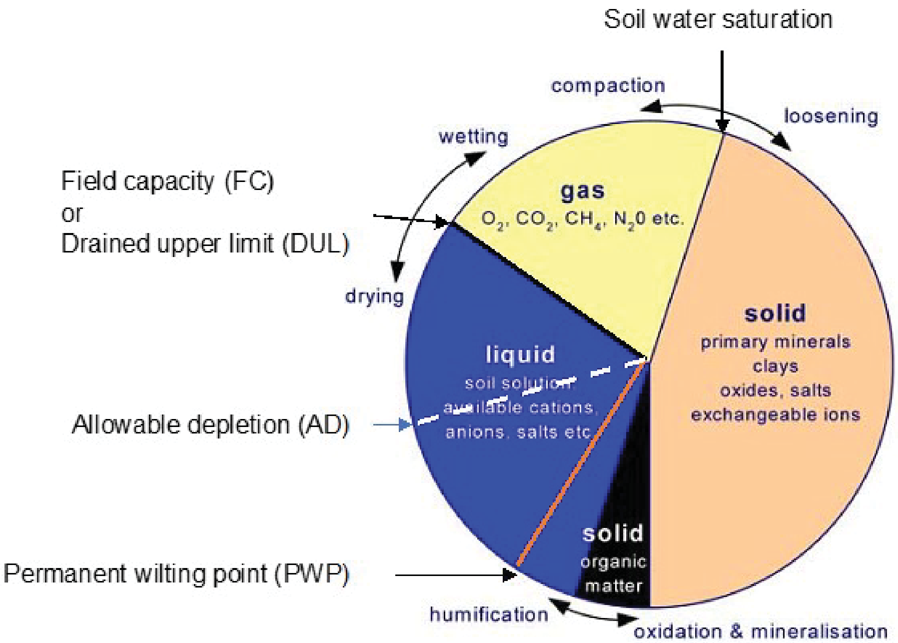

Figure 3.2 Hypothetical soil water management boundaries based on the volumetric fractions of the three-phase system of soils.

Firstly, field saturation boundaries represent conditions where almost all the air in soil pores is replaced by water. For example, the volumetric water content at saturation point (SP) for the hypothetical case will be 0.5 (fraction), 50% or 0.5 mm water mm^{-1} soil depth, assuming there is no dissolved air in the soil water. In reality, SP can be estimated from total porosity (TP) of the soil, which depends on the measured bulk density (BD), determined using either the clod or core method. Particle density (PD) is assumed to be 2.65 g cm^{-3}. When applying Equation 3.4 for a typical sandy soil with bulk density of 1.6 g cm^{-3} at Vaalharts, the result is a total porosity of 40%. Under stagnant groundwater table conditions (TP = SP), provision should be made for dissolved air that might vary between 1 and 7%. For example, the saturation point for the sandy soil will be 34% (40% pores minus 6% dissolved air). This value is also important in calibrating soil water sensors for managing groundwater tables to prevent waterlogging.

$$TP = \frac{PD-BD}{PD} \quad (3.4)$$

The second soil water management boundary is the drained upper limit (DUL), replacing the outdated "field capacity" concept (Hillel, 2004; Hensley et al., 2011). This water management boundary reflects on soil conditions where the internal drainage becomes insignificantly low after the soil was saturated and allowed to drain freely. In practice, it means that leaching can only commence when the soil water content is above the DUL. Irrigators should account for the deficit between the actual water content in the soil and DUL to estimate the amount of water required for leaching.

The DUL can be derived from silt-plus-clay content (Equations 3.5 to 3.8):

$$DUL = 0.43(X_1) + 0.0002(X_1)^2$$ Boedt and Laker (1985) (3.5)

Where: DUL = %; X_1 = silt-plus-clay percentage (fraction < 0.02 mm).

$$DUL = 0.005322(X_2) - 0.00979(X_3) + 0.124322$$ Streuderst (1985) (3.6)

Where: DUL = v v^{-1}; X_2 = CEC (me 100 g^{-1}) + clay percentage (fraction < 0.02 mm); X_3 = fine sand+silt percentage (fraction = 0.002-0.1 mm).

$$DUL = 0.0037(X_4) + 0.139$$ Van Rensburg (1988) (3.7)

Where: DUL = v v^{-1}; X_4 = silt-plus-clay percentage (fraction < 0.05 mm).

$$DUL = \frac{54.70(clay\ \%)}{24.53(clay\ \%)}$$ Van Antwerpen et al. (1994) (3.8)

Where: DUL = %; Vertic soils are excluded and equations are applicable to the sugarcane industry.

The third important water management boundary is permanent wilting point (PWP). This boundary reflects on the condition where most crops experience permanent wilting, associated with a soil matrix potential of approximately -1500 kPa (-15 000 cm or -15 bar) or soil water tension of +1500 kPa (+15 000 cm or +15 bar). This represents the point where water is held so tight by the soil that the plant cannot extract it, in other words, soil water is not available to the plant. The PWP can be determined in the laboratory using a pressure plate apparatus or it can be estimated with regression equations using easily measurable soil properties (Equations 3.9 to 3.12):

$$PWP = 0.00337(X_1) + 0.0187$$ Hutson (1986) (3.9)

Where: PWP = volumetric soil water content (v v^{-1}); X_1 = silt-plus-clay %

$$PWP = 0.3068(X_2) + 0.2183$$ Van der Merwe (1973) (3.10)

Where: PWP = volumetric soil water content (%); X_2 = silt-plus-clay % (fraction < 0.02 mm)

$$PWP = 0.00385(X_1) + 0.0125$$ Van der Merwe (1973) (3.11)

Where: PWP = volumetric soil water content ($v\ v^{-1}$); X_1 = silt-plus-clay % (fraction < 0.05 mm)

$$PWP = \frac{91.94\ (clay\ \%)}{135.34 + clay\ \%}$$ Van Antwerpen et al. (1994) (3.12)

Where: PWP = volumetric soil water content (%)

The fourth boundary is the allowable depletion managing boundary, also called "readily available water" (RAW) in the SAPWAT programme. A classic approach in irrigation scheduling is to use 50% of the volumetric space between the DUL and PWP as a rule of thumb for calculating the allowable depletion boundary. There are more advanced methods to estimate the allowable depletion as explained in Hensley et al. (2011). These methods are sophisticated and integrate weather, crop and soil as part of the soil-plant-atmosphere continuum. In this case, both the lower and upper limits of plant available water are dynamic and the difference between the two boundaries gives the profile available water capacity (PAWC) (Bennie et al., 1988), also termed "total available water" (TAW) in the SAPWAT programme. Typical values for drained upper limit, wilting point and total available water are given in Table 3.1 for different soil texture classes and can be used as a guideline.

Models like BEWAB and SWAMP are designed to make estimations of the PAWC (Van Rensburg et al., 2012). These models were developed from in situ measurements made at farms located in the central part of South Africa. These models can also be used to demonstrate how the build-up of salts, and thereby the increase in osmotic pressure, reduces plant available water (Van Rensburg et al., 2012).

Table 3.1 Typical soil water characteristics for different soil types (Allen et al., 1998)

Soil texture class	Soil water characteristics			Evaporation parameters	
				Water that can be depleted by evaporation	
	Drained upper limit ($mm\ m^{-1}$)	Permanent wilting point ($mm\ m^{-1}$)	Total available water (TAW) ($mm\ m^{-1}$)	Readily evaporable water (REW) or AD (mm)	Total evaporable water (TEW) (mm)
Sand	70-170	20-70	50-110	2-7	6-12
Loamy sand	110-190	30-100	60-120	4-8	9-14
Sandy loam	180-280	60-160	110-160	6-10	15-20
Loam	200-300	60-170	130-180	8-10	16-22
Silt loam	220-360	90-210	130-190	8-11	18-25
Silt	280-360	120-220	160-200	8-11	22-26
Silt clay loam	300-370	170-240	139-180	8-11	22-27
Silty clay	300-420	170-200	130-190	8-12	22-28
Clay	320-400	200-240	120-200	8-12	22-29

3.4 Crop coefficients as an atmospheric based irrigation scheduling method

The objective of scientific based irrigation scheduling methods is to provide in the crop water requirement for a specific irrigation cycle. This is quantified by indirect measurement of the crop water use through one of several available methods, one of them being the crop coefficient (K_c). The use of crop coefficients is probably the most common irrigation scheduling approach followed worldwide. Therefore, it is important to understand the theory behind this method. Crop coefficients are derived from the relation between actual evapotranspiration (ET_c, mm day^{-1}) and the reference evapotranspiration (ET_0, mm day^{-1}) and is described by Equation 3.13.

$$K_c = \frac{ET_C}{ET_O}$$ (3.13)

3.4.1 Reference evapotranspiration

The ET_0 can be measured directly using a Class A evaporation pan (not commonly used these days) or indirectly through the Penman-Monteith equation (Equation 3.14) (Allen et al., 1998). The Penman-Monteith equation includes meteorological variables such as air temperature, humidity, wind velocity and radiation – all variables that can be measured with a standard weather station installed in an area with clipped cool-season grass (Figure 3.3). Irrigation and Drainage Paper No. 56 (Allen et al.,1998) defines a reference crop as a hypothetical crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\, u_2)} \tag{3.14}$$

Where ET_0 = reference evapotranspiration (mm d^{-1}); R_n = net radiation at the crop surface (MJ m^{-2} d^{-1}); G = soil heat flux density (MJ m^{-2} d^{-1}); T = mean daily air temperature at 1.4 m height (°C); u_2 = wind speed at 2 m height (m s^{-1}); e_s = saturated vapour pressure (kPa); e_a = actual vapour pressure (kPa); $e_s - e_a$ = saturated vapour pressure deficit (kPa); Δ = slope of vapour pressure curve (kPa °C^{-1}); γ = psychrometric constant (kPa °C^{-1}).

Figure 3.3 Example of an automatic weather station.

3.4.2 Evapotranspiration

The actual evapotranspiration (ET_c) from a soil-crop-atmosphere continuum is comprised of two components, i.e. evaporation of water from the soil surface (E_S) and evaporation from the canopy surface via the stomata, referred to as transpiration (T). Irrespective the type of surface, three conditions are necessary for the process to occur and persist (Hillel, 2004). Firstly, there must be a continual supply of heat to convert liquid water to a gas. Secondly, there must be a continual removal of vapour from the soil-crop-atmosphere continuum. Thirdly, there must be a continual supply of water from the soil, roots and shoots to the atmosphere. The first two conditions are generally external to the soil and crop and are influenced by meteorological factors.

Concerning evaporation from the soil surface (E_s) as a sole process, it is clear that the third condition depends on the water content of the soil and the soil's conductive properties. The actual evaporation rate is determined either by the atmopheric demand, or by the soil's own ability to supply the water. In practice, just after a wetting episode, the soil will be able to supply water to meet the evaporative demand for a certain time period (Dlamini et al., 2016), mainly due to high hydraulic conductivity. As the soil water content decreases over the drying period, hydraulic conductivity will decrease to a rate lower than the atmospheric demand, especially in semi-arid environments. In such environments, E_s from a bare soil surface is approximately 1 mm day^{-1} in summer and 0.5 mm day^{-1} during winter. Depending on the type of irrigation system, E_s is a significant mode of water loss, in the region of 10% to 30% of the total water-use (Van Rensburg, 2010). Hence, controling E_s as an unproductive water loss is a major management focus under irrigation conditions. The E_s can be lowered through optimising mulching rates, plant density and irrigation frequency. The lower E_s and other losses of unproductive water, the more water is available for transpiration, providing the possibility to increase yield (Botha et al., 2012).

The rate of transpiration is influenced by crop density, height and age. The denser the canopy, the higher the transpiration rate of that crop, reaching a maximum value with a leaf area index value of approximately 3 to 6. Usually higher growing crops transpire more than lower growing crops, because of an increase in air turbulence in the canopy. Younger, immature crops transpire less than older, mature crops because of a lower canopy cover. Crops at the end of their active growing stage, where leaves start to turn yellow, also transpire less. Transpiration rates can vary from approximately 0.1 mm day^{-1} to around 10 mm day^{-1}.

3.4.3 Characteristics of crop coefficients (K_c)

As the crop grows from seedling to maturity, the leaf surface area changes, starting with a canopy cover of about zero (low) after germination, through full cover to eventually reach a lower level again at maturity. At low levels of canopy cover, transpiration levels are low and it increases as the canopy cover expands towards its maximum during the peak transpiration period. Transpiration decreases again after the physiologcal ripening stage when the crop moves into the drying-off stage. The K_c generally follows the trend of the canopy development and transpiration over the season. This relationship between canopy cover (percentage soil surface cover) and the crop coefficient, is represented by the FAO 4-stage crop growth curve (Figure 3.4). The curve subdivides growth and development of a crop into four stages. The initial stage is the period from planting to about 10% canopy cover; the development stage is from 10% canopy cover to about 70% to 80% canopy cover. The mid-season stage is from 70% to 80% canopy cover up to first signs of maturity where leaves start to turn yellow. Finally, the late season stage is the period between first signs of maturity and full maturity (Van Heerden and Walker, 2016).

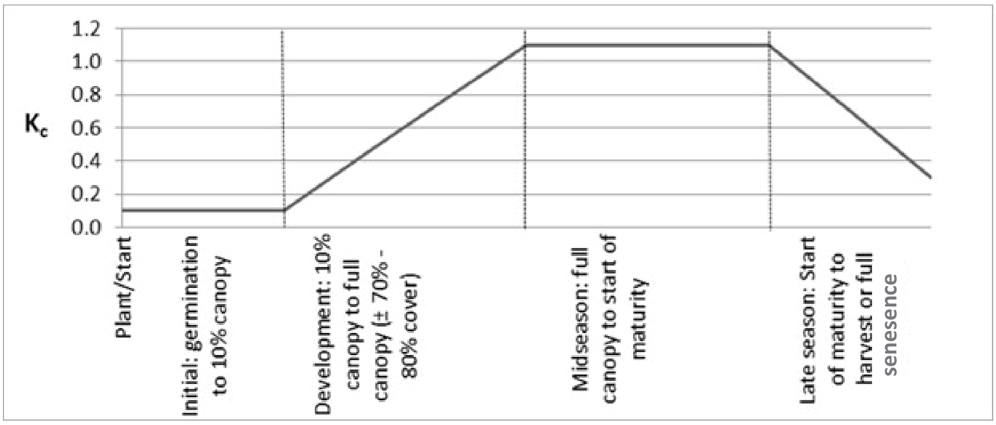

Figure 3.4 The FAO four-stage crop growth curve (adapted from Van Heerden and Walker, 2016).

3.4.4 Estimation of crop water use (ET_c)

As explained, the objective of obtaining K_c values is to use it for estimating crop water requirement for an irrigation cycle. With the understanding that K_c depends on the actual ET of a crop over its life cylce, it is clear that crop coefficients are site specific and will vary spatially and temporally according to water supply and demand of a specific crop. Nonetheless, measuring actual evapotranspiration in a crop field together with ET_0 provides the opportunity to calculate K_c for different soil-crop-atmosphere conditions. Some models, such as SAPWAT, make use of historically determined K_c data for different growth stages of crops. It is important to verify these coefficients at the site before recommending large scale use.

Figure 3.5 illustrates results of such a K_c-verification experiment where simultaneous measurements of ET_0 and ET_c were made on a daily basis. The K_c is obtained by growing a crop in lysimeters, consecutively measuring the daily water extraction and dividing it by the daily reference evapotranspiration (ET_c/ET_0) and then graphing the results (Figure 3.5) (Allen et al., 1998). A module to perform this procedure is included in SAPWAT4. Crop coefficients for a wide range of soil and climate conditions are available in the SAPWAT water management programme (Van Heerden et al., 2008).

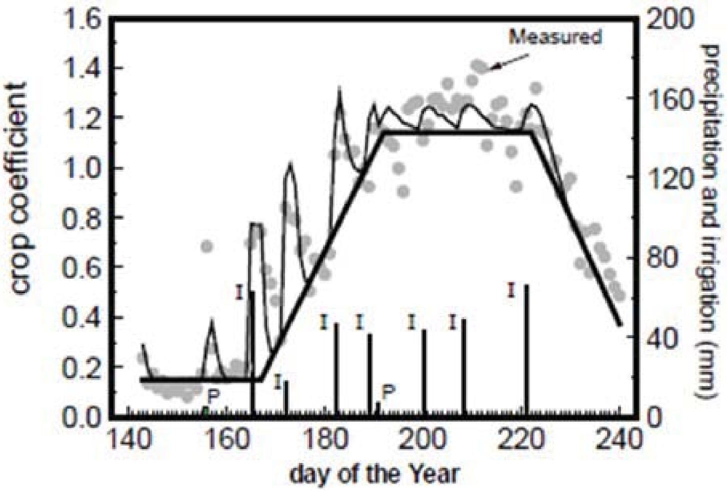

Figure 3.5 Verification of crop coefficient values of the four-stage crop growth curve (Allen et al., 1998).

To use K_c for estimating water use of a crop, Equation 3.15 can be applied (Allen et al., 1998; Van Heerden et al., 2008). The most accurate means of estimating crop irrigation requirement is to use daily values, but estimates can also be based on longer time periods, such as weekly or monthly calculations (d, days), in which case Equation 3.15 changes to Equation 3.16.

$$ET_C = (ET_0)(K_c) \tag{3.15}$$

Where: ET_C = mm day^{-1}; ET_0 = mm day^{-1}

$$ET_C = (ET_0)(K_c)(d) \tag{3.16}$$

Where: ET_C = mm; d = days; ET_0 = mm day^{-1}

Tabel 3.2 summarises the crop water use (ET_c) calculated using Equation 3.15 for the first two weeks of plant establishment of maize cultivated in the Luckhoff district. Weekly estimations are summarised in Table 3.3 for the same crop and site. According to these calculations, 668 mm of water is required for irrigation of maize. Water quality of the Orange River is good (EC = 20 mS m^{-1}) and therefore leaching is not required to control salts.

Table 3.2 An example of daily crop water use (ET_c) estimated from the reference evapotranspiration (ET_0) and crop coefficient (K_c): maize, medium grower (120 days) in the Luckhoff district

Plant establishment phase (days)														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
ET_0 mm day^{-1}	4	4	4.2	3	5	4	4	5	5	5	6	6	6.2	6
K_c	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
ET_c mm day^{-1}	0.4	0.4	0.4	0.3	0.5	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.6

Table 3.3 An example of crop water use (ET_c) estimations on a weekly basis over the season, derived from ET_0 and K_c values: maize, medium grower (120 days) in the Luckhoff district

Plant growth phase	**Week**	**ET_0 (weekly) mm day^{-1}**	**K_c (weekly)**	**ET_c (weekly) mm day^{-1}**
Plant establishment phase (week)	1	4	0.1	2.8
	2	5.6	0.1	3.9
	3	5.9	0.1	4.7
Vegetative phase (week)	4	7.6	0.3	18
	5	7.4	0.4	21
	6	8.6	0.5	33
	7	9	0.6	40
	8	7.3	0.5	26
	9	8.3	0.5	29
	10	9	0.7	44
Reproductive phase (week)	11	9	0.8	53
	12	10	0.9	63
	13	10	1	72
	14	10	1.1	79
	15	10	1.2	84
Ripening phase (week)	16	8.9	0.9	54
	17	10.1	0.6	41
	18	1.7	0.1	0

3.5 Irrigation scheduling using soil water sensor technology

Advances in technology of soil water sensors for irrigation scheduling stands on three pillars, i.e. the continuous logging probe, telemetry and web-based irrigation software.

3.5.1 Continuous logging probes

A great effort was made to improve precision and accuracy of continuous logging probes over the last decade. Recent advances in technology and basic soil physics have shown that capacitance-based soil water sensors have improved considerably since field experiments conducted by Everson et al. (1998). Gebregiorgis and Savage (2006) evaluated both the Deviner 2000 (capacitance) and PR1 (dielectric) probes in irrigation scheduling experiments with three types of cover crops at Cedara. The research showed that both instruments were sufficiently accurate to estimate irrigation requirements, provided they were properly calibrated. This led to the development of laboratory calibration techniques of capacitance probes by Van der Westhuizen and Van Rensburg (2011). Based on precision norms (R^2

= 0.99) and accuracy (RMSE = 0.002 to 0.005 mm mm^{-1}), they concluded that the sensor-specific calibration (EC-10 and EC-20 sensors) was excellent for coir over the full water content range, i.e. from dry to saturation. Another conclusion from this research was that each sensor should be calibrated individually. Hence, as an attempt to help the hydroponic industry with water scheduling, Van der Westhuizen and Van Rensburg (2013) developed a so-called rapid-calibration procedure.

Concerning capacitance-probe technology, it is clear that multilevel sensor probes are far more popular than single level sensor probes installed in fields under annual and permanent crops. However, multi-level probes pose challenges regarding calibration of individual sensors, because it is difficult to isolate the sensor from surrounding influences in the field. In an attempt to isolate the sensor from surrounding influences, Nhlabatsi (2010) developed an evaporation-desorption procedure to calibrate sensors of multilevel-sensor probes in the laboratory. Bello et al. (2019) used the procedure to develop texture specific calibration curves for HydroScout capacitance sensors. These authors concluded that volumetric water content was well predicted with the texture-specific calibration curves (RMSE = 0.001 mm mm^{-1}; D-index = 0.99), although it is preferable for sensors to be site-specifically calibrated.

Although capacitance probes have many advantages, the accuracy of their measurements depends on a sound understanding of the factors that affect the sensor output values (Bittelli, 2011). These factors include electrical conductivity (EC), clay percentage and type, dissolved salts in the soil solution, geometric properties, electronic features of the sensors and soil temperature (Robinson et al., 2003; Bogena et al., 2007; Evett et al., 2012). Soil temperature fluctuates significantly in the top 30 cm of the soil and affects diurnal patterns of capacitance probe measurements (Jones et al., 2005; Chanzy et al., 2012; Fares et al., 2016). The main reason for this is that temperature influences the dielectric permittivity of soil (Chanzy et al., 2012). Bello et al. (2019b) showed that at constant water contents, the response of the sensors to temperature can be classified into three stages: between 15°C and 38°C with no temperature effect on the readings (constant stage); between 3°C and 15°C, where the readings declined with temperature (falling stage) and 2°C to 3°C, where the readings were influenced but had no specific pattern (erratic stage). This pattern might differ between probe manufacturers.

An additional feature of most of the multi-level probes is that it can also measure temperature. These temperature sensors are reliable in terms of accuracy, precision and consistency in readings (Mjanyelwa et al., 2016) and temperature corrections can be made for the constant and falling stages (Bello et al., 2019b). In addition to probe quality indicators, such as accuracy and precision, the ideal soil water sensor should also be affordable, durable and simple to install (Gebregiorgis and Savage, 2006).

Salts can also influence the performance of sensors and the effect thereof needs to be characterised in salt affected soils. Unfortunately, none of the currently available capacitance probes have the ability to measure electrical conductivity.

3.5.2 Telemetry

In order to collect and convey data from the probe to the irrigation management software, some form of communication or telemetry is usually required. Telemetry systems employ a wide range of cellular, radio, satellite and other communication methods to send data and instructions to and from each measurement station in the field. The most common method for connecting farm telemetry to the Internet is via 2G or 3G cellular telephone modem (Figure 3.6). These units transmit data from capacitance sensors at fixed intervals (varying from 15 minutes up to one hour) sending it to a cloud server. Units have on-board memory, so when the signal is too poor to send soil moisture data at the appointed time the unit will still acquire the data and store it until the signal is re-established. Small solar panels keep the internal battery charged, avoiding loss of data.

Figure 3.6 Automatic solar powered 3G telemetry unit (Aquacheck SA).

Some systems make use of radio signal to communicate with a base station or hop signal from one node to another. The greatest challenge, however, is maintaining useable signal strength – doing so requires good planning and patience. Maximum useful range between radio transceivers is between 1.6 and 3.2 km with good line of sight between nodes, and perhaps 1.2 km in taller tree crops. The base station then relays the data to a central cloud-based data server via cellular telephone modem.

For farms located in areas where cellular telephone signal strength is marginal or non-existent and radio communication is not an option, roaming data loggers are available to collect probe data manually. Wireless communication facilitates quick and easy downloading of probe data in the field. Once data is uploaded to the cloud, the same irrigation management software as used by the automatic systems described above, can be used to manage probe data.

Real-time water monitoring facilitated by reliable telemetry allows growers to manage farm operations from their offices, tablets, and/or phones – saving them a great deal of time and ultimately money.

3.5.3 Web-based irrigation software

Raw probe data on its own is of little value and for this reason a software programme is usually required to present the data in an attractive and meaningful manner. The first software programmes were very modest with limited graphical capabilities. These programmes could do little more than just draw simple graphs of the measured data. One big drawback of these early PC-based systems was that each computer had to be visited in order to upload the latest software version. As computer technology advanced, many of the probe software programmes nowadays have quite sophisticated and powerful graphic interfaces with the ability to personalise the software, as well as import or export data from/to external sources. Technology has advanced so far that a grower can, for example, log in and view his probe data instantly via the internet, although he may be thousands of kilometers away from his farm. Many companies also provide access via various cell phone applications.

The main aim of irrigation software is to facilitate the decisions of when and how much to irrigate for a given soil-crop-atmosphere irrigation system by visualising probe data. Irrigation software aims to integrate important agronomic attributes essential for irrigation decisions, including irrigation system, soil type, crop type, active rooting depth and root zones. Most software programmes offer crop specific management parameters, factory probe calibration functions, integration with environmental parameters, including ET_0 data, integrated soil-water-balance models, rooting depth offsets, display of total root zone water status, individual sensor level water status, upper and lower plant available water management levels for the entire root zone, as well as for individual sensor levels. Some software programmes have options for a summary report of current soil water status, amount of water and days required to recharge the profile with real-time data display. A very important feature of the software programmes is that the data are accessible from any device at any given time as mentioned above.

Examples of typical graph-outputs from irrigation software are displayed in Figures 3.7a and b, courtesy of ProbeSchedule software and HydraWize Precision Farming Solutions. Similar types of graphs are also available for AquaCheckWeb. The graphs give insight into irrigation events, irrigation depth and level of water status relative to the upper and lower limits of plant available water (DUL and PWP). An experienced user can also derive important information regarding internal drainage, root activity, daily water-use stepping, active rooting depth and signs of crop water stress.

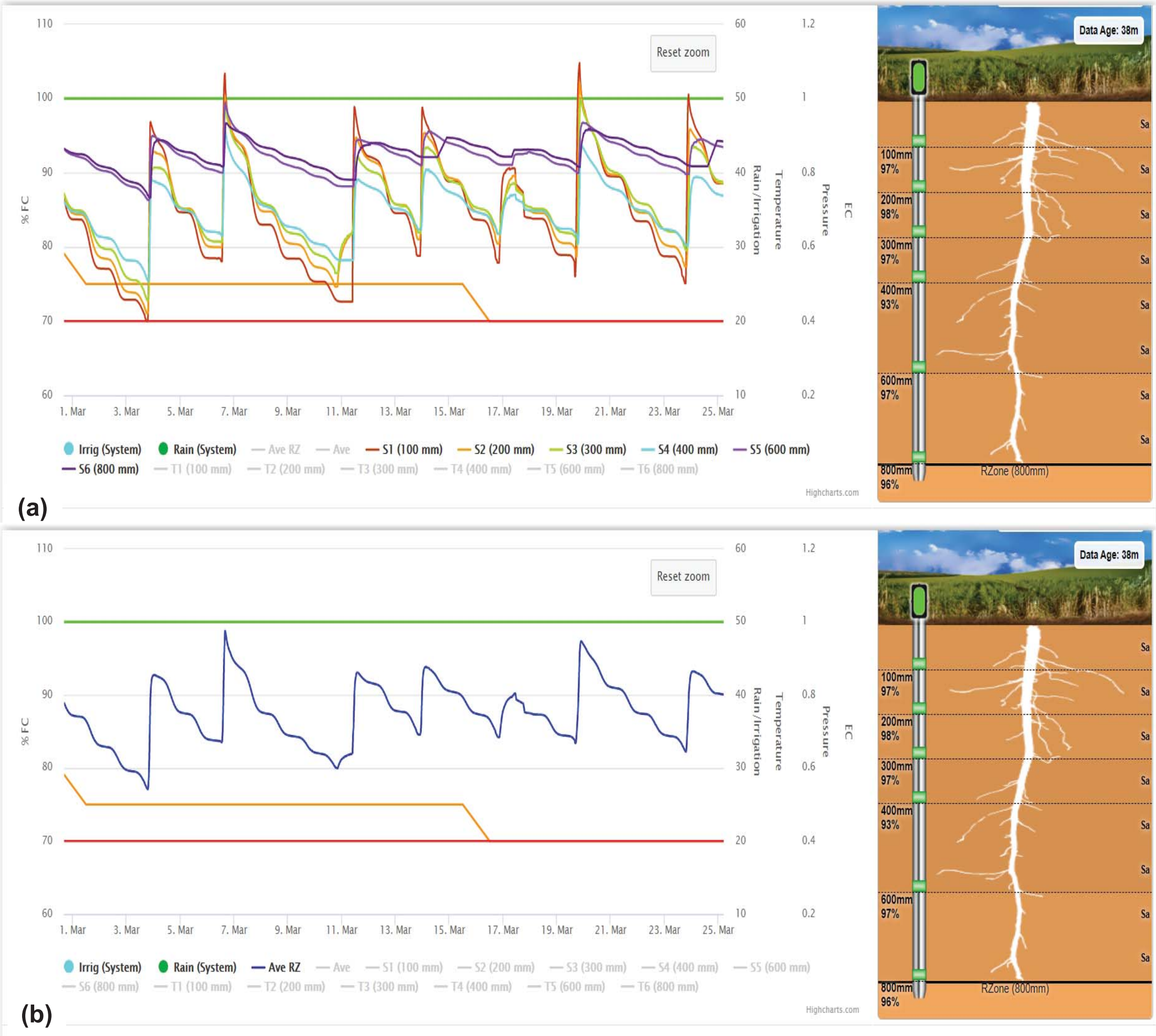

Figure 3.7 (a) Separate level graph with sensor status and active rooting depth and (b) average root zone graph with upper and lower limits of plant available water (graphs courtesy of ProbeSchedule software and HydraWize Precision Farming Solutions).

3.5.4 Practical considerations

From a practical viewpoint, three important questions need answering: How are probes installed? Where should probes be installed in a field? What should the positioning of the probes be relative to emitters?

Before installation, probe sensors should be tested in air (0% water content) and distilled water (100% water content) at 25°C (room temperature). Through this test, also called the laboratory-test confirmation, faulty sensors can be eliminated.

The primary principle for probe installation is to obtain continuous soil contact along the exterior surface of the probe. A good probe installation will have no air gaps at any position along the probe length. This is achievable by augering a shaft with a smaller or similar diameter to the probe, depending on the soil type. The shaft is then filled with water and left for a few minutes to equilibrate with the soil matrix. A steel probe, with similar dimensions to the electronic probe is used to smoothen the wall of the shaft, whereafter the probe is finally inserted. Some soils may require the addition of a slurry mixture to ensure good contact between soil and probe. Probes should be left for about 3 days to settle and then an in situ sensor response test is done as follows: The soil profile is wetted by inserting a single ring with a diameter of approximately 40 to 50 cm (similar to that used for determination of saturated hydraulic conductivity, Figure 3.8) into the soil, around 5 cm deep, with the probe in the centre of the ring. The ring is filled with water until about two pore volumes have been infiltrated. For example, a 1 m length probe and a soil with a porosity of 50% (pore volume is 0.5 $cm^3\ cm^{-3}$ corresponding to the saturation point) will require roughly 200 litres of water (2 x 0.5 $cm^3\ cm^{-3}$ x 3.14 x $[25\ cm]^2$ x 100 cm = 196 250 cm^3) to ensure a saturated soil profile over the measuring length of the probe.

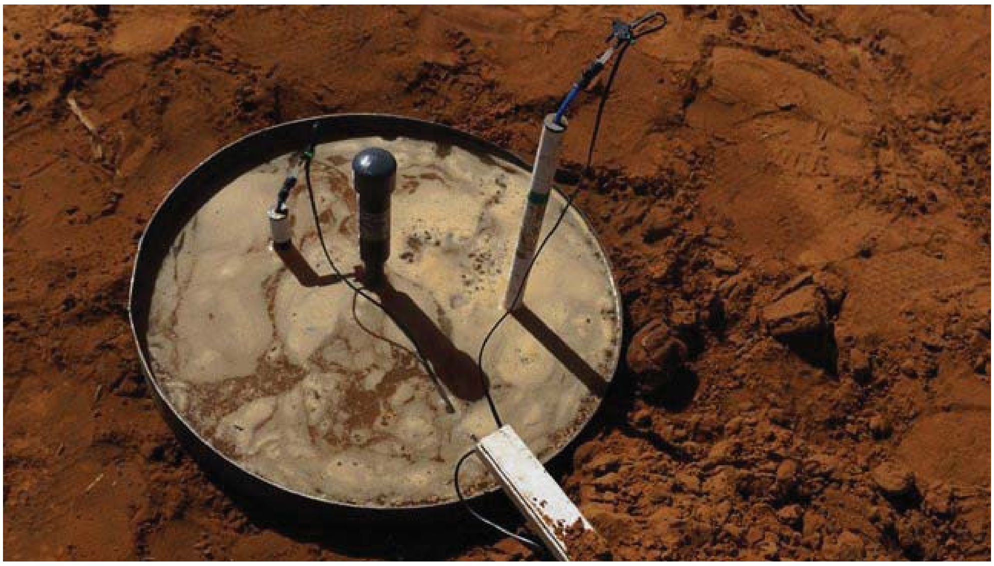

Figure 3.8 Testing sensor response after installation of a 1-m length probe. Soil was wetted up to saturation, requiring about 200 litres of water. In this example tensiometers were also installed.

Sensor readings should be very close to the saturation point of the soil, in this example it is 50%. It is very difficult to sample soil at saturation, therefore a calculation of the saturation point (SP) is required. The saturation point can be calculated from the bulk density of the soil (Equation 3.17). As an example, assume that the bulk density of a soil is 1.6 $g\ cm^{-3}$ and particle density is 2.65 $g\ cm^{-3}$:

$$SP = \frac{PD - BD}{BD} \tag{3.17}$$

Where SP = (2.65 g cm^{-3} -1.32 g cm^{-3})/2.65 g cm^{-3}
= 0.5 (v v^{-1}) or cm^{3} cm^{-3} or 50%

Probes can also be further calibrated using gravimetric soil water content determined from samples taken during the drying cycle. It is advisable to obtain the help of a specialist for calibrating each sensor.With respect to where to install a probe, the principle is that the probe location should represent a specific management area. A probe site should never be selected without considering soil variation across the field or block. Soil properties associated with water storage and movement, such as depth, clay content, organic matter, bulk density, saturated hydraulic conductivity and soil water management boundaries are all very important in identifying the ideal site. Management zones within crop fields can be obtained by electromagnetic induction techniques (Volume 2 of this project, Van Rensburg et al., 2020) or through grid sampling techniques. See examples of management zones for a centre pivot and a vineyard in Figures 3.9a and b, respectively. The best practice is to install a probe in each management zone, but it is not always feasible. In the case of the pivot example shown here, a probe should be installed at least in the red zone (usually where the profile is very sandy or shallow) as a guide to decide when and how much to irrigate. For the vineyard example, it is even more complicated because the farm is divided into blocks, with different cultivars, age and water management zones. Here blocks of similar cultivars or ages or irrigation system types can be grouped together and managed as separate units. However, also here the principle to follow in selecting the most appropriate site for soil water monitoring, is to choose a site where PAWC is at its lowest.

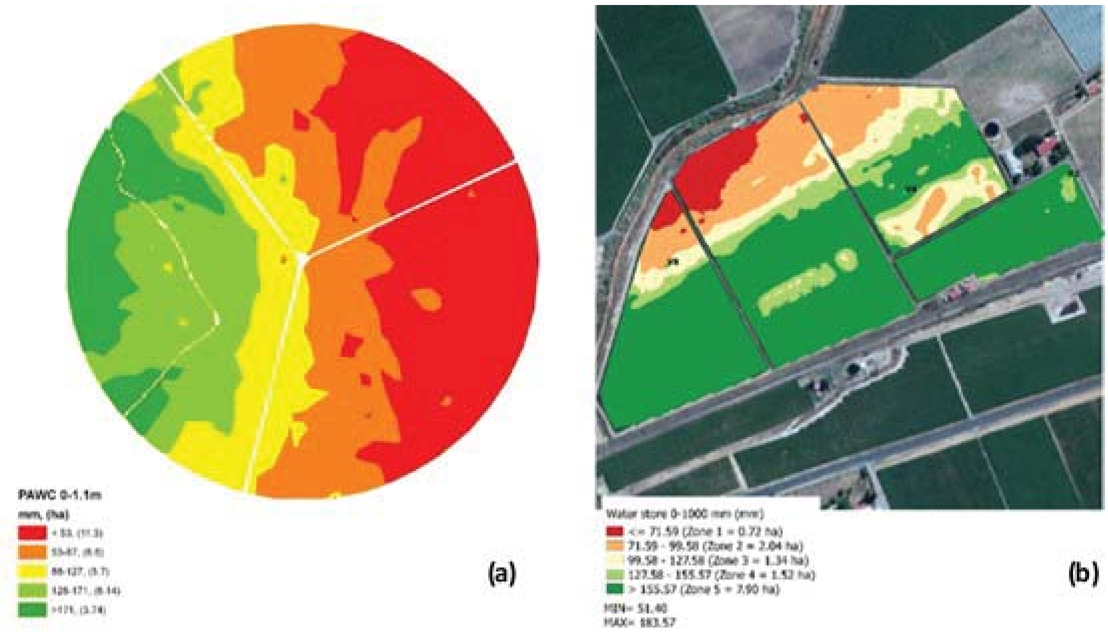

Figure 3.9 Examples of water management zones: (a) represents sugar cane under centre pivot irrigation, while (b) is a farm with several vineyards.

Probe position refers to the distance relative to the irrigation emitter and the probe. The general rule of thumb is to place the probe in the wetting zone of the emitter so that the probe can pick up any irrigation event if very small amounts are applied. For drip the distance between the emitter and probe should be between 10 to 15 cm and for micro, slightly further, but still in the wetting zone. For tree crops, the position should be a third inside the leaf drip zone of the tree. For smaller, younger trees the probe can initially be placed closer to the main stem and moved further away as the crop ages. For centre pivot irrigation systems, the probe should be as close as possible under the emitter and in the crop row always next to a strong actively growing plant. In crops such as maize and wheat always remember to remove or protect all equipment prior to harvest operations and in sugarcane it should also be protected against fire damage.

3.6 Irrigation planning and scheduling models

In South Africa several 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), MyCanesim (Singels and Smith, 2009) and SWAMP (Bennie et al., 1998; Barnard et al., 2013; Barnard et al., 2015). Any of these models can be used for irrigation planning and scheduling and allow for most of the processes governing water transport in the soil-plant-atmosphere system. The models do however vary in their complexity in terms of the information required for simulations. For the purpose of this report only SAPWAT4 and SWAMP will be briefly discussed.

3.6.1 SAPWAT 4

SAPWAT4 is an easy-to-use computer application for planning of irrigation water requirements (Van Heerden and Walker, 2016) and the programme is available from the author (psvh2017@outlook.com). An advantage of the programme is that it also caters for salt management. The amount of water required for leaching is also calculated. Unfortunately, the programme cannot be used to discriminate between different irrigability classes in terms of waterlogging. However, it combines long term average climate data, soil and crop characteristics, irrigation system characteristics and irrigation strategies to estimate crop irrigation requirements. Irrigation system designers also use this programme to design systems suitable for specific situations, taking into consideration the system application rate and cycle lengths between irrigations (Figure 3.10).

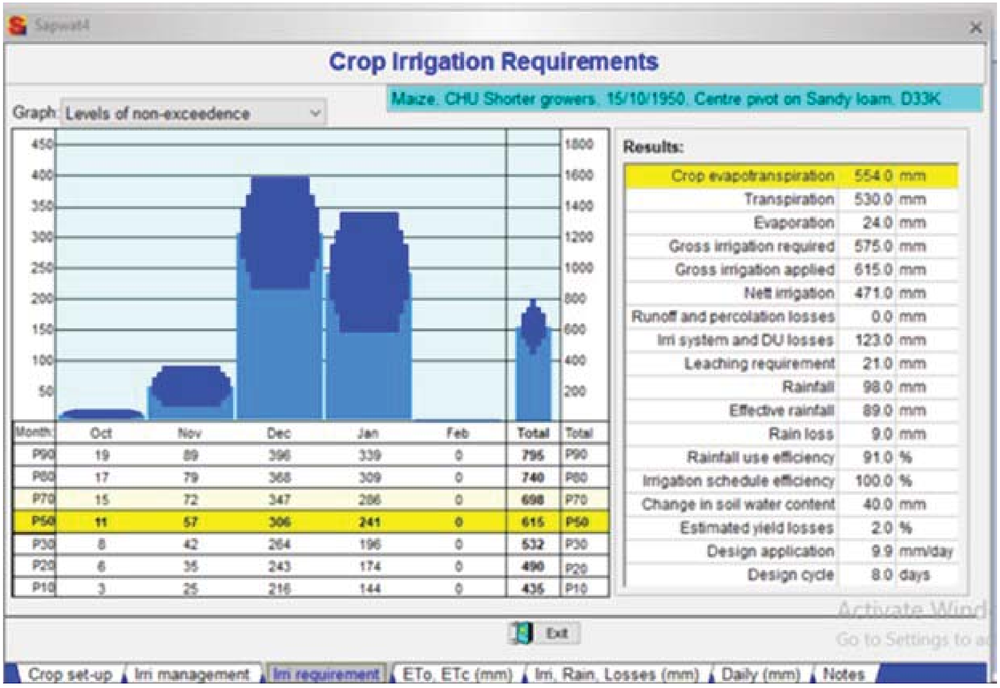

Figure 3.10 SAPWAT4 results screen for estimating irrigation requirements for short-grower maize planted during middle October under a centre pivot in the Douglas area.

Figure 3.10 shows the estimated monthly and total water requirements for maize. The histogram gives the average value and estimated irrigation requirements for different values of non-exceedance. The P-values in the table below the histogram indicates the levels of non-exceedance. The average (P50) shows a total crop requirement of 615 mm, which will not be exceeded in 50% of the growing seasons, while the 740 mm shown next to the P80 value indicates a water requirement necessary to give enough water for 80% of seasons. For planning and management requirements the P50 value is usually accepted. Rainfall use efficiency and irrigation scheduling efficiency is also shown. The aim should be to go for the highest possible rainfall use efficiency, because unlike irrigation water, it is free. On the right in Figure 3.10, irrigation water use and rainfall use efficiencies are shown. Crop evapotranspiration is subdivided into transpiration and evaporation. Gross irrigation requirement is indicated, as well as gross irrigation applied. The difference between these two values indicates effective precipitation use. System losses, as a result of inherent deficiencies, and leaching requirements are shown. In this case leaching requirement is based on soil water conductivity of 200 mS m^{-1}, a default value built into SAPWAT4, and the sensitivity of maize to salt content of the soil (threshold value = 170 mS m^{-1}). For the design of irrigation systems, the maximum daily application rate required, as well as shortest irrigation cycle lengths are shown.

The E_s of the top 30 cm soil depth is, however, influenced by prevailing atmospheric conditions, soil texture and water content. If the water content of the soil is at or near DUL, then the rate of E_s will be high. The E_s can be sub-divided into two phases, i.e. readily evaporative water (energy limiting stage) and the falling rate stage (Figure 3.11). If the soil is at or near to DUL, evaporation is limited to available atmospheric energy – referred to as readily evaporative water. The higher the atmospheric energy level, the faster evaporation will take place. When readily evaporative water has been depleted, the falling rate stage is reached, where soil surface evaporation tends to become zero. The dimensionless evaporation coefficient (K_r) is used when estimating irrigation requirements on the split K_c approach where transpiration and evaporation are included in the calculation as two separate variables in the equation. Soil surface evaporation of readily evaporative water varies from approximately 2 mm day^{-1} on sandy soils to around 15 mm day^{-1} on clay soils. Total evaporation of soil water is limited to about 6 mm day^{-1} on sandy soils and to 25 mm day^{-1} on clay soils (Allen et al., 1998; Van Heerden et al., 2008).

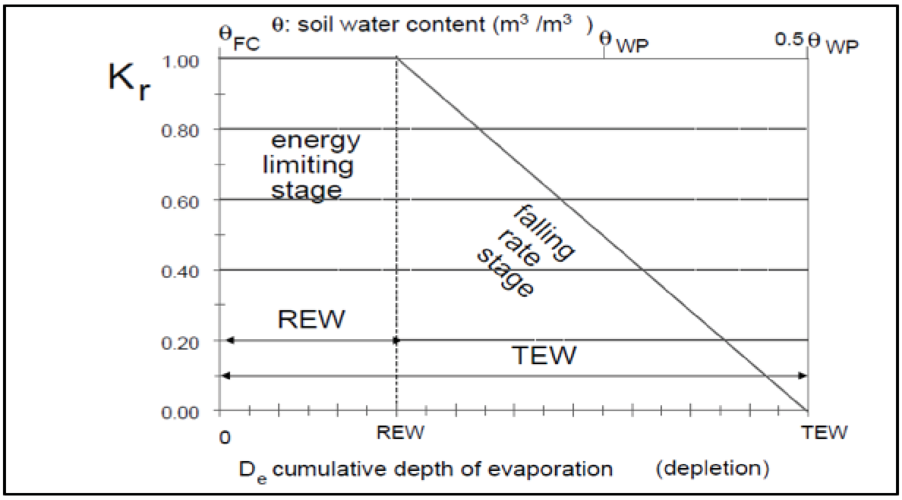

Figure 3.11 Soil evaporation reduction coefficient, K_r. The effect of the two stages, the energy limiting stage and the falling rate stage of soil surface evaporation (Allen et al., 1998) (REW = readily evaporable water; TEW = total evaporable water; K_r = dimensionless evaporation coefficient).

3.6.2 *Soil WAter Management Programme, SWAMP*

This model was first developed by Bennie et al. (1998) for rain-fed cropping systems to support field observations of water management in semi-arid central South Africa (Bennie and Hensley, 2001; Hensley et al., 2011). Table 3.4 provides a summary of processes simulated by SWAMP.

Table 3.4 Summary of processes simulated by the Soil WAter Management Programme, SWAMP (Bennie et al., 1998; Barnard et al., 2013; Barnard et al., 2015)

Infiltration	Rainfall and irrigation are infiltrated in a single event; hence, run-off must be subtracted from rainfall and/or irrigation amounts.
Salt addition	Salts added through rainfall and/or irrigation are determined by multiplying the volume of water with the corresponding electrical conductivity (EC) and a parameter that converts EC to salt content (kg salt ha^{-1} mm^{-1} water).
Redistribution of water	Macroscopic approach, i.e. mass transport of water through soil pores according to convection. Hence infiltrated water is distributed by means of the cascading principle.
Redistribution of salt and leaching	Redistribution and finally leaching of salt through miscible displacement (the solution is mixed by a combination of dispersion and diffusion) as a function of percolation from a soil layer is determined using leaching curves as described by Barnard et al. (2010).
Evaporation	Cumulative evaporation from bare soil surface is determined with the Ritchie equation, which is reduced with a factor equal to one minus the fractional shading in the presence of a crop.
Potential transpiration	Seasonal potential transpiration of a crop (refers to non-limiting water supply from soil) is determined using the approach of De Wit (1958), according to Hanks and Rasmussen (1982). Hence, seasonal potential transpiration is related to maximum biomass production with a crop specific parameter and the mean atmospheric evaporative demand (ET_0) over the growing season. Daily values are then determined with a generated four growth phase equation.
Root density	Increases in rooting depth and total length per unit surface area are determined using a crop specific root growth rate parameter and the distribution of roots among soil layers (root density) as proposed by Gerwitz and Page (1974).
Matric potential	A water retention function is used to determine the matric potential from volumetric soil water content simulations.
Osmotic potential	The relationship between soluble salt concentration and osmotic potential as proposed by Borg (1989) is used to determine the osmotic potential from EC_e simulations. EC_e is the electrical conductivity of a soil layer when saturated with water. Osmotic potential is therefore adjusted for the actual simulated soil water content experienced by plant roots.
Actual transpiration	Water uptake by plant roots is calculated according to Philip (1966), i.e. a dynamic physical continuum that is divided into a demand (potential transpiration) and supply component. The supply component is determined according to Bennie et al. (1988) using an algorithm that computes the water supply of a soil layer that depends on the rooting density, matric and osmotic potential and critical leaf water potential.
Maximum capillary rise	The approach of relating the maximum upward flux (capillary rise) from a groundwater table to a specific height above the water table (capillary fringe) as proposed by Malik et al. (1989) is used.
Water table uptake	The sum of daily root water uptake from each layer within the capillary fringe is taken as water table uptake when root water uptake for a specific layer is less than maximum capillary rise for that layer. When root water uptake for the specific layer is more than maximum capillary rise for that layer then water table uptake is equal to maximum capillary rise.
Salt addition through water table uptake	Salts added through water table uptake is determined by multiplying the volume of water by the electrical conductivity of the shallow water table and a parameter that converts EC to salt content (kg salt ha^{-1} mm^{-1} water).
Crop growth and yield	A popular approach of not simulating plant growth per se is used, i.e. water uptake is simulated and the seasonal uptake related to seasonal potential uptake to calculate the relative yield.

In 2003, adaptations to the model was made to include capillary rise from shallow groundwater tables by relating the maximum upward flux from a water table to a specific height above the water table (Ehlers et al., 2003). In 2013 Barnard et al. (2013) illustrated that the model could also be used in irrigated cropping systems to assess current on-farm water management practices by farmers. Furthermore, SWAMP was adapted successfully in 2015 to simulated water uptake of field crops grown in sand to sandy loam soils under osmotic stress (soil salinity). The model does not rely on the well-known salinity threshold and slope parameters (Barnard et al., 2015). Recently, SWAMP was adapted and algorithms included to determine irrigation requirements of field crops for different scheduling strategies using specific soil-crop-atmosphere conditions. With these adaptations the aim was to use limited inputs, i.e. information that does not require calibration, for example mean ET_0 over the growing season, soil depth, silt-plus-clay of each soil layer, initial soil water content and target grain yield. In addition, mostly default parameters (information that usually require calibration) were used and hence, no calibration is required by the user. The default parameters have been determined for fields crops grown on sandy loam soils in semi-arid central South Africa. Currently there is no commercial version available that includes the salinity and irrigation scheduling algorithms. It is anticipated that SWAMP will be available in Visual Basic (VB) for Microsoft Excel soon and can be requested at the Department Soil, Crop and Climate Sciences, University of the Free State (https://www.ufs.ac.za/natagri/departments-and-divisions/soil--and-crop--and-climate-sciences-home).

3.7 Summary

The aim of this section was to empower BCOs with knowledge on irrigation scheduling principles to conserve irrigation water, hence reducing the amount of salts that are irrigated over a crop field. Water conservation can only be achieved through the understanding of the soil water balance of a crop system. Unproductive losses of water are attributed to uncontrolled evaporation from the soil, runoff and deep drainage. Productive losses are mainly associated with transpiration, but also with controlled deep drainage where leaching is required when the salt content of the soil approaches the threshold osmotic value of the crop. Two scheduling approaches were presented, namely the application of the crop coefficient method and capacitance-based soil water technology. Both these approaches operate within the soil water boundaries that define the upper limit (drained upper limit) and the lower limit (permanent wilting point) of plant available water. Various aspects of the crop coefficient method were explained, i.e. reference evapotranspiration, actual evapotranspiration, characteristics of crop coefficients and estimation of crop water use. With respect to irrigation scheduling with capacitance technology, aspects such as advances in soil water probe technology, telemetry and web-based irrigation scheduling software, were discussed. Practical considerations regarding how and where to install probes in the crop field, as well as positioning of probes relative to emitters were also covered as guidelines. Lastly, two models were included in this chapter as part of the level one support system – SAPWAT that forms the basis for crop coefficient scheduling and water management planning, as well as SWAMP that follows a pragmatic irrigation scheduling approach.

CHAPTER 4. FUNDAMENTALS OF APPLIED SALT MANAGEMENT

4.1 Introduction

Apart from irrigation scheduling (Chapter 3), BCOs need to have knowledge of nine pointers that will enable management of salts in irrigated fields, these include quality of irrigation water, suitability of soils for irrigation, irrigation systems, drainage systems, sources of salts, salt thresholds for soils, salt tolerance of crops, monitoring of salts and leaching. Each of these pointers are discussed with the aim that the information serves as a guide for decision making on salt management at a practical level.

South Africa, as many other countries, experience a water shortage relative to available land for irrigation. Water shortages will increase in the future due to poor quality drainage water from urbanised, industrial and irrigation areas that enters our major river systems (Du Preez et al., 2000). In 2017, the 1996 irrigation water quality guidelines were revised into a software-based decision support system (DSS), allowing for a risk-based approach and more site-specificity (Du Plessis et al., 2017). This software is used to assess quality of irrigation water with regards to the effect that different constituents have on soil quality, crop yield and quality, as well as irrigation equipment. A Tier 1 assessment with this DSS represents a rapid “conservative” irrigation water quality assessment. With Tier 2, the user can choose between selectable site-specific conditions. According to Du Plessis et al. (2017) this “provides 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”. As a software-based DSS, computer skills are required.

4.2 Soil sampling for salt monitoring

Soil sampling techniques form the basis for determining distribution of salts in a crop field. Fortunately, soil sampling for nutrient sampling is well establish in the literature (Steenekamp, 2019) and the same principles can be adopted for salt monitoring. However, Steenekamp (2019) was concerned about the inconsistent use of terms and concepts throughout literature, and introduced a flow diagram (Figure 4.1) wherein the terms “approach”, “method”, “design” and “pattern” was used to provide clarity on the different stages of deciding how and where to sample soils. Accordingly, two approaches were identified, i.e. a traditional and a site-specific approach. These approaches are discussed in more detail in the following sections.

4.2.1 Traditional sampling approach

Soil survey sampling in South Africa, is reported by soil unit and per soil type. The traditional sampling approach is to make use of a whole-field composite sampling method where many selectively random samples are taken (Figure 4.2). The term “selectively random”, means that only relevant areas that represent most of a field are selected for sampling. Sometimes a field is divided into smaller sections and each section is sampled separately, referred to as stratified random sampling. A systematic sampling design in the form of a zigzag pattern can also be followed (Franzen and Cihacek, 1998; Peters and Laboski, 2013).

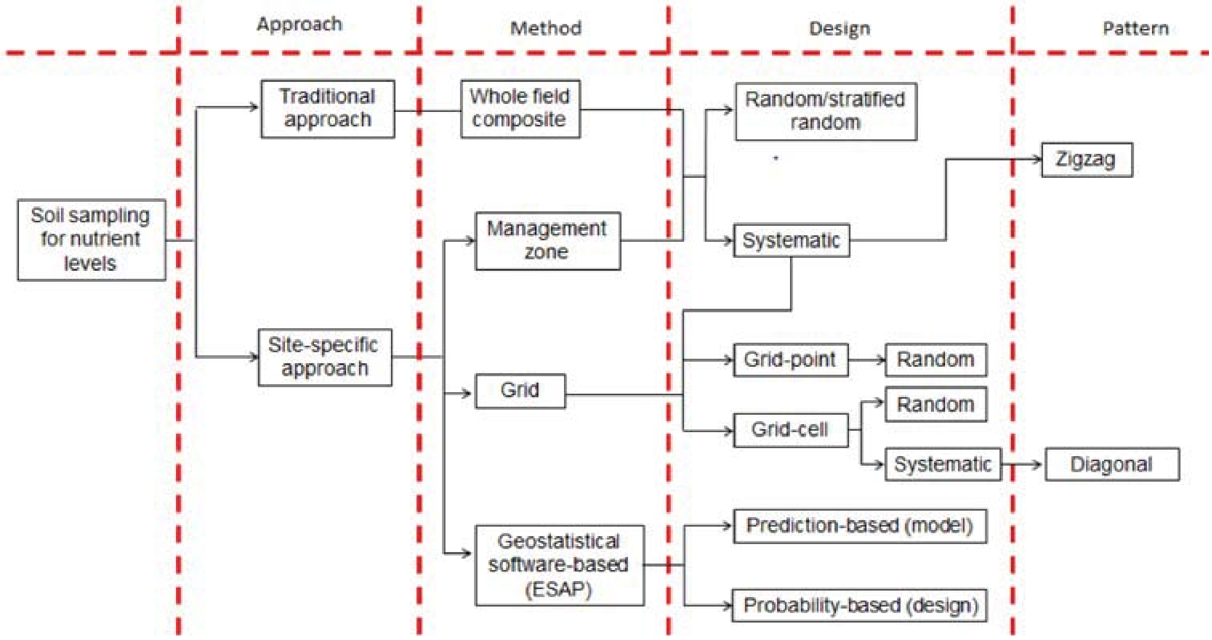

Figure 4.1 Flow diagram developed from literature showing approaches, methods, designs and patterns with respect to soil sampling for determining plant nutrient or salt levels (Steenekamp, 2019).

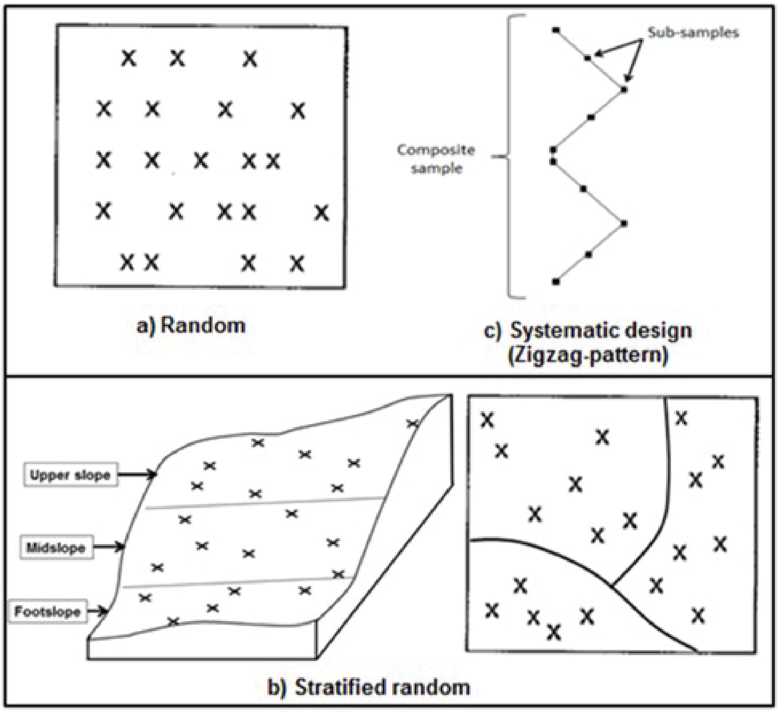

Figure 4.2 Illustration of a) random, b) stratified random and c) systematic designs in the traditional sampling approach (Franzen and Cihacek, 1998; Peters and Laboski, 2013).

Composite sampling involves gathering and mixing individual samples from various sampling points over a field or section of a field to form a single homogenized sample (Sheppard and Addison, 2007). The average conditions that exist in the sampled area are then represented by the composite sample and the analysis results are used to make a single recommendation for the whole field or a section of it (EPA, 2005; Walworth, 2011; Peters and Laboski, 2013).

The main advantage of the whole-field approach is the relatively low cost involved, since only one sample is analysed to represent a whole field (Franzen and Cihacek, 1998). Unfortunately, one particular disadvantage is that extremes are sometimes not detected due to the diluting effect when soil samples are composited (EPA, 2005).

4.2.2 Site specific sampling approach

4.2.2.1 Grid sampling method

The grid sampling method involves sampling soils systematically at fixed intervals (Jones et al., 2014) and each sample is analysed separately (Walworth, 2011). Two sampling designs stem from grid sampling, namely grid-point and grid-cell sampling (Figure 4.3). In the design of grid-cell sampling, one or multiple samples are randomly or systematically collected throughout a cell to prepare a composite sample. In grid-point sampling, it is recommended that samples be taken within a 3 to 6 m radius of the grid point (Franzen and Cihacek, 1998).

Regarding grid density, grid spacing should be determined after considering field uniformity (Franzen and Peck, 1995). When creating maps of soil properties or variable nutrient applications, the closer the grid spacing the more reliable the interpolation and correlation between sampling points (Knowles and Dawson, 2018).

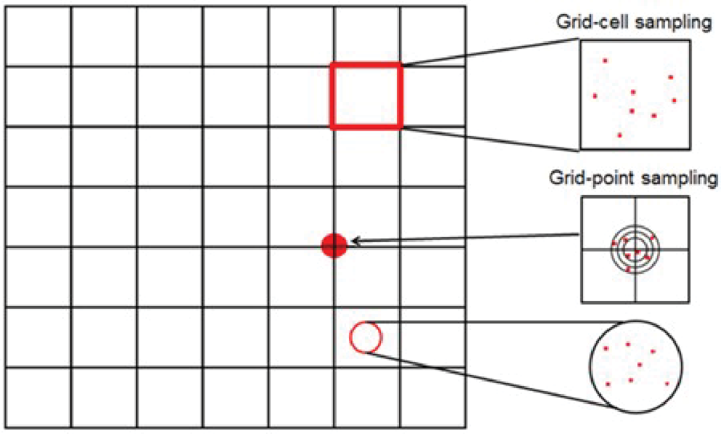

Figure 4.3 Illustration of the difference between grid-cell and grid-point sampling design (Jones et al., 2014; Rains et al., 2016).

4.2.2.2 Management zone sampling method

The variation in salt levels over fields is the motivation behind the use of management zone sampling, also termed directed soil sampling. Different soils are divided into distinct zones that can be sampled and managed separately (Dinkins and Jones, 2008). Once management zones for a specific field have been identified, the sampling design within each zone can be random or systematic (James and Wells, 1990; Peters and Laboski, 2013).

Differences that are useful in delineating management zones in a field include inherent factors such as soil texture, drainage, depth and colour, as well as slope. Other forms of variability are caused by management, for example crop history, yield, fertilisation and land shaping (Jones et al., 2014; Knowles and Dawson, 2018). Sometimes information collected by technologies of precision agriculture are also implemented to evaluate the spatial distribution of various factors that influence nutrient availability to identify uniform management zones (Ferguson et al., 2007; Dinkins and Jones, 2008; Peters and

Laboski, 2013). Such resources include topography or digital elevation maps, soil survey maps, yield maps, EC_a measurement maps, as well as aerial images and normalised difference vegetation index (Ferguson et al., 2007; Dinkins and Jones, 2008; Peters and Laboski, 2013; Jones et al., 2014).

4.2.2.3 Geostatistical software-based sampling method

Geostatistics is a tool that implements information on spatial variability through the detection, estimation and mapping of spatial patterns of soil or plant variables (Haberle et al., 2004). Soil apparent electrical conductivity (EC_a) measurements are a type of supplementary sensor data frequently used to develop soil sampling schemes to identify where to sample soils (Heil and Schmidhalter, 2017) and to help identify, quantify and predict various soil or crop properties (Corwin et al., 2010).

The geostatistical software, such as ESAP, uses EC_a data as input for electrical conductivity modelling (Amezketa, 2007) and is useful in the improvement of sampling network efficiency to assist researchers in obtaining the maximum amount of information from the smallest number of soil samples (Yates and Warrick, 2002). The software uses EC_a data to direct soil sampling as a means of characterising spatial variability of those soil properties that correlate with EC_a at a particular study site. Characterising spatial variability with EC_a-directed soil sampling is based on the notion that when EC_a correlates with a soil property or properties, the spatial EC_a information can be used to identify sampling locations based on the degree of variability in EC_a measurements (Corwin et al., 2010). Currently, two EC_a-directed sampling designs are used, i.e. prediction-based (model) sampling and probability-based (design) sampling. An example of prediction-based sampling is depicted in Figure 4.4 for a sugar cane field under a pivot and dryland conditions. In this case twelve sampling points were predicted and georeferenced for actual sampling of soils to be analysed for dissolved salts.

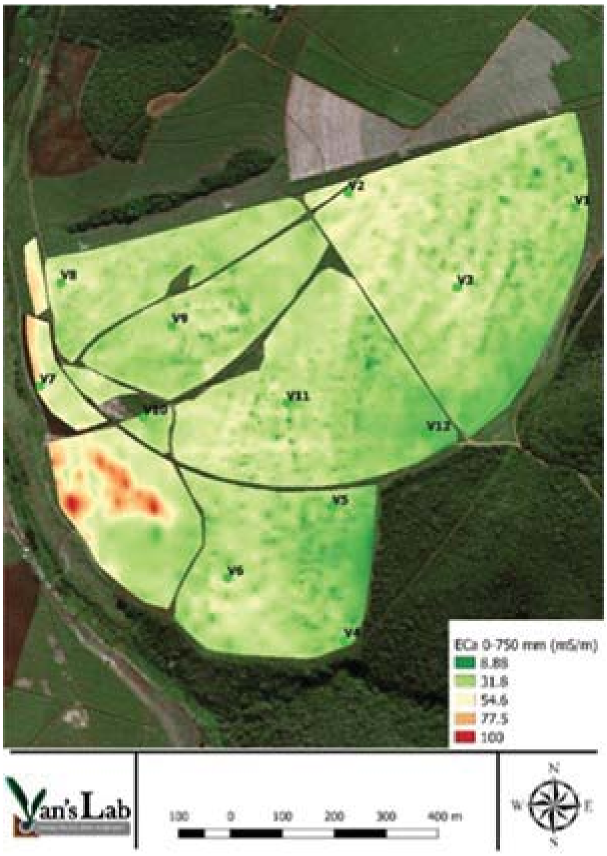

Figure 4.4 Illustration of modelled sampling points in a crop field under sugarcane (courtesy: Van's Lab).

4.2.3 Choosing a suitable site-specific sampling method

The reasons for choosing a particular site-specific sampling method are summarised in Table 4.1. These reasons can be used as a guide when deciding which method to choose, depending on the objective of sampling and available resources.

Various motivations exist for choosing a grid sampling method, these include when investigating sodium adsorption ratio (SAR), exchangable sodium percentage (ESP) and when past management has significantly changed salt levels of the field. A disadvantage is that grid sampling is more time consuming and expensive due to the large number of soil samples that need to be collected and analysed. However, occasionally there are patterns in soil ions that can only be detected with grid sampling, since it ensures better coverage of the field if the grid is dense enough (Ferguson and Hergert, 2009).

Table 4.1 Reasons for using grid sampling, management zone sampling or geostatistical software-based sampling (ESAP-RSSD)

Grid sampling [a]	**Management zone sampling** [b]	**Geostatistical software-based (ESAP-RSSD) sampling** [c]
Unknown field history. Can provide a soil database that can be used for many years. Ensures good coverage of the field. High fertiliser application rates in the past. History of manure application. Allows variable rate gypsum or lime application. Merger of individual fields with different cropping histories. Requires a lower level of interpretive skill compared to zone and RSSD sampling.	Unknown field history. Spatial information sources available. Clear relationship between landscape and yield data or aerial images. Investigation and mapping of soil calcium, magnesium, sodium and pH. Allows variable rate gypsum and lime application. High in-field variability. Long cropping history. Zone delineation is validated by experience of the field. Less expensive than grid sampling.	Gathering EC_a data with EMI sensors is fast, easy and relatively inexpensive. Large volumes of reliable EC_a data available. Potential spatial variability determination of soil properties that influence EC_a. RSSD allows assessment of spatiotemporal changes in soil properties. Automatic selection of sampling points saves time and effort. Number of samples needed for calibration is much lower than for grid sampling. RSSD permits delineation of site-specific management units that can be managed separately.

[a] Franzen & Cihacek, 1998; Bouma et al., 1999; Ferguson and Hergert, 2009; Jones et al., 2014; Rains et al., 2016
[b] Franzen & Cihacek, 1998; Ferguson et al., 2007; Dinkins and Jones, 2008; Ferguson and Hergert, 2009; Jones et al., 2014
[c] Corwin et al., 2003; Corwin and Lesch, 2005; Amezketa, 2007; Adamchuk, 2010; Corwin et al., 2010; Doolittle and Brevik, 2014

With regards to zone sampling, one main consideration for choosing this method is that it is much less expensive than grid sampling. The number of soil samples taken is greatly reduced because individual samples in a zone can be mixed to form one or a few composite samples (Dinkins and Jones, 2008) thereby minimizing laboratory costs (Rains et al., 2016). However, to apply management zone sampling, the soil sampler or supervisor requires more interpretive skills and a higher degree of soil and crop knowledge to identify sampling locations, compared to grid sampling. It takes time to review resources that are spatially variable. Aerial images or topography maps are useful to identify spatial patterns and decide on management boundaries and sampling locations (Franzen and Cihacek, 1998).

Sampling based on geostatistical software modelling, specifically ESAP-RSSD that uses EC_a data as input, holds many advantages. This process is cost effective (Amezketa, 2007), since fewer samples are needed for soil property calibration than with systematic grid sampling. The mobile equipment used for the gathering of EC_a data allows fast and easy measurement. Furthermore, such a survey provides large volumes of reliable EC_a data that is suitable for ESAP-RSSD modelling to select calibration sites (Corwin et al., 2010; Doolittle and Brevik, 2014). A further advantage of using EC_a data to identify sampling locations, is that the spatial variability of the variety of soil properties that influence EC_a could potentially be established. Unfortunately, a greater level of technical knowledge is required for ESAP-RSSD compared to other sampling designs, but software is available (ESAP) that significantly reduces the statistical expertise required (Corwin et al., 2010).

4.3 Suitability of soils for irrigation

The cost of developing an area for irrigation is high and therefore it is important that the area under consideration be evaluated in terms of the proposed development. Irrigation causes marked changes in land resources and influences changes in the physical, chemical and biological characteristics of the soil. Therefore, it is important to take into account as many of the potential changes as possible during the evaluation of land areas for irrigation development.

The soil-crop-water system is complex and embodies numerous resource components that need to be integrated during irrigation development. A multi-disciplinary approach to the assessment of land for irrigation is therefore essential. Although emphasis is placed on soil aspects, it is essential to remember that the evaluation is of the "land", and not the soil in isolation. All aspects of the environment need to be considered, including soil, climate, water source, water quality and location, among others. A multi-disciplinary team may include soil scientists, agronomists, horticulturists, engineers and irrigation designers, and they have to keep all factors in perspective and integrate them. In addition, agricultural economists, and for large irrigation schemes also sociologists and political scientists, will have input in the greater project plan.

Consequences of incorrect selection of irrigation areas could be disastrous. Inappropriate selection of land for irrigation could lead to waterlogging or salinisation, rendering those areas unfit for continued irrigation. Therefore, in the case of virgin soils or soils that were uncultivated for more than ten years, authorization by government (plough certificate) is of utmost importance before any irrigation development can commence. The person responsible for the soil survey has to be registered with the South African Council for Natural Scientific Professions as a Certificated or Professional Natural Scientist, practising in Soil Science. The soil scientist will conclude on the irrigation potential of the land, categorising the soil according to five classes that will direct management of the soils in terms of irrigation.

4.3.1 Suitability assessment

A stepwise interactive procedure, discussed below, is recommended to identify land and water resources for potential irrigation development. It is advisable to start on a broader scale, looking at wider areas with less detailed mapping, and then move progressively to greater detail in mapping and planning procedures. Work effort is then progressively concentrated on the potentially more promising areas, excluding areas of lower potential.

The stepwise procedure proposed by Hensley and Laker (1980) is comprehensive and well suited to planning irrigation development. It can be used effectively as a framework for soil survey aspects and water evaluation. The most important soil related components are summarised below:

i. Preliminary investigation (broad scale 1:100 000 to 1:250 000) those areas that warrant more intensive investigation are identified. Important to the soil scientist, are the areas that can be serviced with water.
ii. Intermediate investigation (1:50 000 scale) is directed at identifying the dominant soil forms and families.
iii. Detail investigation (1:10 000 scale or better) is directed at detailed scale soil, land and irrigation potential surveys. It is performed for detailed planning, management and implementation programmes. It is important to identify all soil and water parameters having practical significance to development and future management. During this phase it is important to compile detailed soil characteristics, irrigation potential and crop suitability reports and maps. Advice should be given on leaching of salts, amelioration, drainage and reclamation if required, to engineers, plant scientists and agriculture economists.
iv. For larger irrigation projects economic analyses and sociological and health-related factors may require inputs from soil, water and land aspect.
v. Detailed engineering design require considerable soil related inputs.
vi. Implementation and monitoring of the irrigation project should be carried out with soil related limitations clearly in mind.

4.3.2 Procedure for detailed soil and irrigation potential assessment

The most important soil related components to consider include (but are not limited to) the following:

Minimum site properties to be recorded at each observation site:

i. Topography, terrain unit and slope
ii. Micro relief, rockiness, erosion degree and type, flooding hazard, compaction, etc.
iii. Depth and effective depth
iv. Evidence of root and water impeding layers
v. Parent material
vi. Soil form/family
vii. Presence and depth of any water table
viii. Evidence of surface crusting

For each horizon, the following should be recorded:

i. Texture: Field estimate of clay percentage and dominant sand grade (confirm with laboratory analysis)
ii. Soil structure

iii. Soil colour
iv. Extent and colour of mottling
v. Presence of lime and gypsum
vi. Mechanical limitations

Minimum soil chemical analysis per sample and calculations for assessment of salinity, sodicity, and alkalinity:

i. Evidence of root and water impeding layers
ii. Electrical conductivity of the saturation extract (salinity hazard and determination of threshold values for salt sensitive crops)
iii. Soluble cations (minimum: sodium, calcium and magnesium) of the saturation extract to calculate sodium adsorption ration (SAR)
iv. Soluble anions (minimum: chlorine, sulphates) of the saturation extract
v. pH (water)
vi. Exchangeable cations (minimum: sodium, calcium, magnesium and potassium)
vii. Cation exchange capacity to calculate exchangeable sodium percentage (ESP)

Soil chemical analysis for fertility assessment:

i. Phosphate status
ii. Potassium status
iii. Acidity/alkalinity (pH)
iv. Lime/gypsum requirement
v. Additional special crop specific requirements

Minimum soil physical analysis per sample:

Particle size distribution, minimum clay, silt and sand (at least 3-fraction, but preferably 7-fraction analysis)

Minimum soil physical properties per map unit:

i. Available water capacity
ii. Soil infiltration rate

Water quality assessment:

i. Electrical conductivity
ii. Cations: sodium, calcium, magnesium (to calculate SAR), potassium, and boron
iii. Anions: chloride, sulphate, nitrate, nitrite, and phosphate

iv. pH and pHs to calculate the Langelier Index to determine if the water has a corrosive or scaling-dissolving tendency on irrigation equipment
v. Water class rating and the effect thereof on soils, crops and irrigation equipment

Soil reports and maps:

Aspects that should be presented in the report include (but are not limited to) the following:

i. Summary including major findings and recommendation and a table showing the area (in ha) for each soil and land class
ii. A statement of objectives for the survey
iii. A location map
iv. Description of the survey procedure
v. Brief description of the geology, topography, climate and vegetation
vi. A description of each soil or land class map unit
vii. Tabulated properties of the soil analysis
viii. Summary of irrigation water quality
ix. Soil and land class irrigation assessment and recommendations
x. Referencing of source material and a reference list
xi. Appendix: Detailed soil description and accompanying detailed soil analyses tables.

The following maps (minimum) are to be produced. Maps are to be produced on a GIS system.

i. Soil map
ii. Irrigation potential map
iii. Effective soil depth map
iv. Clay content (A and B horizons)

4.3.3 Irrigation potential classes

Procedures for the assessment of land for irrigation development in South Africa have been developed and reviewed by Louw (1967), MacVicar (1976), Irrigation Planning Staff (1980), Hensley and Laker (1980), Eloff (1984), Schoeman (1987), Bester and Liengme (1989), Dohse et al. (1991) and Nell (1991). The criteria considered for evaluating soil irrigability classes are defined quantitatively and are given in ranges of soil properties. The classes are defined in terms of the degree of soil limitations. The most limiting property of the soil is fixed to assign the irrigability class. For example, if a soil has all the desirable properties for a specific class except one, the soil would be assigned to a lower class appropriate to the limiting factor (undesirable property). The five soil irrigability classes proposed by Bhattacharjee (1979) are used internationally and were also slightly adapted for South African conditions.

The following irrigation classes are mostly used:

i. Class 1: Highly suitable for irrigation with few or no limitations or preconditions. Topography is flat, soils are well drained, of moderate permeability and are deep, medium textured with good available water holding capacity.
ii. Class 2: Suitable for irrigation with slight limitations such as undulating topography, moderately well drained soils, moderately slow or moderately rapid permeability or moderate depth of soil.
iii. Class 3: Low suitability with moderately severe limitations such as significantly rolling topography, imperfect or somewhat excessively drained soils, slow or rapid permeability, or shallow soils.
iv. Class 4: Not suitable for irrigation under most conditions with severe limitations.
v. Class 5: Soils with severe limitations, not recommended at all, such as soils in natural waterways, soils in the river floodplain, soils presently eroded or soils showing the presence of any permanent or potential water table.

A number of soil parameters are used to quantify the irrigation potential classes, but only effective soil depth, soil wetness and texture are given below to illustrate the procedure.

Soil depth provides the volume of soil material for root development, water storage and nutrient uptake. Effective soil depth can be considered as the depth that is freely permeable to plant roots and water. For the derived soil irrigability classes, effective soil depth would mostly be:

i. Class 1: 900 to 1500 mm
ii. Class 2: 600 to 900 mm
iii. Class 3: 300 to 600 mm
iv. Class 4: 150 to 300 mm
v. Class 5: 0 to 150 mm

Soil wetness is a reflection of the rate of water removal from the soil by both runoff and percolation. Position, slope, infiltration rate, surface runoff, permeability and redoximorphic features are significant factors influencing the soil wetness class. Profile morphology is used to determine the depth of water saturation and the maximum height of signs of hydromorphy is used as depth limit.

i. Class 1: Dry soil profile
ii. Class 2: Wet in some part between 1000 and 1500 mm
iii. Class 3: Wet in some part between 500 and 1000 mm
iv. Class 4: Wet in some part between 250 and 500 mm
v. Class 5: Wet in some part above a depth of 250 mm

Soils with more than 10% and less than 25% clay and without significantly differing textural layers are considered irrigable (Irrigation Class 1). Soils with distinctly different textural layers, less than 10% clay or more than 35% clay are classified as Irrigation Class 3 or higher.

Irrigation Classes 1 and 2 can be recommended for irrigation. Irrigation Class 3 is normally not recommended for large-scale irrigation development under average conditions, but small areas may be considered if they adjoin or are enclosed by areas of Classes 1 and 2.

4.4 Sources of salts and their contributions

The major sources of salts in soil are irrigation water, drainage water, shallow water tables, fertilisers, rain (near the coast) and in situ salt content of the parent material. Each will be briefly discussed:

i. **Irrigation water:** Irrigation water contains a certain concentration of salts depending on its quality. With good quality irrigation water, containing 0.02 to 0.03% salt, approximately 320 kg of salt is applied per hectare with every 100 mm irrigation. This can easily lead to an annual addition of up to 3 tons of salt per hectare. For example, Table 4.2 illustrates salt sources and amounts that can be expected in the Vaalharts Irrigation Scheme on sandy soils with a long term irrigation water quality of 47 mS m^{-1}. The total salts irrigated amounted to 5466 kg per ha over a two year period.

ii. **Drainage water:** The water quality of drainage water is always poorer than the irrigation water due to build-up of salts over the profile. The quality of drainage water varies considerably over season(s) and needs to be monitored before used as an irrigation water resource. This is also illustrated as changes in movement of salt into the water table through percolation (S_P) over crop seasons in Table 4.2. A total of about 13 tons of salt per ha ended up in the drainage water over two years.

iii. **Shallow groundwater tables:** Salts in shallow water tables will move along the capillaries in the soil matrix, it is also termed capillary rise. It is a suction in the soil that creates upward movement of water from a static water table due to soil water evaporation and plant transpiration. Table 4.3 gives an indication of salts that move along the capillary water way from the water table (wt) into the root zone to be taken up by the plant (S_{WTU}). In this case about 8 tons of salt was transported from the water table towards the root zone. The plants will absorb the water, leaving the salts behind in the rhizosphere. Hence, salts increase in the root zone unless sufficient leaching occurs.

iv. **Fertilisers:** Depending on the crop, fertilisers can contribute significantly to salt additions to soils. Table 4.3 shows that a wheat-maize rotation can add about 750 kg of salts per ha per year.

v. **Rainfall:** Addition of salts through rain water is relatively low in the interior irrigation areas (Table 4.2), but near the coast the salt load can be high.

vi. **Parent material:** Parent material can release significant amounts of salt through weathering of minerals under irrigation. In semi-arid areas this may be the main reason for salinity and sodicity. Humid and sub-humid areas seldom have problems with salinity, but are often prone to sodicity due to the high sodium content of the parent material.

More important to understand is the contribution of salt sources towards salt in the soil solution. It is a very formidable task to determine individual contributions, mainly due to the complex nature of the processes and the fact that it is site specific. Therefore, it is advisable to use a level three technology approach to solve the problem using a salinity-model.

For example, the salt balance of a sandy soil under a centre pivot was calculated using the SWAMP-model at the University of the Free State (Van Rensburg et al., 2012). Net gain ($+S_D$) or loss ($-S_D$) of salt from the potential root zone (2000 mm) through upward or downward drainage as calculated from the change in salt content of the soil (ΔS_{Soil}), net addition of salt through fertilisers (S_F), addition through rainfall (S_R), irrigation (S_I) and capillary rise (S_{WTU}), as well as movement of salt into the water table through percolation (S_P) and out of the potential root zone through the artificial drainage system (S_{AD}) (Van Rensburg et al., 2012).

Table 4.2 Net gain (+S_D) or loss (-S_D) of salt from the potential root zone (2000 mm) through upward or downward drainage for a measuring point at Vaalharts Irrigation Scheme as calculated from the change in salt content of the soil (ΔS_{Soil}), net addition of salt through fertilisers (S_F), through rainfall (S_R), irrigation (S_I) and capillary rise (S_{WTU}), as well as movement of salt into the water table through percolation (S_P) and out of the potential root zone through the artificial drainage system (S_{AD}) (Van Rensburg et al., 2012)

Crop	ΔS_{Soil}	S_F	S_R	S_I	S_{AD}	$\pm S_D$	S_{WTU}	S_P
	kg ha^{-1}							
Wheat	1596	415	31	2018	0	**-867**	2717	3583
Maize	-1843	351	53	1277	0	**-3524**	3032	6556
Fallow	-675	0	18	0	0	**-694**	0	694
Groundnuts	2381	175	39	2171	0	**-4**	2342	2345

4.5 Salt thresholds for soils

Salts are an essential component of soils and are necessary to maintain its structure and sustain plant growth. However, excess salts can damage the soil structure and can also affect germination, growth and yield of certain crops. With this in mind, it is important to take note of the most important salt indicators for classifying salt affected soils, namely electrical conductivity (EC_e), sodium adsorption ratio (SAR_e) and pH_e. These indicators are measured using the saturated paste extract method (Non-Affiliated Soil Analysis Work Committee, 1990), where soil water is sucked from a soil paste at -60 kPa and then analysed for its electrical conductivity and dissolved cations (calcium, magnesium and sodium) and pH. As an alternative to SAR, some laboratories also use the exchangeable sodium percentage (ESP). Based on the combination of the three indicators, salt affected soils can either be classified as saline, sodic (alkaline) or saline-sodic. The classification of salt affected soils by Chhabra (1996) and its effect on the physical condition of soils are summarised in Table 4.3.

Table 4.3 Summary of the indicators and norms for classifying salt affected soils (Chhabra, 1996)

Classification	pH	EC (mS m^{-1})	*SAR	**ESP	Physical soil condition
Slightly saline	< 8.5	200-400	< 13	< 15	Normal
Saline	< 8.5	> 400	< 13	< 15	Normal
Sodic	> 8.5	< 400	> 13	> 15	Poor
Saline-Sodic	< 8.5	> 400	> 13	> 15	Varies
High pH	> 7.8	< 400	< 13	< 15	Varies

* SAR = $Na^+/\sqrt{(Ca^{++} + Mg^{++})/2}$; ion concentrations are expressed as me ℓ^{-1}
** ESP = Na^+/ CEC; where CEC represents the cation exchange capacity of soil

In summary, salinisation is the secondary increase of the total salt concentration in the soil to such a degree that the osmotic potential of the soil solution will have a detrimental effect on water uptake of plants. Alkalisation is characterised by the displacement of adsorbed calcium, magnesiu and potassium on the cation exchange complex by sodium. This leads to the dispersion of clay with the consequent degradation of soil structure, decline in infiltration rate, crust formation and a general degradation in the physical condition of the soil. Table 4.4 gives guidance on when to expect dispersion of clays in soils that occur in the sugar industry.

Table 4.4 SAR rating interpretation and critical SAR for different soil forms in the South African Sugar Industry (Van Antwerpen et al., 2013)

Soil Forms	Critical SAR
Champagne, Inanda, Cartref, Clovelly, Dundee, Fernwood, Griffin, Hutton, Oakleaf, Shepstone, Shortlands	15
Arcadia, Rensburg, Bonheim, Mayo, Milkwood, Tambankulu, Willowbrook	10
Estcourt, Glenrosa, Katspruit, Kroonstad, Longlands, Mispah, Swartland, Valsrivier, Wasbank, Westleigh	6

4.6 Salt thresholds for crops

Saline soils are characterised by a high salt concentration in the soil solution without the physical soil properties being affected. The detrimental effect on plants can primarily be attributed to an osmotic effect, as water uptake by crops is hindered by a drastic increase in the osmotic potential of soil water. An indication of the salt sensitivity of crops in general is given in Table 4.5, while Table 4.6 summarises the osmotic impact on yield of specific crops.

Table 4.5 Suitability of various soil salinity levels for crop production in general

Electric conductivity of saturated extract ($mS\ m^{-1}$ at 25 °C)		Suitability
0-200	Low	No danger of salinity
200-400	Medium	Detrimental to salt sensitive crops
400-800	High	Detrimental to most crops
800-1600	Very high	Only salt resistant crops can be planted

Table 4.6 Impact of osmotic stress on crop yields (electrical conductivity of a saturation paste extract, EC_e = $mS\ m^{-1}$, and electrical conductivity of the irrigation water, EC_i = $mS\ m^{-1}$)

Yield Potential	100%		90%		50%	
	EC_e	EC_i	EC_e	EC_i	EC_e	EC_i
Field crops						
Cotton (*Gossypium hirsutum*)	800	530	1 000	670	1 800	1 200
Maize (*Zea mays*)	170	110	250	170	590	390
Sugar cane (*Saccharum officinarum*)	170	110	340	230	1 000	680
Wheat (*Triticum aestivum*)	600	400	740	490	1 300	870
Vegetable crops						
Beetroot (*Beta vulgaris*)	400	270	510	340	960	640
Carrot (*Daucus carota*)	100	70	170	110	460	300
Lettuce (*Lactuca sativa*)	130	90	210	140	510	340
Onion (*Allium cepa*)	120	80	180	120	430	290
Potato (*Solanum tuberosum*)	170	110	250	170	590	390
Tomato (*Lycopersicon esculentum*)	250	170	350	230	760	500
Forage crops						
Barley (*Hordeum vulgare*)	600	400	740	490	1 300	870
Clover (*Trifolium pratense*)	150	100	320	220	1 000	680
Lucerne (*Medicago sativa*)	200	130	340	220	880	590
Ryegrass(*Lolium perenne*)	560	370	690	460	1 200	810
Fruit crops						
Date palm (*Phoenix dactylifera*)	400	270	680	450	1 800	1 200
Grape (*Vitis* sp.)	150	100	250	170	670	450
Orange (*Citrus sinensis*)	170	110	230	160	480	320
Strawberry (*Fragaria* sp.)	100	70	130	90	250	170

Toxic concentrations of chorine (Cl) and boron (B) can also occur in conjunction with salt accumulation. A boron concentration higher than 1.5 mg ℓ^{-1} in the saturation extract is toxic to most plants. For example tobacco is highly sensitive to chlorine in soils as it negatively affects the burning quality when smoked.

4.7 Irrigation systems

The purpose of an irrigation system is to artificially apply the desired amount of water, at the correct application rate, uniformly over the whole field, at the corrrect time, with as little as possible unproductive water consumption occuring, as economically as possible.

The irrigation systems currently in general use, are differentiated as follows:

i. *Flood or gravity irrigation systems* where water that flows under gravitation is applied to the field. This includes basin, border, furrow, short furrow and contour irrigation.

ii. *Mobile irrigation systems* is powered to move over a field on its own while it irrigates the field. This includes centre pivot, linear and travelling gun systems

iii. Static irrigation systems:

- *Sprinkler irrigation systems* are moved mechanically or manually from one position to another, to irrigate the entire field surface. This includes quick couple, dragline, hop-along, big gun, side-roll and irrigating boom systems.
- *Micro irrigation systems* are permanent after installation and are not normally moved. This includes micro and drip systems.

Water that is distributed with irrigation systems may also transport salts and deposit it onto the field. With respect to water placement and its influence on salt distribution in the field, irrigation systems can be divided into two categories, namely point application irrigation and non-point application irrigation (Hanson et al., 2006). Irrigation methods in each of these categories have certain advantages and disadvantages and all known factors should be considered before attempting to improve salinity control by changing the irrigation method.

4.7.1 Point application irrigation

This group comprises of flood or gravity irrigation systems, as well as drip irrigation from the static irrigation systems group.

Flood irrigation includes basin, border, furrow, short furrow, contour irrigation and wild flood systems. Wild flood is a system where water is discharged from an outlet onto a field that is not levelled. Efficiency varies with conditions of each situation. Border irrigation is the discharge of irrigation water over long, levelled beds of 2 to 8 m in width and 100 to 400 m in length and a slope of 0.2 to 0.4%. The flowrate and the slope, as well as width and length of the irrigation beds are varied with infiltration rate to obtain the highest possible degree of irrigation efficiency. Efficiency normally varies from 60 to 95% depending on the design and type of supply system (Reinders et al., 2010). The poorer the irrigation efficiency the higher the risk for waterlogging and salt accumulation. Distribution of salts will vary spatially since some parts of the field will be under-irrigated, normally the lower end of the field, and other parts over-irrigated, nearest to the water-inlet. Differences in the rate of infiltration are caused by land slope, degree of compaction, textural changes and soil chemistry. High spots in the field also receive less water because they are covered by less water for a shorter period (Ayers and Westcot, 1985).

Furrow irrigation refers to distribution of irrigation water over the field by means of shallow furrows between row crops, 0.75 to 1.5 m apart. The slope and length of the furrows and strength of the current depend on the infiltration rate of the soil. Good water quality is required with furrow irrigation, because salt accumulation can take place on the ridges when water of a poor quality is used (Figure 4.5). This salinity problem can be overcome by planting on the sides of the ridges.

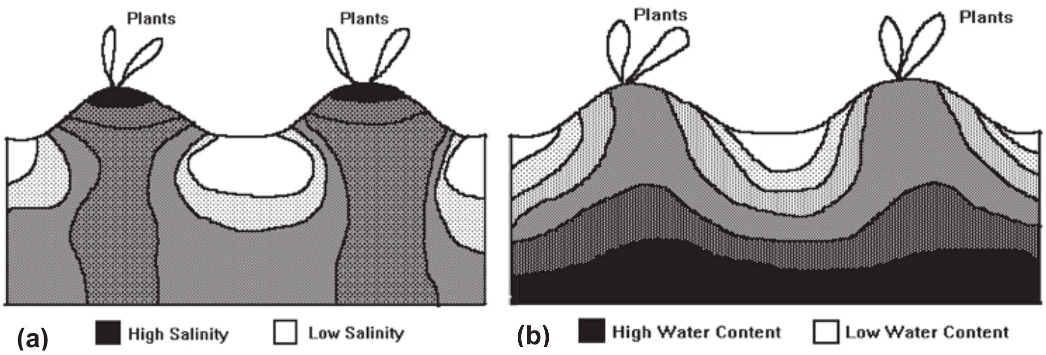

Figure 4.5 Salt patterns as affected by water movement in a furrow: a) salt patterns following irrigation, b) soil water content patterns after irrigation (Hanson *et al.,* 2006; Mndzawe, 2019).

The efficiency of furrow irrigation can, under certain conditions and good management, be better than border irrigation. Flood irrigation is especially suitable for clayey soils with a low infiltration rate. The amount of water that can be applied increases with a decrease in the flow rate and slope, in other words the period that the water is left on the soil for infiltration.

Drip and subsurface drip irrigation: Drip irrigation is the drop by drop application of water in the row to supplement daily water consumption. Advantages of drip irrigation are (i) that only a small section of the soil surface is wetted, drastically reducing evaporation losses and (ii) that only the parts of the field with the highest rooting density is wetted, increasing the effectiveness of water consumption. Subsurface drip irrigation can also be done by installing dripping lines 200 to 400 mm beneath the soil surface. Irrespective of the type of drip irrigation, the principle is that salts will follow the direction of water movement, as indicated in Figure 4.6 for subsurface drip. The graphs show that salts will accumulate at the soil surface between emitters and at the outside edges of the area wetted by the water applicators. With time, this salt accumulation may become appreciable and creates a hazard if the salt is then moved into the root zone of the crop by rain. It is recommended that regular irrigations continue in the event of rain, at least until 50 to 100 mm of rain was recorded. If rainfall is insufficient, supplemental leaching with the localised system may be needed (Ayers and Westcot, 1985).

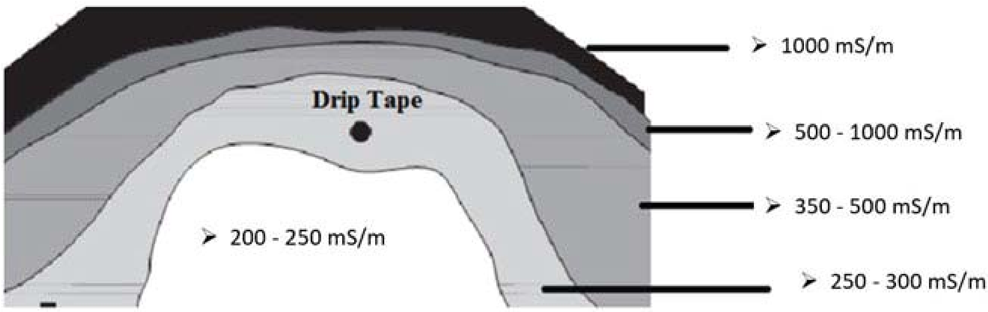

Figure 4.6 An example of a salt distribution pattern for sub-surface drip irrigation systems (Hanson *et al.,* 2006; Mndzawe, 2019).

Subsurface irrigation refers to a special type of irrigation where perforated pipes are installed in the subsoil to control the water table height. This system is only effective in regions with high rainfall. In arid areas it leads to the accumulation of salts within the root zone and on the soil surface.

4.7.2 Non-point application irrigation

This group comprises of mobile irrigation systems, as well as sprinkler irrigation in the static irrigation systems group. These systems are normally called overhead irrigation systems. Different designs, namely static, mobile and self-driven systems, are available. The efficiency of the systems varies according to the design and area covered. For centre pivots, Van Rensburg et al. (2012) reported coefficients of uniformity that varied between 85 and 93% for the central irrigation areas. They found that the system efficiency decreased with 0.5% per ha, when increasing from 30 to 50 ha coverage.

Concerning salt management of overheard irrigation, salts move downwards with the applied water in a piston-type action over the entire field and salt will form layers in the profile as indicated in Figure 4.7, especially in sandy and sandy loam soils.

(a)

(b)

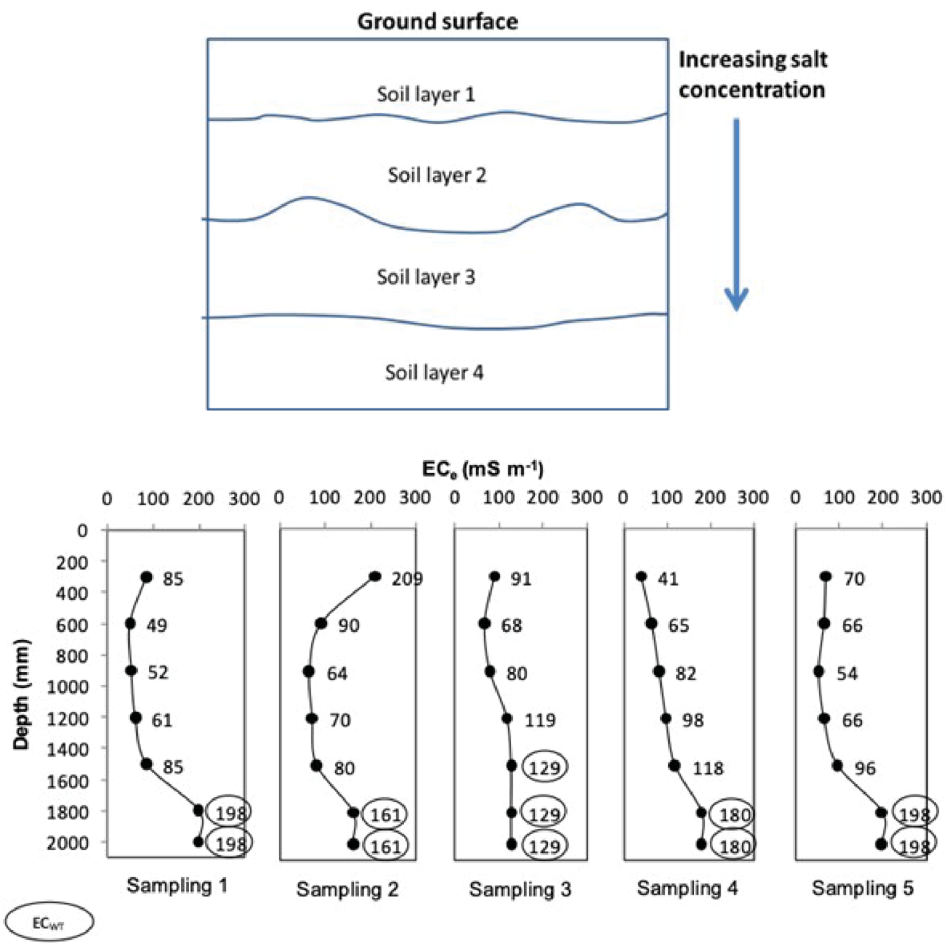

Figure 4.7 a) Illustration of conceptual movement of salts and its distribution in layers along a sandy profile (Hanson et al., 2006; Mndzawe, 2019) and b) actual salt profiles, expressed as electrical conductivity of the soil extract (EC_e), under a centre pivot in a sandy soil with a water table (EC_{wt}) at 1800 mm depth. Samples were taken during July 2007, December 2007, April 2008, November 2008 and May 2009 (Van Rensburg et al., 2012).

Using low quality water with overhead sprinkler systems may damage the leaves of certain sensitive plants, plus evaporation losses and energy requirements can be high. Irrigation water containing a high proportion of slightly soluble salts, such as calcium, bicarbonate and sulphate, causes a white scale formation on leaves or fruit. The deposits often build up on the leaves and fruit and are of special concern when flowers, vegetables or fruits are grown for the fresh market. The deposit reduces the marketability of fruit and foliage and, in the case of fruit like apples and pears, requires expensive treatment (acid wash) before marketing (Ayers and Westcot, 1985). If salt deposits are observed on plants, irrigation water should be analysed and methods should be applied to reduce the bicarbonate content through acid addition to water supply.

Overhead sprinkling of sensitive crops can also cause toxicities. Excessive quantities of sodium and chloride in irrigation water are absorbed through leaves. Extreme cases have resulted in severe leaf burn and defoliation and are associated with periods of high temperature and low humidity (below 30%), frequently aggravated by windy conditions. To lower the risk of toxicity one could irrigate at night, avoid periods of high wind, control sprinkler drift, increase sprinkler rotation speeds, increase rate of application, or more drastically, change the irrigation method.

4.8 Drainage systems

The purpose of agricultural drainage is to remove excess water from the soil to enhance crop production. In some soils, natural drainage processes are sufficient for production of agricultural crops, but in many other soils, artificial drainage is needed for efficient agricultural production (Reinders et al., 2016).

In arid and semi-arid areas, the role of drainage is to prevent irrigation induced waterlogging and salinity, not only by removing excess surface and subsurface water, but also by removing soluble salt brought in by irrigation water (Ritzema, 2009). Drainage at farm level can be divided into surface and subsurface drainage (Ritzema, 2009). A surface drainage system is the diversion of excess water from the surface of the land (Ritzema, 2006). These systems collect and control water entering and leaving the irrigation site. Subsurface drainage is the removal of excess water and salts from the soil via groundwater flow to installed drains (Ritzema, 2006). Subsurface drainage systems control shallow groundwater tables below the crop root zone (FAO, 2005).

Surface drainage can be improved by levelling the land to prevent accumulation of water and to minimise waterlogging. The installation of subsurface drainage systems changes the drainage capacity and water dynamics of the soil, and can prevent waterlogging in two ways: (1) relief drainage, which lowers an existing high groundwater table to below the crop root zone, and (2) interception drainage, preventing waterlogging and high groundwater tables on lower ground by intercepting seepage and transmission of groundwater from higher ground (Queensland Department of Environment and Resource Management, 2011).

Even though artificial drainage systems are essential in protecting irrigated fields from salinity and shallow groundwater tables (Duncan et al., 2008), they are costly. Artificial drainage is necessary when it is impractical and uneconomical to control sources of excess water and maintain natural drainage systems (Sommerfeldt et al., 1988). The depth and spacing of internal drainage systems is of crucial importance. Table 4.7 shows the ranges of depth and spacing generally used for placement of drains in fields (Hillel, 2000). Inefficient depth and placement will prevent a set of drains from lowering the water table to the extent necessary.

Table 4.7 Prevalent depths and spacing of drainage pipes for different soil types (Hillel, 2000)

Soil type	Hydraulic conductivity (mm day^{-1})	Spacing between drains (m)	Depth of drains (m)
Clay	1.5	10-20	1-1.5
Clay loam	1.5-5	15-25	1-1.5
Loam	1.5-20	20-35	1-1.5
Fine, sandy loam	20-65	30-40	1-1.5
Sandy loam	65-125	30-70	1-2
Peat	125-250	30-100	1-2

In general, water table depths should be maintained at a greater depth in more arid areas compared to humid climatic regions, because of the higher evaporation rate and more rapid increase in groundwater table salinity. In soils where the salinity risk is higher, such as in medium and fine textured soils, the water table should also be kept at greater depths (Hillel, 2000). Where there is a mechanical limitation to the depth of drain placement, adjacent lines can be placed closer together to increase effectiveness.

A study by Ritzema et al. (2008) showed that within one or two seasons of installation of subsurface drainage, crop yields increased by an average of 54% for sugarcane, 64% for cotton, 69% for rice and 136% for wheat. Yield increases were attributed to the reduction of water tables by 25% and soil salinity levels by 50% in drained fields compared to non-drained ones. A nationwide monitoring programme in Egypt revealed that installation of subsurface drainage resulted in a 35 to 50% decrease in areas affected by soil salinity (Ali et al., 2001).

4.8 Quality of irrigation water

Being a water scarce country, there is continuous competition between different water user sectors in South Africa to increase their share of the available supply. Since the major portion of the water in storage is used for irrigation, it is arguably the sector most under pressure to relinquish some of its share to other users. In addition, the quality of available water supplies is deteriorating due to poor quality runoff and drainage water from urbanised, industrial and irrigation areas that enters the major river systems (Du Preez et al., 2000). It is anticipated that irrigators will in future be increasingly faced with the challenge to maintain or increase production using the same or a reduced quantity water of a poorer quality. Amongst others, this will necessitate the use of appropriate tools for assessment of the fitness for use (FFU) of water available for irrigation, giving due consideration to the site-specific conditions that may influence the assessment.

In the past, FFU of water for irrigation was primarily assessed based on the classification system developed by the US Salinity Laboratory Staff (1954) and guidance provided by the FAO (Ayers and Westcott, 1985) and learned societies (Tanji, 1990). More recently, managers of water resource quality at the Department of Water and Sanitation (DWS), identified the need for water quality guidelines in order to help them establish water quality levels that would not jeopardise irrigation, as well as other water users in a specific area. By using these levels as targets for managing the quality of water resources, water quality managers try to ensure that water resource quality remains fit for its intended use. Several countries developed similar water quality guidelines catering for a range of water uses, including irrigation (Department of Water Affairs and Forestry, 1996; ANZECC, 2000; CCME, 2008; Standard Methods Committee, 2018). The guidelines for irrigation was based largely on guidelines provided by the FAO and learned societies, supplemented and modified to some degree by local experience. In addition to its primary purpose of providing guidance to water resource managers establishing water quality levels that would be acceptable for irrigation purposes, the South African guidelines also found application to assess the FFU of irrigation water. A common feature of these earlier guidelines is that they were generic in nature and largely ignored site-specific considerations.

Recently, DWS identified the need for the development of water quality guidelines that differ in fundamental ways from those developed earlier. Firstly, the envisaged guidelines had to be risk-based – a fundamental change in philosophy from earlier guidelines. Secondly, they had to provide for much greater site-specificity, a widely recognised limitation of previous generic guidelines. Thirdly, they had to be available primarily as a software-based Decision Support System (DSS). The envisaged guidelines have now been developed for irrigation, emanating from a project initiated by the WRC through a directed call with published terms of reference and co-funded by the Department of Agriculture, Forestry and Fisheries (Du Plessis et al., 2017). As with the earlier guidelines, the DSS mainly uses internationally accepted cause-effect relationships to assess the effect water quality constituents have on soils, crops and irrigation equipment, but in addition, it also takes into account site-specific characteristics to produce a risk based FFU assessment of irrigation water quality. In view of these advanced features, it is foreseen that the DSS will increasingly become the assessment tool of choice for assessing the FFU of irrigation water. Although the DSS provides assistance to water resource managers with establishing water quality levels that would be acceptable for irrigation purposes, so called Water Quality Requirements, it is its functionality to assess the FFU of irrigation water that will be discussed in more detail here.

A basic premise of the new DSS is that the FFU of water for irrigation is determined by the extent to which water constituents determine the success of an irrigation development. The three most important components of an irrigation development affected by water composition were identified as soil quality, crop yield and quality, and the irrigation equipment used to convey and distribute water. Problems with any of these components can jeopardise the success of an irrigation development. These components are, in turn, subdivided into several "suitability indicators", each addressing a different aspect of the success determining components (soil quality, crop yield and quality, and irrigation equipment). For each of the suitability indicators, the current state of knowledge was assessed and an approach selected to calculate and evaluate its effect. Next, the criteria that define FFU categories for each suitability indicator were decided upon. The procedures used to calculate the direct and indirect effects of irrigation water constituents on suitability indicators and the criteria used to categorise the severity of these effects, are described in more detail by Du Plessis et al. (2017).

4.8.1 Two levels of water quality assessment

The DSS operates at two different levels, or Tiers, to assess FFU of water for irrigation. These levels of assessment vary in their input requirements, calculating procedures and output.

For Tier 1 assessments of FFU, only the composition of the irrigation water is required as input. The output is a rapid "conservative" assessment of irrigation water quality with outcomes similar to the current South African generic guidelines (Department of Water Affairs and Forestry, 1996). Should the Tier 1 assessment indicate no potential water composition problem, the water is deemed fit for use on all crops, under all but the most exceptional circumstances. On the other hand, should the Tier 1 assessment identify potential undesirable effects associated with irrigation water composition, a more comprehensive, site-specific evaluation, as provided by a Tier 2 assessment, is indicated.

Tier 2 assessments allow the user to select site-specific characteristics applicable to the specific situation that needs to be evaluated. This provides 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. Tier 2 assessments, therefore, allow the user to assess how the implementation of alternative site-specific management options (e.g. a different crop, soil texture, irrigation management, etc.) can be expected to modify the effect that irrigation with water of a specific composition may have on soil quality, crop yield and quality, and irrigation equipment. In other words, Tier 2 assessments demonstrate how the adoption of different management options may reduce or overcome the problematic effects associated with water of a specific composition. It would, for example, explain why water of a specific composition can be successfully used in one climatic area and not another.

Calculating procedures

The effect that water constituents have on suitability indicators can be either direct (e.g. when water with a high chloride concentration causes scorching of wetted leaves) or indirect (when the suitability indicator is affected by the nett effect of processes taking place within the soil-plant-atmosphere continuum). Direct effects are easy to predict from cause-effect relationships. Indirect effects are more difficult to predict, since the cause-effect relationship is more complex.

When irrigation water is added to soil, the soil acts as a temporary store of water from where plant roots extract water as needed in between irrigation applications. The dissolved water constituents are transported into the soil and interact with soil constituents, thereby changing its composition. Since most irrigation water constituents are actively excluded from uptake by plants, they tend to accumulate in soil and further change the soil composition. The nett effect of these processes on soil composition need to be estimated to assess the indirect effects water composition have on some suitability indicators of soil quality and crop yield. Because of the involved nature of these interactions, they are modelled using a simplified dynamic soil water balance model for Tier 2 applications, while a steady state calculating procedure that relies on conservative simplifying assumptions, is used for Tier 1.

Tier 1 calculations of soil-crop-water interactions assume an idealised 4-layer soil, where crops withdraw 40% of their water requirement from the top layer, 30% from the second, 20% from the third and 10% from the bottom layer (Rhoades, 1982, as quoted by Pratt and Suarez, 1990). The steady state (or equilibrium) concentration of soluble constituents in each layer is calculated from the concentration of constituents in the irrigation water, assuming a 10% leaching fraction for the profile. Tier 2 calculations make use of a simplified version of the dynamic Soil Water Balance (SWB) model (Singels et al., 2010), that is run for a minimum of 10 years using data from an appropriate user selectable weather station to calculate the water requirements and uptake of a user selected crop. It also simulates transient salt transport and simplified soil chemical interactions (Annandale et al., 1999). Model output is used to calculate the value of variables that determine the magnitude of several soil quality and crop yield indicators. For example, mean seasonal soil salinity is calculated to derive crop yield and other outputs, and this in turn can be used to calculate the likelihood with which specific yield intervals occur over time.

4.8.2 Water quality constituents and suitability indicators

The DSS provides for assessing the fitness of a given water source for irrigation by considering the concentrations of eight major constituents, two biological constituents, three nutrients and twenty trace elements. Constituents are evaluated for the effect they have on soil quality, crop yield and quality, as well as irrigation equipment. At least the concentrations of the major constituents are required in order to conduct a FFU assessment. While analyses for other constituents are not mandatory, their effect on FFU will only be assessed if analyses are provided.

Suitability indicators of soil quality:

The impacts irrigation water quality constituents have on soil quality are primarily indirect because of the interaction between the water constituents and soil components. This interaction is modified by the fact that soil also acts as a temporary store of water for plant use, and that crops extract almost pure water, leaving most of the water constituents in the soil. The degree to which these constituents accumulate in soil and interact with soil components, determines how water constituents affect soil quality. The DSS considers the following suitability indicators to assess the effects irrigation water constituents have on soil quality:

i. Root zone salinity

ii. Soil permeability

iii. Oxidisable carbon loading

iv. Trace element accumulation

Suitability indicators of crop yield and quality:

The impact irrigation water quality constituents have on crop yield and quality are both direct and indirect. Direct contact of irrigation water with a crop mostly affects crop quality, while indirect impacts mostly affect crop yield. Indirect impacts are a consequence of the accumulation and redistribution of irrigation water constituents within the root zone. The DSS considers the following suitability indicators to assess the effects irrigation water constituents have on crop yield and quality:

i. Effect of root zone salinity, boron, chlorine and sodium on crop yield

ii. Leaf scorching when crops are wetted by chlorine and sodium

iii. Contribution to nitrogen, phosphorus and potassium uptake by the crop

iv. Microbial contamination

v. Qualitative crop damage by atrazine.

Suitability indicators of irrigation equipment:

The impact irrigation water constituents have on irrigation infrastructure to distribute and apply water, is a direct result of the interaction between water quality constituents and irrigation equipment. This interaction is determined primarily by the material irrigation equipment is made of, or the type of irrigation system used. The DSS considers the following suitability indicators to assess the effects of irrigation water constituents on irrigation equipment:

i. Corrosion or scaling of irrigation equipment

ii. Clogging of drippers

4.8.3 Presentation of DSS output and risk

Throughout the DSS, water quality is assigned to one of four colour coded FFU categories, indicative of the increasing risk associated with using the water. The classification system is based on a DWS system, describing four suitability categories, defined in generic terms applicable to any water use (Table 4.8).

Table 4.8 A generic description of the DWS fitness-for-use classification of water

Fitness-for-use category	Description
Ideal	A water quality that would not normally impair the fitness of the water for its intended use
Acceptable	A water quality that would exhibit some impairment to the fitness of the water for its intended use
Tolerable	A water quality that would exhibit increasingly unacceptable impairment to the fitness of the water for its intended use
Unacceptable	A water quality that would exhibit unacceptable impairment to the fitness of the water for its intended use

4.8.4 Generating and displaying DSS output

For Tier 1 assessments of FFU, only the composition of the irrigation water is required to generate DSS output. To conduct Tier 2 FFU assessments the user must in addition to the composition of the irrigation water, also specify the site-specific characteristics that should be considered during the evaluation. Site-specific characteristics are selectable from pre-populated drawdown lists or data bases. The DSS currently has a built-in data base for more than 50 South African weather stations, each with 50 years of clean data. The DSS database also contains crop yield response data for 158 agricultural crops for their response to salinity, 60 for their response to boron, 54 for their response to chloride and 74 crops for their response to sodium.

While a Tier 1 assessment is executed instantaneously, Tier 2 assessments take longer, depending on the number of years selected for simulation. A minimum of 10 years is required, but improved results can be obtained by running simulations for up to 45 years. The results of a FFU assessment are captured in several electronic output pages that summarise how the different suitability indicators are affected. The output can be printed or stored electronically.

i. The cover page presents information on the user's description of the assessment that was conducted and the water analysis. For Tier 2 assessments it also captures the site-specific characteristics considered during the evaluation and a summary of the seasonal water balance components.

ii. The second page presents an overview of the four suitability indicators that characterise soil quality, for both Tiers 1 and 2.

iii. The third page presents an overview of the five suitability indicators that characterise crop yield and quality for Tier 1, and for Tier 2, when a single or perennial crop has been selected for assessment. In cases where a crop rotation has been selected for evaluation in Tier 2, a fourth page is produced that provides an overview of the five suitability indicators, characterising crop yield and quality for the second crop.

iv. The fourth page (or the fifth page in the case where a two-crop rotation is being evaluated) presents an overview of the two suitability indicators that characterise the effect of water constituents on irrigation equipment, for both Tiers 1 and 2.

4.8.5 Example of DSS output

Root zone salinity is one of four suitability indicators used to assess the effect of irrigation water composition on soil quality. Root zone salinity serves as a general indicator of the ability of soil to support the growth of crops varying in their tolerance to soil salinity. The DSS output for root zone salinity is used here to illustrate the differences and similarities between the output for Tiers 1 and 2 (see Tables 4.9 and 4.10), using the same water composition, with an EC of 150 mS m^{-1}.

Note the similar look and feel of the output of the two Tiers. This can largely be attributed to the fact that the first three columns, identifing the suitability indicator under consideration, the FFU categories and the criteria defining the FFU category, are identical for the two Tiers. Where possible, this convention was followed for the description of the output for all suitability indicators.

For the Tier 1 FFU evaluation (Table 4.9), the DSS calculates and reports a single root zone salinity, which places it in the “acceptable” FFU category. Since the value of the predicted root zone salinity is given (and not only the FFU category in which it falls), information is conveyed to the user about how close the root zone salinity is to the boundary of the specific FFU category in which it falls.

Table 4.9 Tier 1 output: root zone salinity as affected by irrigation water with EC of 150 mS m^{-1}

	Fitness for Use	EC_e (mS m^{-1})	Predicted equilibrium root zone salinity (mS m^{-1})
Root zone salinity	Ideal	0-200	
	Acceptable	200-400	**282**
	Tolerable	400-800	
	Unacceptable	>800	

For Tier 2 assessments, the DSS calculates at least 10 (and up to 45) annual mean root zone salinity values (one for each year the SWB model is run, using site-specific climatic data). Because of the variability in rainfall and other climatic variables, these values would be expected to cover a range and not necessarily to fall into the same FFU category. The results of the Tier 2 assessment are reported as the % of time that the values fall within a specific FFU category (Table 4.10). In this way, information is conveyed to the user about the longer-term risk of experiencing different levels of root zone salinity. These differences are brought about by differences in rainfall and crop water demand, as well as in salt build-up or leaching, because of climatic differences from year to year.

Table 4.10 Tier 2 output of how root zone salinity is affected by irrigation water composition

	Fitness for Use	EC_e (mS m^{-1})	% of time root zone salinity will fall within FFU category
Root Zone Salinity	Ideal	0-200	**85**
	Acceptable	200-400	**15**
	Tolerable	400-800	
	Unacceptable	>800	

4.8.6 Conclusion

The DSS for assessment of FFU of irrigation water, provides firstly for an uncomplicated assessment (Tier 1) that is generic in nature with output that is similar to earlier irrigation water classification systems that were paper based, did not consider site-specific considerations or tried to quantify risk associated with using a particular water. The DSS also provides for a more dynamic assessment of the FFU of irrigation water (Tier 2). The Tier 2 assessment uses a scaled-down Soil Water Balance-chemistry model to simulate changes in the soil-plant-atmosphere continuum, on which to base its FFU assessment. This provides a significantly enhanced assessment of how a 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. Although more involved and time consuming to conduct, it is foreseen that Tier 2 assessments will increasingly be used to assess the FFU of more problematic irrigation waters, while Tier 1 assessments will be used for more regular assessments.

4.9 Leaching

With the soil water management boundaries as background, it is clear that salt removal through deep drainage (leaching) can only occur when the actual water content of the soil rises above the drained upper limit (DUL) boundary. This is an important principle in the estimation of the irrigation water requirements for leaching.

The necessary leaching requirement (LR) can be calculated using Equation 4.1 (Rhoades, 1974; Rhoades and Merrill, 1976), where EC_i (mS m^{-1}) is the electrical conductivity of the irrigation water and EC_e (mS m^{-1}) the electrical conductivity of soil solutions extracted from a saturated soil paste. The EC_e values would then typically be the target mean salinity level of the root zone, which normally corresponds to the threshold salinity level for a specific crop. The depth of irrigation water applied (mm) for the specific leaching requirement can be calculated with Equation 4.2, where ET (mm) is the crop water requirement (evapotranspiration).

$$LR = \frac{EC_i}{5(EC_e) - EC_i} \tag{4.1}$$

$$I = \frac{ET}{1 - LR} \tag{4.2}$$

For a more in-depth analysis, leaching curves can be constructed, representing the fraction of excess salts removed as a function of the depth of leaching water per unit depth of soil (Barnard et al., 2010). Excess salts refer to the salts that will be removed until a level of EC under existing soil-irrigation-water-drainage equilibrium conditions is reached, generally equal to salinity of the irrigation water. Hence, the depth of leaching requirement (D_w), irrespective of soil depth (D_s), soil salinity and irrigation water salinity, can be derived from the general regression Equation 4.3.

Estimations of the leaching requirement for a loamy sand and sandy loam soil, respectively, were made using Equation 4.3, where various initial salinity levels were leached with an EC_i of 50 mS m^{-1} until almost 100% of the excess salts were removed from a soil depth of 1 200 mm. The actual EC_e at the end of leaching was taken as 80 mS m^{-1} for all the initial EC_e levels. The results were compared with values recommended by Van der Merwe et al. (1975) in Table 4.11. The guidelines recommended by

Van der Merwe et al. (1975) and the guidelines estimated using Equation 4.3 are similar, with the average leaching requirements over the various salinity levels corresponding well with one another.

$$y = a\left(1 - exp^{-b(x)}\right) \qquad (4.3$$

Where x $= \frac{D_w}{D_s}$

D_w $= \left[\frac{\left(ln\left(\frac{-y}{a+1}\right)\right)}{b}\right](D_s)$

y $= 1 - \left(\frac{EC_{e\ actual} - EC_i}{EC_{e\ initial} - EC_i}\right)$

$EC_{e\ actual}$ $= target\ soil\ salinity$

a $= 1$

b $= -10.15\ for\ sandy\ soil\ and - 7.35\ for\ sandy\ laom\ soil$

Table 4.11 Leaching guidelines generated with Equation 4.3 (mm 1200 mm^{-1} soil depth) and from Van der Merwe et al. (1975)

$EC_{e\ initial}$	**$EC_{e\ actual}$**	**Soil type**			
		Loamy sand		**Sandy loam**	
		Van der Merwe et al. (1975)	**Eq. 4.4**	**Van der Merwe et al. (1975)**	**Eq. 4.4**
400	80	160	290	260	401
600	80	240	344	390	475
800	80	320	381	530	526
1000	80	400	409	650	564
1600	80	560	466	910	644
Mean		336	378	546	522

As a best management practice, it is recommended that the irrigation requirement should not be decreased to accommodate the osmotic effect of reduced water uptake. The corresponding over-irrigation will result in higher irrigation-induced leaching of salts. This auto-adjustment of salt leaching is nature's way of keeping soil salinity within acceptable levels. A disadvantage of most direct measurements of soil water depletion (neutron probe) is that the measured irrigation requirement will be equal to the actual salinity induced lowered crop water use. In such cases, it is recommended that the irrigation requirement be multiplied by an acceptable leaching factor. When real time simulation models with a salinity function are used to estimate the actual ET or irrigation requirement, it is recommended that the osmotic correction option be disabled.

4.10 Conclusion

This chapter focused on the nine most important pointers for salt management in soils with the aim to set guidelines for assisting behavioural change officers (BCOs) in their daily work in the irrigation sector. The first pointer guides the thinking process of deciding on how and where to sample soils. The second pointer highlights the suitability of soils for irrigation, concluding that unsuitable soils will not only harm the sustainability of the farm, but also negatively impact on the immediate and downstream environment. Pointer three discusses the major sources of salts in context with salt accumulation in soils, and stresses the need to reduce salt contributions. Pointer four elaborates on the threshold's levels of salts in soils, while pointer five provided insight into the sensitivity of crops towards salt levels in soils. Pointers six and seven concentrate on irrigation and drainage systems, respectively, and their importance to manage water as well as salt accumulation/removal in soils. Pointer eight offers guidance on water quality indicators and norms. The last pointer guides the user in calculating the amount of water required to manage leaching of excess salts from the soil. The aim of these pointers is to reduce the impact of salts on the soil, crop and environment, and this can only be achieved against a background of sound irrigation scheduling practices.

CHAPTER 5. SOLUTIONS

5.1 Introduction

The previous chapters were dedicated to fundamentals or technical aspects of salt management, principles in irrigation scheduling and socio-economic awareness as underlying foundation for making critical decisions concerning water and salt management. This concluding chapter focuses on solutions for controlling salts in soils in the form of a practical guide. Two approaches to salt management is proposed, namely proactive and reactive measures. Both these approaches have their own practical applications and values.

5.2 Proactive measures

The salinity procedures of Ehlers et al. (2006), as presented in Figure 5.1, was adopted for proactive management of salts in soils. The Ehlers procedure is embedded in: (i) soil properties, such textural properties, profile available water capacity, internal and external drainage, presence of shallow water tables, salinity status of the soil and water table, (ii) crop properties, such as potential yield, crop water demand and salt tolerance of the crop (Table 5.1), (iii) climate, especially rainfall, and irrigation water quality. The procedure depends on the assessment of drainage conditions, whether drainage is restricted or not. If drainage is restricted, then one of two options can be followed, based on the electrical conductivity of the soil paste extract (EC_e). If the EC_e is smaller than the threshold of the crop then procedure A is recommended, otherwise procedure B needs to be followed. In the case of freely drained soils two procedures are recommended, also depending on the EC_e. If the EC_e is smaller than the threshold of the crop then procedure C is recommended. If the EC_e is higher than the threshold of the crop, then procedure D needs to be followed (which is technically a reactive measure to salt management). The diagram in Figure 5.1 can be used to select a suitable root zone salinity management procedure as a best management practice.

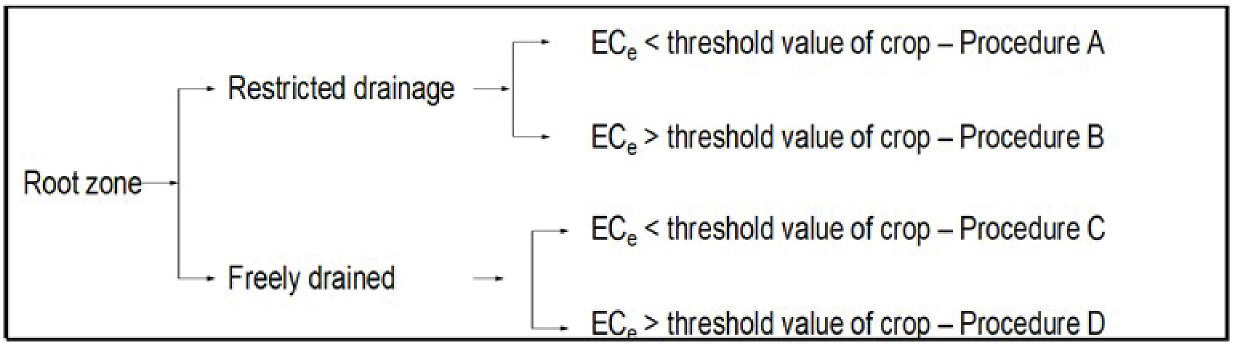

Figure 5.1 Diagram for selecting the appropriate salinity management procedure for a root zone (EC_{sw} = mean EC_{sw} of the root zone; under saturated soil conditions it can be assumed that EC_{sw} will be comparable to EC_e) (Ehlers et al., 2006).

Table 5.1 Salt tolerance of different crops (after Rhoades and Loveday, 1990 and Ehlers et al., 2006) and other relevant information necessary for salt management calculations in Tables 5.2 to 5.5

Crop	Threshold EC_{sw} ($mS\ m^{-1}$)	b-value	Max RD (mm)	Max biomass ($kg\ ha^{-1}$)	HI	β-value	Max CWD (mm)	Water table contribution		
								CF	TWT	SWT
Bean (dry)	100	-0.0009	1500	12860	0.35	1.35	620	0.00016	100	0.0015
Cotton	770	-0.00052	2000	18600	0.35	1.35	1200	0.00031	700	0.0005
Maize	350	-0.00073	2200	25300	0.45	1.4	958	0.00043	350	0.0004
Onion	120	-0.0016	800	78000	0.9	1.20	800	0	100	0.0015
Pea (dry)	105	-0.00096	1500	8400	0.40	1.25	618	0.00025	100	0.0010
Peanut	320	-0.0029	2000	14450	0.30	1.37	818	0.00034	300	0.0012
Potato	170	-0.0012	1500	62400	0.9	1.52	858	0	170	0.0015
Soybean	500	-0.0020	1500	14280	0.35	1.40	845	0.00034	350	0.0015
Sorghum	680	-0.0016	2000	17150	0.35	1.45	636	0.00037	500	0.0005
Sunflower	-	-	1800	8500	0.45	1.40	638	0.00037	-	-
Wheat	600	-0.0007	2000	14000	0.40	1.26	684	0.00045	400	0.0003

RD = rooting depth; HI = harvest index; CWD = crop water demand; CF = correction factor (crop type dependent);
TWT = threshold salinity of crop; SWT = reduction factor for the salinity above the threshold value (crop type dependent)

Proactive measures aim to assess root zone salinity on a site-specific basis and the steps for each procedure is summarised below:

Procedure A: This procedure consists of six steps (Table 5.2) and represents conditions where salts that are added to the root zone accumulate without any possibility for leaching. The mean salinity of the root zone is lower than the threshold value for the irrigated crop. The column on the left outlines the steps that can be followed under these conditions, while the column on the right gives an example for each step with maize as test crop. Background for the example: The soil is a sandy loam with 15% silt-plus-clay percentage, there is a restricting layer at 1600 mm depth and the depth of the water table was at 1200 mm. Electrical conductivity of the irrigation water (EC_i) was 20 mS m^{-1} and the average electrical conductivity of the soil water or root zone ($EC_{e(sw)}$) 200 mS m^{-1}.

Procedure B: This procedure consists of seven steps (Table 5.3) and represents conditions where salts that are added to the root zone accumulate without any leaching. The mean salinity of the root zone is higher than the threshold value for the cultivated crop. Therefore, lower yields than the potential is expected due to osmotic stress and irrigation should be proportionally reduced to compensate for the expected yield decline. When EC_e of the soil rises above the most tolerant crop's threshold, then yield losses will occur and artificial drains need to be installed to recover soils. The reclamation process is explained in the next section under reactive measures.

The steps that guide the calculations of procedure B are summarised in the column on the left, and an example using cotton as test crop is presented in the column on the right. Background for the example: It is a sandy loam soil (15% silt-plus-clay) with a restricting layer at 1800 mm depth. The water table was at a depth of 1400 mm. The average EC_i and $EC_{e(sw)}$ were 40 mS m^{-1} and 900 mS m^{-1}, respectively. Due to financial constraints, the farmer could not install a subsurface drainage system.

Table 5.2 Steps for managing salts under restricted drainage where the EC_e is lower than the salinity threshold of maize as test crop

Description of steps	Example with maize as test crop
Step 1: Determine seasonal crop water demand (CWD, mm) for a target biomass yield (Table 5.1). **Step 2:** If a shallow water table is present, calculate water table uptake (MWT_f, fraction of crop water demand, taken as 1): $MWT_f = 0.1 + CF\ (2000 – WTD) + 0.004\ (\%S+C)$ (5.1) CF = crop type dependent correction factor, see Table 5.1 WTD = depth to top of water table (mm) S+C = soil particles < 0.05 mm (silt plus clay %) $MWT_{mm} = MWT_f \times CWD$ (5.2) **Step 3:** Calculate irrigation requirement (IR, mm) $IR = CWD – MWT_{mm}$ (5.3) **Step 4:** Calculate increase in root zone salinity (ΔEC_{sw}) over growing season: $\Delta EC_{e(sw)} = [(EC_i \times IR \times 0.0783)/z] \times 69.918$ (5.4) $\Delta EC_{e(sw)}$= increase in mean $EC_{e(sw)}$ per mm depth EC_i = Electrical conductivity of irrigation water (mS m^{-1}) z = Soil depth to restriction (mm) **Step 5:** Calculate initial salinity for next season: $EC_e(ns) = EC_e(in) + \Delta EC_{e(sw)}(ts)$ (5.5) EC_e = electrical conductivity of saturated paste extract (ns) = next season (in) = initial status this season (ts) = this season **Step 6:** Compare the initial $EC_{e(sw)}$ for the next season with the EC_e threshold of the crop to be planted. If ECe_{sw} next season < EC_e threshold, the procedure can be repeated from Step 1 for the following season. If $EC_{e(sw)}$ next season > EC_e threshold, the soil should be drain or Procedure B should be followed.	**Step 1: Seasonal crop water demand** CWD = 958 mm (Table 5.5, col 8) **Step 2: Water table uptake** CF = 0.00043 (Table 5.5, col 9) WTD = 1200 mm (given) Silt + clay % = 15% (given) $MWT_f = 0.1 + 0.00043\ (2000 – 1200) + 0.004\ (15) = 0.504$ or 50.04% $MWT_{mm} = 0.504 \times 958 = 482$ mm **Step 3: Irrigation requirement** IR = 958 – 482 = 476 mm **Step 4: Δ Root zone salinity** EC_i = 20 mS m^{-1} (given) IR = 476 mm z = 1600 mm $\Delta EC_{e(sw)} = [(20 \times 476 \times 0.0783)/1600] \times 69.918 = 32.6$ mS m^{-1} **Step 5: Salinity of next season** $EC_e(in)$ = 200 mS m^{-1} (given) $\Delta EC_{e(sw)}(ts)$ = 33 mS m^{-1} (Step 4) $EC_e(ns)$ = 200 + 33 = 233 mS m^{-1} **Step 6: Outcome** The EC_e is lower than the threshold salinity of wheat (600 mS m^{-1}, Table 5.1, col 2). Wheat can be cultivated in the next season and the crop will not be damaged by salts in the soil.

Table 5.3 Steps for managing salts under restricted drainage and where EC_e is higher than salinity threshold of cotton as test crop

Description of steps	Example with cotton as test crop
Step 1: Calculate expected relative yield (Y_r), variables available in Table 5.1: $Y_r = 1 - b\ (EC_{e(sw)} - a)$ (5.6) a = Salinity threshold (mS m^{-1}) b = Slope (fractions of 1 per mS m^{-1}) $EC_{e(sw)}$ = Mean electrical conductivity of soil water taken from root zone (mS m^{-1})	**Step 1: Relative yield (Y_r)** $EC_{e(sw)}$ = 900 mS m^{-1} (given) b = 0.00052 (absolute value, Table 5.1 col 3) a = 770 (Table 5.1 col 2) Y_r = 1 – 0.00052(900 – 770) = 0.93
Step 2: Determine CWD at target yield for non-saline conditions.	**Step 2: Crop water demand (CWD)** CWD = 1200 mm (Table 5.1 col 8)
Step 3: Calculate water table uptake and then water table contribution (WTC, mm) with Equations 5.1 and 5.2. For water tables with an $EC_{e(sw)}$ larger than threshold EC_e of cultivated crop, the water table contribution under non-saline conditions is decreased, using Equation 5.7: WTC = MWT x [1 – (($EC_{e(sw)}$ – TWT) x SWT)] (5.7) WTC = water table uptake under saline conditions, expressed as a fraction of the seasonal CWD, taken as 1. $EC_{e(sw)}$ = electrical conductivity of soil water above water table (mS m^{-1}). TWT = threshold salinity of the crop (Table 5.1). SWT = crop type dependent reduction factor for the salinity above the threshold value (Table 5.1). MWT = fractional water table uptake under non-saline conditions, simulated with SWB or SWAMP, or estimated with Equation 5.1.	**Step 3: MWT & WTC** MWT (Eqs 5.1 and 5.2) CF = 0.00031 (Table 5.1, col 9) WTD = 1400 mm (given) Silt + clay % = 15% (given) MWT_{mm} = 0.346 x1200 = 415 mm WTC = Eq 5.7 $EC_{e(sw)}$ = 900 mS m^{-1} (given) TWT = 700 mS m^{-1} (Table 5.1, col 10) SWT = 0.0005 (Table 5.1, col 11) WTC = 415 x 0.93 = 374 mm
Step 4: Calculate irrigation requirement (IR) at adapted yield (Y_r): IR = (CWD x Y_r) – WTC (5.8)	**Step 4: IR** Y_r = 0.93; CWD = 1200 mm WTC = 374 mm IR = (1200 x 0.93) – 374 = 742 mm
Step 5: Calculate increase in root zone salinity ($\Delta EC_{e(sw)}$) over the growing season, using Equation 5.4.	**Step 5: Δ Root zone salinity** EC_i = 40 mS m^{-1} (given); IR = 476 mm; z = 1600 mm $\Delta\ EC_{e(sw)}$= [(40x476x0.0783)/1600)]x69.918 = 65 mS m^{-1}
Step 6: Calculate initial salinity for next season [$EC_{e(sw)}$ (ns)] with Equation 5.5.	**Step 6: Next season's EC_{sw}** $EC_{e(sw)}$(in) = 900 mS m^{-1} (given) $\Delta\ EC_{e(sw)}$(ts) = 65 mS m^{-1} $EC_{e(sw)}$(ns) = 900 + 65 = 965 mS m^{-1}
Step 7: Repeat from Step 1 for the following season. Consider selecting more salt tolerant crops or artificial drainage because the yield will decline further with every season.	**Step 7: Outcome for next crop (wheat)** Salinity threshold of wheat = 600 mS m^{-1}, which means that salinity will induce crop water stress and a yield reduction is expected. Convince farmer to install drains.

Procedure C: This procedure consists of four steps (Table 5.4) and represents conditions where salt additions can be removed from the root zone through natural leaching. Mean root zone salinity is lower than the threshold value of the cultivated crops. The objective of this procedure is to irrigate according to the crop water demand (CWD) in order to minimise the quantity of applied salts. It is assumed that leaching of the root zone during high rainfall periods will be sufficient to keep salinity within acceptable limits. The procedure is described in the column on the left and an example using peanut as test crop is presented in the column on the right. Background for the example: It is a sandy soil (10% silt-plus-clay) with no restricting layer, soil depth is 1500 mm. Average EC_i and initial $EC_{e(sw)}$ of the soil water were 100 mS m^{-1} and 200 mS m^{-1}, respectively. The $EC_{e(sw)}$ was 700 mS m^{-1} at the end of the season.

Table 5.4 Steps for managing salts under free-drainage conditions where EC_e is lower than salinity threshold of peanut as test crop

Description of steps	**Example with peanut as test crop**
Step 1: Determine CWD at the target yield (Y_{max}) for non-saline conditions. Y_{max} = Biomass x HI **Step 2:** Irrigate according to target yield where IR = CWD **Step 3:** Take representative soil samples of the root zone, at least every 3 years, for determination of $EC_{e(sw)}$ **Step 4:** If $EC_{e(sw)} < EC_e$ threshold of most sensitive cultivated crop, continue with Procedure C. If $EC_{e(sw)} \geq EC_e$ threshold of most sensitive cultivated crop, change to Procedure D.	**Step 1: Crop water demand (CWD)** CWD = 818 mm (Table 5.1, col 8) **Step 2: Irrigate to minimise water application** Select the irrigation method and strategy that will help to conserve water without reducing the target yield through water or osmotic stress. **Step 3: Monitoring of salts** Select suitable soil sampling methods and corresponding salt analysis. For example: $EC_{e(sw)}$ = 700 mS m^{-1} (given) **Step 4: Outcome** The EC_e wheat = 600 mS m^{-1} (Table 5.1 col 2) $EC_{e(sw)} > EC_e$ of crop, change to Procedure D

Procedure D: This procedure consists of five steps and represents conditions in a freely drained root zone, but where the addition of salts exceeds the removal by leaching. This procedure actually falls in the scope of reclamation of a soil that is already salt affected, and will be discussed in the following section.

5.3 Re-active measures: Reclamation of salt-degraded soils

If salts have accumulated uncontrollably in the soil then the type of salt affection, i.e. saline, sodic or a combination of the two, should be established. The second step is to delineated the area to be reclaimed.

5.3.1 Reclamation of saline soils

Recovery or correctional measures are limited to the removal of the salts from the solum through leaching with **high quality** irrigation water, with or without artificial drainage. Attention should also be given to removal or decreasing the effect of the source. Surface drainage can reduce excessive water and salt addition through accumulation of run-off from higher lying areas.

To remove excess salts from a freely drained root zone, the natural leaching rate should be accelerated by irrigating more than the required crop water demand. This can be done in two phases: (i) reducing the salinity level to the threshold value of salt tolerant cultivated crops, and (ii) thereafter to the salinity level of the desired salt sensitive crop. **Procedure D** of Ehlers et al. (2006) is proposed to reclaim such a salt affected area (Table 5.5). Background for the example: similar cultivation conditions than given in the example of procedure C, with a peanut-wheat rotation followed directly by a salt sensitive crop like beans. The DUL is 225 mm and soil water content are 150 mm over a rooting depth of 1500 mm.

Table 5.5 Steps for managing salts under free-drainage conditions where EC_e is higher than the salinity threshold of peanut-wheat rotation as test crops

Description of steps	Example with peanut-wheat rotation
Step 1: Determine CWD at target yield for non-saline conditions. **Step 2:** Calculate leaching requirement (LR) with Equations 5.2 and 5.3. Target $EC_{e(sw)}$ = Threshold EC of crop (i) Irrigation adaption on daily basis, or (ii) During the season (specific period where rainfall is high), then irrigate according to target yield where IR = CWD. **Step 3:** Determine amount of irrigation required to wet the root zone to drained upper limit (mm). I_{DUL} = DUL – SWC DUL = drained upper limit, mm water of rooting zone SWC = soil water content, mm water in rooting zone **Step 4:** Total irrigation (I_{dt}, mm) to be additionally applied above the crop water demand $I_{dt} = I_{ds} + I_{DUL}$ **Step 5:** Take representative soil samples of the root zone, after end of season to confirm change in salt load.	**Step 1: Crop water demand (CWD) for beans** CWD = 684 mm (Table 5.1, col 8) **Step 2: Leaching requirement (LR) and Irrigation depth (Id)** EC_i = 100 mS m^{-1} Target $EC_{e(sw)}$ = 100 mS m^{-1} LR = 100 / ((5 x 100) – 100) = 0.25 (i) If ET rate, for example, is 10 mm day^{-1}, then I_d = 10 / (1 – 0.25) = 13.3 mm day^{-1} (ii) For the season use the CWD: I_d = 684 / (1 – 0.25) = 912 mm $I_{ds} = I_d$ – CWD = 912 – 684 = 228 mm. **Step 3: Water required to meet DUL (I_{DUL})** I_{DUL} = 225 mm – 105 mm = 120 mm **Step 4: Outcome** Additional irrigation for salt leaching I_{dt} = 228 + 120 = 348 mm. **Step 5: Ground truthing of root zone salts** Perform suitable soil sampling and salt analysis

A guideline for the approximate quantities of water needed to recover a saline soil is provided in Table 5.6. For example, if a sandy loam soil profile is 1000 mm deep with an average EC_e of 800 mS m^{-1}, the amount of irrigation water required to leach 75% of the salt is: 1000 mm x 0.35 mm mm^{-1} = 350 mm.

Table 5.6 Approximate amount of water (mm per mm soil depth) required to leach out 75% of salts

Average profile EC_e (mS m^{-1})	Soil type			
	Loamy sand	Sandy loam	Loam	Loamy clay
400	0.1	0.17	0.24	0.27
600	0.16	0.26	0.36	0.4
800	0.21	0.35	0.48	0.53
1000	0.27	0.43	0.6	0.66
1600	0.37	0.61	0.84	0.93
2000	0.50	0.65	1.2	1.33
2500	0.50	0.65	1.2	1.7

5.3.2 Reclamation of sodic soils

It is more difficult to recover sodic than saline soils. Recovery is based on the principle that the excess adsorbed sodium on the exchange complex is displaced by calcium and that the sodium is then leached from the soil. This process is complicated by the fact that the flow of water through sodic soils is drastically reduced by dispersed and swelling clay that blocks the soil pores during wetting, thereby complicating the washing in of calcium and washing out of sodium. To overcome this problem to a large extent, large amounts of organic matter (i.e. 50 to 100 t ha^{-1}) is incorporated with gypsum at the beginning of the reclamation process.

For reclamation purposes sodic soils are divided into two classes, namely soils without free lime present and soils with free lime.

5.3.2.1 Soils without free lime

In these soils pure gypsum ($CaSO_4 \cdot 2H_2O$) is used as reclamation reagent. The guideline factor to calculate the amount of gypsum to be applied is summarised in Table 5.7. The following are taken into consideration: (i) 1 cmol of Ca will exchange 2 cmol of Na per kilogram of soil, (ii) bulk density of the soil, (iii) depth (mm) of soil to be reclaimed, and (iv) pureness of the gypsum (assumed to be 70% in this example, any other pureness will affect the values pro rata).

Table 5.7 Guideline for calculating the quantity of pure gypsum (kg gypsum ha^{-1} mm^{-1} soil depth) required to reclaim sodium affected soil

Na in soil (cmol kg^{-1})	Soil bulk density (kg ha^{-1})								
	1000	**1100**	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**
0.5	6.1	6.7	7.3	7.9	8.6	9.2	9.8	10.4	11.0
1	12.2	13.5	14.7	15.9	17.1	18.3	19.6	20.8	22.0
1.5	18.3	20.2	22.0	23.8	25.7	27.5	29.3	31.2	33.0
2	24.5	26.9	29.3	31.8	34.2	36.7	39.1	41.6	44.0
2.5	30.6	33.6	36.7	39.7	42.8	45.9	48.9	52.0	55.0
3	42.8	40.4	44.0	47.7	51.4	55.0	58.7	62.4	66.0
3.5	36.7	40.4	44.0	47.7	51.4	55.0	58.7	62.4	66.0
4	48.9	53.8	58.7	63.6	68.5	73.4	78.3	83.2	88.0
4.5	55.0	60.5	66.0	71.5	77.0	82.5	88.0	93.5	99.0
5	61.1	67.3	73.4	79.5	85.6	91.7	97.8	103.9	110.1
5.5	67.3	74.0	80.7	87.4	94.2	100.9	107.6	114.3	121.1
6	73.4	80.7	88.0	95.4	102.7	110.1	117.4	124.7	132.1
6.5	79.5	87.4	95.4	103.3	111.3	119.2	127.2	135.1	143.1
7	85.6	94.2	102.7	111.3	119.8	128.4	137.0	145.5	154.1
7.5	91.7	100.9	110.1	119.2	128.4	137.6	146.7	155.9	165.1
8	97.8	107.6	117.4	127.2	137.0	146.7	156.5	166.3	176.1
8.5	103.9	114.3	124.7	135.1	145.5	155.9	166.3	176.7	187.1
9	110.1	121.1	132.1	143.1	154.1	165.1	176.1	187.1	198.1
9.5	122.3	134.5	146.7	159.0	171.2	183.4	195.6	207.9	220.1
10	116.2	127.8	139.4	151.0	162.6	174.2	185.9	197.5	209.1

Calculating the required reagent: For example, to calculate the amount of gypsum required per ha to reclaim the following sodium affected soil: the soil has a concentration of 2.5 cmol Na^+ kg^{-1} in the topsoil (300 mm deep) and the bulk density is 1600 kg ha^{-1}. **Solution:** Step 1, find the concentration of sodium (cmol kg^{-1}) in the first column of Table 5.7 (i.e. 2.5 cmol kg^{-1}). Step 2, find the column with the desired bulk density (i.e. column 8, 1600 mS m^{-1}) and where the row and column intersect is the amount of gypsum required per ha per mm of soil depth (i.e. 48.9 kg gypsum ha^{-1} mm^{-1}). Step 3, multiply the answer in Step 2 with the soil depth, i.e. 300 mm. **Answer** is 14670 kg gypsum ha^{-1}. Do not apply more than 5000 kg gypsum per hectare per season if crops are to be planted. There might be impurities in the gypsum source (heavy metals and trace elements) that may harm the crop.

Remarks on amendment: The required amount of gypsum is worked in and mixed well with the soil before the process of leaching the soil is started. If water infiltration decreases drastically, it will be necessary to: (i) Additionally add molasses meal or large quantities of organic material and mix it with the soil; or (ii) An adequate amount of gypsum can be mixed with the irrigation water in order to increase the electrolyte concentration to such a degree that a reasonable rate of infiltration can be maintained. Make sure that borehole water has a lower SAR than that of the soil, it can be used initially and then change to higher quality water. The leaching amount required can be derived from Table 5.6 using the 1000 EC row as a guide. About one month after leaching, soil samples should be taken and analysed for extractable Na concentration to assess the reclamation process. The reason for checking the progress is that some sodic soils contain soluble sodium carbonate that also needs to be neutralised with gypsum, if present.

5.3.2.2 Soils with free lime

In these soils reclamation reagents with an acidifying action is used. The sulphuric acid that is formed in most cases dissolves the lime in the soil, releases calcium which displaces the sodium on the exchange complex. Acidifying reagents that are commonly used include ferrosulphate, aluminium sulphate and sulphur. In practice, ferrosulphate and aluminium sulphate are too expensive, therefore sulphur is recommended. The reaction is as follows:

$$2S + 2H_2O + 3O_2 \text{ ---> } 2H_2SO_4$$

The H_2SO_4 reacts with lime to form gypsum in the soil:

$$CaCO_3 + H_2SO_4 \text{ ---> } CaSO_4 + H_2CO_3$$
$$H_2CO_3 \text{ ---> } H_2O + CO_2$$
$$CaSO_4 \text{ ---> } Ca^{++} + SO_4^{=}$$

The calcium displaces the sodium on the exchange complex and the sodium reacts with the sulfate ($SO_4^{=}$) to form sodium sulphate (Na_2SO_4) that leaches out. The rest of the leaching procedure is the same as for soils without free lime.

The guideline to calculate the amount of sulphur to apply is summarised in Table 5.8. The following are taken into consideration: (i) 1 mol S = 1 mol H_2SO_4 = 1 mol $CaSO_4$ = 2 mol of Na^+ on the exchange surface; (ii) 0.5 cmol S will exchange 1 cmol of Na kg^{-1} soil, or 0.16053 g S will exchange 1 cmol of Na kg^{-1} soil; (iii) bulk density of the soil; (iv) depth (mm) of the soil to be reclaimed; and (v) pureness of the sulphur (assumed to be 100% in this example, any other pureness will affect the values pro rata).

Calculating the required reagent: For example, to calculate the amount of sulphur per ha to reclaim the following Na affected soil: the soil has a sodium concentration of 2 cmol Na kg^{-1} in the topsoil (200 mm deep) and the soil bulk density is 1400 kg ha^{-1}. **Solution:** Step 1, find the sodium concentration (cmol kg^{-1}) in the first column (i.e. 2 cmol kg^{-1}). Step 2, find the column with the desired bulk density (i.e. column 6, 1400 mS m^{-1}) and where the row and column intersect is the amount of S required per ha per mm of soil depth (i.e. 4.49 kg S ha^{-1} mm^{-1}). Step 3, multiply the answer in Step 2 with the soil depth (200 mm). The **answer** is 898 kg S ha^{-1}.

Remarks on amendment: The reagents should preferably be worked into moist soils. The total quantity of reclamation reagent should preferably be divided in such a way that it is worked into the soil twice a year in quantities not exceeding 1 tonne of sulphur, iron sulphate or gypsum. In the case of sulphur, at least two months should pass before the first irrigation is applied. Where acidifying reagents are used, the pH of the soil should be adjusted by means of liming if it drops too low. Crops such as barley or wheat can be established as soon as possible. In all cases provision should be made for artificial drainage of the soils to be reclaimed if the subsoil is inadequately drained.

Table 5.8 Guideline factor for calculating the amount of sulphur (kg S per ha per mm soil depth) to reclaim sodium affected soil

Na in soil (cmol kg^{-1})	Bulk density (kg ha^{-1})								
	1000	**1100**	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**
0.5	0.80	0.88	0.96	1.04	1.12	1.20	1.28	1.36	1.44
1	1.60	1.76	1.92	2.08	2.24	2.41	2.57	2.73	2.89
1.5	2.41	2.65	2.89	3.13	3.37	3.61	3.85	4.09	4.33
2	3.21	3.53	3.85	4.17	4.49	4.82	5.14	5.46	5.78
2.5	4.01	4.41	4.82	5.22	5.62	6.02	6.42	6.82	7.22
3	5.61	6.17	6.73	7.30	7.86	8.42	8.98	9.54	10.10
3.5	4.81	5.29	5.77	6.25	6.73	7.22	7.70	8.18	8.66
4	6.41	7.06	7.70	8.34	8.98	9.62	10.26	10.90	11.55
4.5	7.47	8.22	8.97	9.71	10.46	11.21	11.96	12.70	13.45
5	8.03	8.83	9.63	10.43	11.24	12.04	12.84	13.65	14.45
5.5	8.83	9.71	10.59	11.48	12.36	13.24	14.13	15.01	15.89
6	9.90	10.89	11.88	12.87	13.86	14.85	15.84	16.83	17.82
6.5	10.43	11.48	12.52	13.56	14.61	15.65	16.70	17.74	18.78
7	11.24	12.36	13.48	14.61	15.73	16.86	17.98	19.10	20.23
7.5	12.04	13.24	14.45	15.65	16.86	18.06	19.26	20.47	21.67
8	48.42	53.27	58.11	62.95	67.79	72.64	77.48	82.32	87.16
8.5	13.65	15.01	16.37	17.74	19.10	20.47	21.83	23.20	24.56
9	14.45	15.89	17.34	18.78	20.23	21.67	23.12	24.56	26.01
9.5	16.05	17.66	19.26	20.87	22.47	24.08	25.68	27.29	28.90
10	15.25	16.78	18.30	19.83	21.35	22.88	24.40	25.93	27.45

5.4 Conclusions

The aim of this chapter was to provide practical solutions on water and salt management. Two solution approaches were highlighted, a proactive and a reactive approach. The proactive approach is based on the root zone salinity assessment procedure of Ehlers et al. (2006). Accordingly, the assessment is based on drainage conditions, whether drainage is 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 to 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.

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