RISK BASED, SITE-SPECIFIC, IRRIGATION WATER QUALITY GUIDELINES

Meiring du Plessis, John Annandale, Nico Benadé, Michael van der Laan, Sebastian Jooste, Chris du Preez, Johan Barnard, Nicola Rodda, James Dabrowski, Bettina Genthe, Piet Nell

VOLUME 1- DESCRIPTION OF DECISION SUPPORT SYSTEM

WATER RESEARCH COMMISSION

TT 727/17

Risk Based, Site-Specific, Irrigation Water Quality Guidelines:

Volume 1

Description of Decision Support System

Report to the

WATER RESEARCH COMMISSION

and the

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES

by

Meiring du Plessis[1], John Annandale[1], Nico Benade[2], Michael van der Laan[1], Sebastian Jooste[3], Chris du Preez[4], Johan Barnard[4], Nicola Rodda[5], James Dabrowski[6], Bettina Genthe[6] and Piet Nell[7]

[1]Department of Plant and Soil Sciences, University of Pretoria
[2]NB Systems
[3]Department of Water and Sanitation
[4]Department of Soil, Crop and Climate Sciences, University of the Free State
[5]Department of Microbiology, University of Kwa-Zulu Natal
[6]CSIR
[7]Agricultural Research Council, Institute of Soil, Climate and Water

July 2017

WRC Report No TT 727/17
ISBN No 978-1-4312-0910-1

Obtainable from:
Water Research Commission
Private Bag X03
GEZINA, 0031

orders@wrc.org.za or download from www.wrc.org.za

This report emanates from a project entitled:

Revision of the 1996 South African Water Quality Guidelines: Development of a risk-based approach using irrigation water use as a case study (WRC Project No. K5/2399), and forms part of a series of two reports, namely:

Volume 1: Description of Decision Support System
Volume 2: Technical Support

Electronic copies of the DSS can be downloaded from: https://www.nbsystems.co.za/downloads.html

Printed in the Republic of South Africa

ACKNOWLEDGEMENTS

This project was initiated by the Water Research Commission (WRC) through a directed call with published terms of reference and co-funded by the Department of Agriculture, Forestry and Fisheries (DAFF). The authors would like to thank the Reference Group of the WRC Project for the assistance and the constructive discussions during the duration of the project:

Dr GR Backeberg	:	Water Research Commission (Chairman)
Dr S Mpandeli	:	Water Research Commission
Mr N Rossouw	:	Aurecon
Dr J Molwantwa	:	Water Research Commission (Resigned)
Dr N Kalebaila	:	Water Research Commission
Dr K Murray	:	Private Consultant
Prof GO Sigge	:	Stellenbosch University
Dr N Slabbert	:	Department of Water and Sanitation (Resigned)
Mr P Viljoen	:	Department of Water and Sanitation (DWS)
Mr J van Wyk		Department of Water and Sanitation

The authors would furthermore like to thank the individuals participating in user interaction sessions during the demonstration of the *Technology Demonstrator* which was held in Bloemfontein, Stellenbosch and Pretoria during June 2015 for their valuable contributions to enhance the usefulness of the DSS. A special word of thanks is also due to the following individuals who early in 2017 reviewed the draft final DSS and contributed significantly to the identification and introduction of features that improve the usefulness and user friendliness of the final version of the DSS.

Mr Pieter Viljoen	Water Resource Planning Systems, DWS
Mr Jurgo van Wyk	Water Resource Planning Systems, DWS
Mr Geert Grobler	Water Resource Planning Systems, DWS
Mr Nico Rossouw	Water Quality Specialist, Aurecon
Dr Theresa Volschenk	Institute for Deciduous Fruit, Vines and Wine, ARC

The authors would also like to express our appreciation to Professor Martin Fey, for his thorough appraisal and valuable constructive comments as part of a review of the Inception Report, which helped to give direction and focus to the project during its early stages.

Background

The 1996 South African Water Quality Guidelines comprise one of the most widely-used tools in water quality management. However, they are now viewed as significantly out of date. A Phase 1 Department of Water Affairs and Forestry (now DWS, Department of Water and Sanitation) project was completed by a panel of experts in 2008[1]. They performed a needs assessment, developed a general philosophy and described the general specifications of a decision support system (DSS) for revised water quality guidelines for South Africa.

The Phase 1 Report concluded that a review of the South African Water Quality Guidelines published in 1996 was important for the following reasons:

- **National Water Act**: The approach to water resource management within DWS has changed fundamentally as a result of the promulgation of the National Water Act (No. 36 of 1998). Revised guidelines that are compatible with this Act are therefore required.
- **Risk as a common basis**: It was foreseen that the concept of "risk" could potentially provide a common philosophical basis for decision making in different contexts.
- **Latest science and practice**: Assessment of recent advances in guideline determination, both international and local, was deemed necessary to ensure that South African guidelines are based on the latest and most appropriate science and practice.
- **Limited water uses and water quality constituents**: It was deemed necessary to review existing water uses and the water constituents they cover, and if found necessary, to rationalise or extended them.
- **Site specificity**: The 1996 guidelines provided generic guideline values (meaning that local site-specific conditions were not considered). This was identified as a significant shortcoming.

The new guidelines were thus envisaged to be different in a number of fundamental ways. Firstly, they would be risk-based – a fundamental change in philosophy from the 1996 guidelines. Secondly, they would allow for much greater site-specificity – a widely-recognised limitation of the generic 1996 guidelines. Thirdly, they would be made available primarily as a software-based DSS.

The broader DWS initiative envisages the development of a DSS for each significant water user. The first project, which was initiated and mainly funded by the WRC, addresses guidelines for irrigation water use. Subsequent to the initiation of this project, the WRC decided to fund the development of the new generation guidelines for a further two user groups, namely domestic and recreational water use. The development of DSSs for domestic and recreational water use are reported on elsewhere in separate WRC reports.

[1] DWAF (2008). Development of SA Risk-Based Water Quality Guidelines: Phase 1: Needs Assessment and Philosophy by Ralph Heath (Coordinator), K Murray, J Meyer, P Moodley, K Hodgson, C du Preez, B Genthe, N Muller. July 2008. Department of Water Affairs and Forestry, Pretoria, South Africa.

Project Aims

The general aim of this project was to develop a software-based decision support system (DSS) able to provide both generic and site-specific risk-based irrigation water quality guidelines for South Africa. Specific aims were:

i. To develop an intermediate 'technology demonstrator' that demonstrates the most important features.
ii. To engage with stakeholders to elicit comment and recommendations.
iii. To maximise synergy with parallel projects on the development of water quality guidelines for other water uses.
iv. To develop a fully-functioning DSS for irrigation.

Methodology

The project was designed to achieve the general aim of developing a software-based DSS able to provide both generic and site-specific risk-based irrigation water quality guidelines for South Africa. The two main components of the project were thus firstly, to describe the technical considerations that determine the water quality requirements of irrigation water use; and secondly, to capture these technical considerations in a DSS. The DSS was designed to provide water resource managers and users with guidance about the risks associated with using water of a particular composition for irrigation under both site-specific and generic conditions. The DSS that was developed provides, as far as possible, for quantitative fitness-for-use assessments as well as for determining water quality requirements for irrigation water use.

The primary tool for evaluating fitness-for-use or establishing water quality requirements, is a software-based DSS which operates at three tiers:

i. Tier 1 resembles the 1996 generic guidelines (but modified where applicable) which are generated by the DSS. Tier 1 relies on the minimum user defined input, and provides a conservative water quality assessment, highlighting potential problems if the conservative assumptions are not met. Should a Tier 1 evaluation indicate potential problems, a more rigorous and site-specific Tier 2 evaluation is indicated.
ii. Tier 2 allows for site specificity, the extent of which is predetermined by the site-specific variables that are provided for as part of the DSS. The DSS allows a user to conduct a more in-depth water quality assessment and guideline generation, by making use of a relatively sophisticated crop growth - soil water balance and chemistry model which uses selectable site-specific input parameters, to simulate the response of soils, crops and irrigation equipment to irrigation water composition under different climatic and water management conditions.
iii. Tier 3 allows for site specificity in other *ad hoc* contexts where required, possibly using modules of the DSS and other specialised resources as required for a specific purpose. Tier 3 guidelines are of a specialised nature requiring significant expertise and do not explicitly form part of the DSS, although some guidance is provided for conducting Tier 3 investigations.

A clear distinction is maintained between the resource management decision domain (as used by water resource managers and users) and the supporting science (provided through this project). For example, application of the precautionary principle (like in "safety factors") is transparent.

The appropriate informatics as well as approaches for future updating of databases and algorithms received specific attention. For example, both quantitative and more qualitative expert information were consolidated in look-up tables and form an integrated part of decision support. The sources of the information or the way in which they have been derived and applied in the DSS, are reported in Volume 2 of this report (Technical Support), thereby facilitating future updating where deemed necessary.

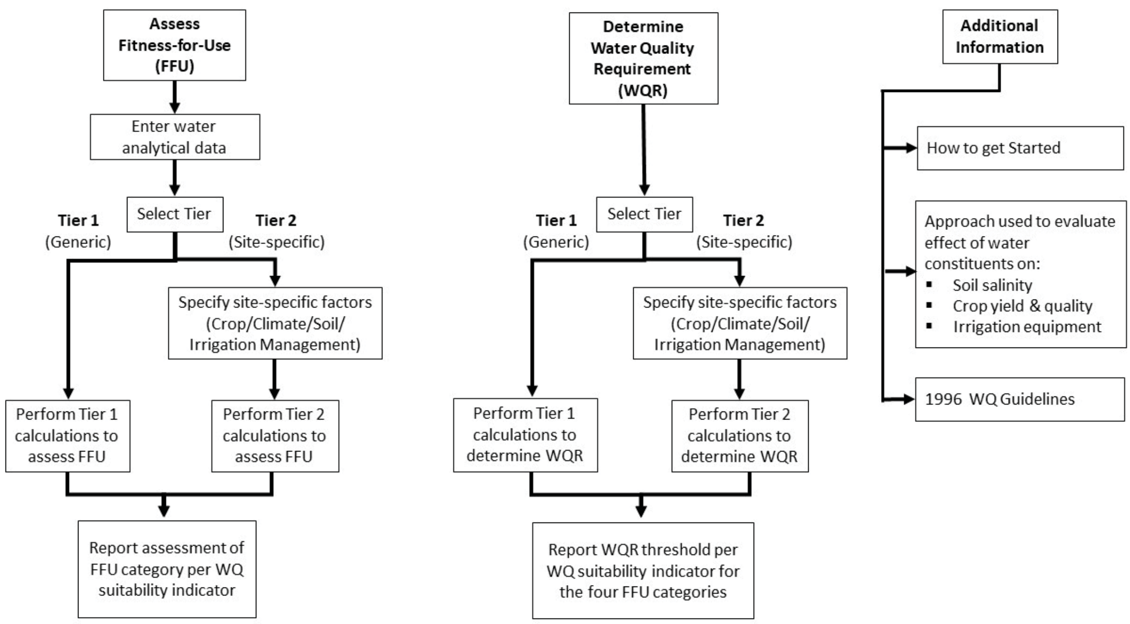
The project was executed in the following phases, which coincided well with the project deliverable schedule:

i. An Inception Workshop during which the project team clarified their understanding of the project aims and agreed on the way forward.
ii. Produced a concise literature review documenting the current understanding of how water constituents, soils, crops, climate, irrigation systems, irrigation management and other factors interact to impact on soil quality, crop yield and quality and irrigation equipment. The review provided the theoretical basis or technical framework for the development of the DSS.
iii. The development of a *Technology Demonstrator*, which consisted of the preliminary software system that demonstrated the most important features of Tiers 1 and 2 for six water constituents representing different categories of constituents.
iv. Demonstration of the Technology Demonstrator to potential user groups, who were in general favourably impressed with the concept, and made several suggestions for improvement.
v. Development of a fully functional draft DSS incorporating all the features and water constituents envisaged for the final DSS.
vi. Testing and evaluation of the draft final DSS by selected South African water quality experts in order to evaluate its user friendliness and acceptability, as well as the confidence which can be placed in its ability to make reliable evaluations.
vii. A draft and final report, documenting the execution of the project and the important features of the DSS.

The Decision Support System (DSS)

The following diagram depicts the overall structure of the DSS. At the highest level, a user has to decide whether he or she wants to use the DSS to assist with:

i. assessing the fitness of a water for irrigation use (as elaborated on below), or
ii. setting water quality requirements for irrigation users (as elaborated on below), or
iii. obtaining additional information, as indicated in the diagram.



After selecting the appropriate DSS functionality to access, the user is guided through a decision tree to choose between different options and select the appropriate route in order to process the user's need and provide output in a user-friendly format.

It is assumed in the DSS, that the fitness for use of a specific water can be categorised into different levels of acceptability and implied risk. The classification system is based on a DWS system which describes four suitability categories to which water quality can be assigned. The four categories are defined in generic terms applicable to any water use and colour coding is employed throughout the DSS to express the evaluated fitness for use of the different indicators of water suitability.

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

The Development Platform

One of the important design criteria stipulated in the project Terms of Reference, is that the Decision Support System (DSS) should make use of open source software. Lazarus was used for the development of the DSS, as it is an open source Delphi compatible cross-platform IDE for Rapid Application Development. It has a variety of components ready for use and a graphical form designer to easily create complex graphical user interfaces. Firebird, which is used for the database, is an open source relational database offering many ANSI SQL standard features and runs on Linux, Windows, and a variety of Unix platforms. Firebird offers excellent concurrency, high performance, and powerful language support for stored procedures and triggers.

Calculating procedures

Both the fitness-for-use of irrigation water and establishment of water quality requirements in the DSS are assessed with regard to the effect its constituents have on soil quality, crop yield and quality as well as irrigation equipment. The philosophical approach adopted was to use simplified conservative assumptions requiring no input to determine Water Quality Requirements, and only the irrigation water composition to establish Fitness-for-Use, for Tier 1 assessments. In this way, a rapid "conservative" irrigation water quality assessment is obtained. Should the Tier 1 assessment indicate no potential problems with the water composition, 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 problems with the water composition, a more detailed, site-specific assessment as provided by a Tier 2 assessment, is indicated.

Tier 2 assessments allow the user to choose between selectable site-specific conditions, in order to provide a significantly enhanced assessment of how the specific water composition can be expected to affect a specific crop, under specific climatic conditions, with defined, selectable, irrigation management when irrigating a soil with a specific, selectable, texture. Tier 2 assessments, therefore, allow the user to assess how the implementation of alternative site-specific management options (e.g. a different crop, soil, irrigation management, etc.), can be expected to modify a fitness-for-use or water quality requirement determination, as the adoption of different management practices may reduce or overcome the problems associated with a specific water composition. Whenever the selectable management options or the modelling procedure provided for in Tier 2, are deemed insufficient or inappropriate for a specific application, a Tier 3 evaluation is called for.

Tier 3 assessments are viewed as specialised in nature. It is anticipated that Tier 3 investigations would focus on specific targeted aspects of water quality assessments. Tier 3 investigations would thus require situation specific on-site investigations and significant expertise. The current DSS does not provide for Tier 3 investigations, although some guidance for conducting Tier 3 investigations using modules of the DSS is provided.

Tier 1 calculations of soil-crop-water interactions assume an idealised 4-layer soil in which 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. The steady state (or equilibrium) concentration of soluble constituents in each layer is calculated from the concentration of constituents in the irrigation water and the leaching fraction for the profile as a whole. Tier 2 calculations make use of a simplified version of the dynamic Soil Water Balance (SWB) model that is run for a minimum of 10 years, using data from an appropriate 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. This output is used to derive yield and other outputs, from which the likelihood with which specific yield intervals occur over time, can be calculated.

Evaluation of fitness-for-use

A fitness-for-use evaluation is carried out in the following steps:

i. Enter the water analysis for the water requiring a fitness for use assessment.
ii. Calculate the value of the parameter that is required to evaluate the impact on the suitability indicator that is being assessed (e.g. in order to evaluate the impact on root zone salinity, a calculation of the value of the soil saturation extract electrical conductivity (ECe), is required). The calculation is carried out using the appropriate calculating procedure for either Tier 1 or Tier 2;
iii. The calculated value is compared with the criteria used to assess the effect on the suitability indicator under consideration, in order to determine the corresponding fitness-for-use category.

For Tier 1 evaluations, a single value of the parameter of interest is calculated and the fitness-for-use category identified, as indicated in the example below for the evaluation of the soil quality suitability indicator, Root Zone Salinity. Since the value of root zone salinity is displayed (and not only the fitness-for-use category), additional information is conveyed to the user about how close the value is to the boundary of a fitness-for-use category.

	Fitness-for-Use	**EC_e interval (mS/m)**	**Predicted equilibrium root zone salinity (mS/m)**
Root Zone Salinity	Ideal	0 - 200	
	Acceptable	200 - 400	**234**
	Tolerable	400 - 800	
	Unacceptable	>800	

For Tier 2 assessments, at least 10 annual mean values are calculated when the SWB model is run for 10 or more years of climatic data. These values are likely to fall into different fitness-for-use categories and are reported as the % of time for which the values fall within a specific fitness-for-use category (as indicated in the example below for the evaluation of the soil quality suitability indicator, Root Zone

Salinity). In this way, information about the longer term fitness-for-use risk associated with using the water is conveyed to the user.

	Fitness-for-Use	EC_e interval (mS/m)	% of time root zone salinity is predicted to fall within a particular Fitness-for-Use category
Root Zone Salinity	Ideal	0 - 200	**60**
	Acceptable	200 - 400	**30**
	Tolerable	400 - 800	**10**
	Unacceptable	>800	

Establishing water quality requirements

Water quality requirements are established by carrying out the following steps.

i. Identify the value of the threshold criterion for each fitness-for-use category of the suitability indicator for which water quality requirements are needed. These values are part of the criteria that are available for the different parameters. In the example below for root zone salinity, the threshold values are 200, 400 and 800 mS/m, and

ii. Through iteration or analytical procedure, determine the concentration of the water constituent that will return each threshold concentration.

For Tier 1 water quality requirement determinations, a single value is calculated for each threshold criterion as indicated in the example below for Root Zone Salinity. An irrigation water EC of 106 mS/m, will, for example, return a root zone salinity value of 200 mS/m and an irrigation water EC of 213 mS/m will return a root zone salinity value of 400 mS/m.

	Fitness-for-Use	EC_e interval (mS/m)	EC range that will give rise to the corresponding root zone salinity category (mS/m)
Root Zone Salinity	Ideal	0 - 200	**<106**
	Acceptable	200 - 400	**106 – 213**
	Tolerable	400 - 800	**213 – 426**
	Unacceptable	>800	**>426**

For Tier 2 calculations, variability in climate and other factors give rise to a range of soil EC_e values for a single irrigation water EC. For purposes of the DSS, the 95th percentile EC_e value associated with an irrigation water EC is used. The irrigation EC corresponding to a fitness-for-use threshold criterion, is obtained through interpolation, by running a number of successive SWB simulations, each time with a higher irrigation EC value. In this way, the irrigation water EC requirements that will give rise to corresponding fitness-for-use category EC_e values, as in the example below, are obtained by interpolation.

	Fitness-for-Use	EC_e interval (mS/m)	EC range that will give rise to the corresponding root zone salinity category for 95% of the time (mS/m)
Root Zone Salinity	Ideal	0 - 200	**<90**
	Acceptable	200 - 400	**90 – 180**
	Tolerable	400 - 800	**180 – 360**
	Unacceptable	>800	**>360**

Suitability Indicators Provided for in the DSS

The DSS assesses fitness for use and establishes water quality requirements for the effect irrigation water constituents have on soil quality, crop yield and quality, as well as irrigation equipment. For each of these, a number of suitability indicators were identified, as indicated below. The criteria used to determine the fitness for use category of each suitability indicator and the relevant calculation procedures, are presented and elaborated upon in the report.

Suitability Indicators		
Soil Quality	**Crop Yield and Quality**	**Irrigation Equipment**
Root zone salinity Soil permeability Oxidisable carbon loading Trace element accumulation	Root zone effects Leaf scorching when wetted Contribution to NPK removal Microbial contamination Qualitative crop damage by atrazine	Corrosion or scaling of irrigation equipment Clogging of drippers

Conclusions and Recommendations

The general aim of this project was to develop a software-based decision support system able to provide both generic and site-specific risk-based irrigation water quality guidelines for South Africa. Specific aims were:

1. To develop an intermediate 'technology demonstrator' that demonstrates the most important features.
2. To engage with stakeholders to elicit comments and recommendations.
3. To maximise synergy with parallel projects on the development of water quality guidelines for other water uses.
4. To develop a fully-functioning DSS for irrigation.

The first two specific aims were addressed during the execution of the project as part of the development and refinement of the fully functional DSS for irrigation. The synergy with the two parallel projects developing guidelines for domestic and recreational use were maximised by regular formal and informal interaction with their research teams during which ideas, approaches and completed deliverables were discussed and shared.

The general aim to develop a software-based DSS able to provide both generic and site-specific risk-based irrigation water quality guidelines for South Africa, was successfully completed as described in this report. The DSS is a user friendly, self-contained system, incorporating the data bases, help files and supporting information that are required to run the DSS.

Designing and establishing the DSS was a major undertaking, and as far as could be ascertained, a world first. For a project of this nature and scope, it is only to be expected that further refinement and the need for additional features would be identified during the course of the project. The more significant of these are to:

i. Enable the use of time series of water constituent analytical data. (The DSS currently provides only for a single water analysis);
ii. Modify the SWB model to create a feedback loop between water and salt stress so that reduced water uptake is simulated during periods of salt stress;
iii. Develop and display an integrated fitness for use evaluation and/or overview summary;
iv. Establish an interface which enables downloading of climate data stored on the internet to the DSS;

v. Establish a facility enabling the import of multiple water constituent analyses (need of analytical laboratories);
vi. To update the DSS to improve user-friendliness and utility based on extensive feedback from actual users;
vii. Enable additional output displays for fitness for use, such as a graph showing how each suitability indicator changes with time, how soil salinity changes with depth, where in the soil profile problems with hydraulic conductivity are expected to be encountered, how the Langelier Index and its implications for corrosion and scaling change with changing temperature, etc.
viii. Update the DSS with intervals of about five years, in order to update its scientific content where necessary to introduce new findings or data.

The report consists of two volumes:
Volume 1: Description of Decision Support System (this report)
Volume 2: Technical Support (on USB at back page)

Electronic copies of the DSS can be downloaded from: https://www.nbsystems.co.za/downloads.html

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDIX

1 BACKGROUND AND INTRODUCTION

The South African Water Quality Guidelines comprise one of the most widely-used tools in water quality management. However, they are now viewed as significantly out of date. A Phase 1 Department of Water Affairs (now Department of Water and Sanitation, DWS) project was completed by a panel of experts in 2008 (DWAF, 2008). They performed a needs assessment, developed a general philosophy and described the general specifications of a decision support system (DSS) for revised water quality guidelines for South Africa.

The Phase 1 Report concluded that a review of the South African Water Quality Guidelines published in 1996 was important for the following reasons:

- **National Water Act**: The approach to water resource management within DWS has changed fundamentally as a result of the promulgation of the National Water Act (No. 36 of 1998). Revised guidelines that are compatible with this Act are therefore required.
- **Risk as a common basis**: It was foreseen that the concept of "risk" could potentially provide a common philosophical basis for decision making in different contexts.
- **Latest science and practice**: Assessment of recent advances in guideline determination, both international and local, was deemed necessary to ensure that South African guidelines are based on the latest and most appropriate science and practice.
- **Limited water uses and water constituents**: It was deemed necessary to review existing water uses and the water constituents they cover, and if found necessary, to rationalise or extended them.
- **Site specificity**: The 1996 guidelines provided generic guideline values (meaning that local site-specific conditions were not considered). This was identified as a significant shortcoming.

The new guidelines were thus envisaged to be different in a number of fundamental ways. Firstly, they would be risk-based – a fundamental change in philosophy from the 1996 guidelines. Secondly, they would allow for much greater site-specificity – a widely-recognised limitation of the generic 1996 guidelines. Thirdly, they would be made available primarily as a software-based DSS.

The broader DWS initiative envisages the development of a DSS for each significant water user. The first project, which was initiated and funded by the WRC, addresses guidelines for irrigation water use. Subsequent to the initiation of this project the WRC decided to fund the development of the new generation guidelines for a further two user groups, namely domestic and recreational water use. The development of DSSs for domestic and recreational water use are reported on elsewhere in separate WRC reports.

The aims for this project to develop revised water quality guidelines for irrigation, were as follows:

General:
To develop a software-based decision support system (DSS) able to provide both generic and site-specific risk-based irrigation water quality guidelines for South Africa.

Specific:
1. To develop an intermediate 'technology demonstrator' that demonstrates the most important features.
2. To engage with stakeholders to elicit comment and recommendations.
3. To maximise synergy with parallel projects on the development of water quality guidelines for other water uses.
4. To develop a fully-functioning DSS for irrigation.

The methodology for this project was designed to achieve the general aim of developing a **software-based DSS** able to provide both **generic** and **site-specific risk-based irrigation water quality**

guidelines for South Africa. The two main components of the project were thus firstly, to describe the technical considerations that determine the water quality requirements of irrigation water use; and secondly, to capture these technical considerations in a DSS. The DSS was designed to provide water resource managers and users with guidance about the risks associated with using water with a particular composition for irrigation under both site-specific and generic conditions. The DSS that was developed provides, as far as possible, for **quantitative fitness-for-use assessments** as well as for **determining water quality requirements** for irrigation water use.

The primary tool for evaluating fitness-for-use or setting water quality requirements, is a software-based DSS which operates at three tiers:

1. Tier 1 resembles the 1996 generic guidelines (but modified where applicable) which are generated by the DSS. Tier 1 relies on the minimum user defined input, and provides a conservative water quality assessment, highlighting potential problems if the conservative assumptions are not met. Should a Tier 1 evaluation indicate potential problems, a more rigorous and site-specific Tier 2 evaluation is indicated.
2. Tier 2 allows for site specificity, the extent of which is predetermined by the site-specific variables that are provided for as part of the DSS. The DSS allows a user to conduct a more in-depth water quality assessment and guideline generation, by making use of a relatively sophisticated crop growth - soil water balance and chemistry model which uses selectable site-specific input parameters, to simulate the response of soils, crops and irrigation equipment to irrigation water composition under different climatic and water management conditions.
3. Tier 3 allows for site specificity in other *ad hoc* contexts where required, possibly using modules of the DSS and other specialised resources as required for a specific purpose. Tier 3 guidelines are of a specialised nature requiring significant expertise and do not explicitly form part of the DSS, although some guidance is provided for conducting Tier 3 investigations.

A clear distinction is maintained between the resource management decision domain (as used by water resource managers and users) and the supporting science (provided through this project). For example, application of the precautionary principle (like in “safety factors”) is transparent.

The appropriate informatics as well as approaches for future updating of databases and algorithms received specific attention. For example, both quantitative and more qualitative expert information were consolidated in look-up tables and form an integrated part of decision support. The sources of the information or the way in which they have been derived and applied in the DSS, are all reported on in Volume 2 of this report (Technical Support), thereby facilitating future updating where deemed necessary.

The project was executed in the following phases, which coincided well with the project deliverable schedule:

i. An Inception Workshop during which the project team;
   - Clarified the concepts of multi-tier, risk-based and site-specific water quality guidelines to a point where all participants shared a common understanding of these concepts and their implications for establishing irrigation water quality guidelines.
   - Obtained consensus on how to incorporate risk-based and site-specific concepts into a procedure to deduce (calculate) site-specific and generic risk-based water quality guidelines for irrigation.
   - Agreed on the conceptual design of the DSS and the provision that would be made to accommodate the above-mentioned calculation procedures, future updates and data handling.

- Proposed definitions of fitness-for-use water quality categories for irrigation that are in line with DWS's water resource classification system, and
- Identified constituents for which water quality guidelines should be developed in line with the guidance provided by the Phase1 Report.

ii. A concise literature review documenting the current understanding of how water constituents, soils, crops, climate, irrigation systems, irrigation management and other factors interact to modify characteristics (called suitability indicators) of soils, crops and irrigation equipment that are important for sustainable agricultural production under irrigation. The agricultural production components that have been identified as important in this regard are: soil quality, crop yield and quality as well as the irrigation equipment used to apply and distribute irrigation water. A specific focus of the literature review was to identify soil, crop and water characteristics which can be used in the DSS as indicators of how the agricultural production components of concern are affected by water constituents, irrespective of their origin. The review aimed to provide users of the DSS with a concise overview of how the interactions between water and its constituents, soils, plants, climate and irrigation equipment determine the sustainability of agricultural production under irrigation. In so doing, the review also provided the theoretical basis or technical framework for the development of the DSS.

iii. The development of a *Technology Demonstrator*, which consisted of the preliminary software system that demonstrated the most important features of Tiers 1 and 2, including user help within the DSS for six water constituents representing different categories of constituents.

iv. Interaction with user groups during a demonstration of the Technology Demonstrator to potential users interested in its ability to establish water quality requirements for irrigation as well as users interested in its ability to assess the fitness of a specific water. The user groups were favourably impressed with the user friendliness of the output screens, the colour coding of fitness-for use categories, general display of output and the clustering of assessment outcomes according to the effect they have on agricultural production systems (soil quality, crop yield and quality and irrigation systems). They were also generally satisfied with the structuring and demonstrated navigation within the DSS. Several suggestions for improvements to the DSS were made.

v. Development of a fully functional draft DSS incorporating all the features and water constituents envisaged for the final DSS.

vi. Testing and evaluation of the draft final DSS by individual South African water quality experts in order to evaluate its user friendliness and acceptability, as well as the confidence which can be placed on its ability to make reliable evaluations.

vii. A draft and final report documenting the execution of the project and the important features of the DSS.

The final report provides an overview of the development of a DSS for evaluating the fitness-for-use of irrigation water with a given composition and the determination of water quality requirements for irrigation water, employing a risk based, site-specific approach. The report is structured as follows:

- Chapter 2 provides an overview of the final DSS;
- Chapter 3 gives a short description of the development platform that was used for the DSS and the fact that use is made of open source software, a key requirement specified in the project Terms of Reference;

- Chapter 4 describes the general approach followed in designing the DSS, with special emphasis on the different approaches used for Tier 1 and 2 assessments, and how fitness-for-use assessments differ from those providing guidance for setting water quality requirements;
- Chapter 5 describes how the input requirements increase when advancing from Tier 1 to Tier 2 assessments and how they differ between using the DSS for either fitness-for-use assessments or for the setting of water quality requirements;
- Chapter 6 describes the procedures and criteria used in the DSS to calculate the impact of water constituents on soil quality and how to interpret the output;
- Chapter 7 describes the procedures and criteria used in the DSS to calculate the impact of water constituents on crop yield and quality and how to interpret the output;
- Chapter 8 describes the procedures and criteria used in the DSS to calculate the impact of water constituents on irrigation equipment and how to interpret the output, and finally,
- Chapter 9 contains a discussion of how successful the project was in meeting its aims, shortcomings that were identified during the course of the project and recommendations for future enhancements to the DSS.

The report consists of two volumes:

Volume 1: Description of Decision Support System (this report)

Volume 2: Technical Support (on USB at back page)

Electronic copies of the DSS can be downloaded from: https://www.nbsystems.co.za/downloads.html

2 OVERVIEW OF THE DECISION SUPPORT SYSTEM

A primary reason for DWS' drive to develop risk-based water quality guidelines was that, in this way, they would establish a common language that can be used by the different water user communities (e.g. recreation, natural environment, livestock watering and aquaculture) when they discuss the setting of resource water quality requirements. Initially it was envisaged that it would be possible to quantify risk with a single number. During the establishment of resource quality requirements, the use of a single "risk value" by all users to calculate their corresponding water quality requirements, would ensure that resource quality requirements calculated by different users would represent a similar level of risk (ill effects) to all of them. This ideal, however, proved to be unattainable within the time constraints for the completion of this project. It was agreed that rather than striving for a single value to express risk, risk would for purposes of the irrigation water quality guidelines, be quantified within a scenario describing the risk being assessed, the consequences should the risk materialise and the likelihood that the risk would materialise. This definition applies to both fitness for use evaluations of water with a given composition and to the setting of water resource quality requirements. While the science and calculations underlying the assessments are the same for both Fitness-for-Use evaluations and for setting Water Quality Requirements, the way in which results are interpreted (on the one hand) and conveyed and presented to the user groups (on the other hand) do differ.

Throughout the DSS, use is made of a colour coded generic classification of water quality which categorise fitness-for-use into four categories, coinciding with an increased risk of using the water. These fitness-for-use categories are described in qualitative generic terms, which are generally applicable to all water uses. It is envisaged that this classification system will be used as a common denominator in the description and classification of water quality by all water user communities for which DSSs are currently under development. The classification system (see Table 2-1) is based on a DWS system which describes four suitability categories to which water quality can be assigned. This four-category system that defines water quality in generic terms, was adopted for use in the classification of irrigation water fitness-for-use. The colour scheme to depict the different categories is used throughout the DSS.

Table 2-1. A generic description of the DWS fitness-for-use classification of water quality

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

The DSS has been designed to cater for two diverging applications, namely:

i. To assess the **fitness-for-use** of a water with a known composition (water analysis) by determining its fitness-for-use category. This is the more conventional application, and

ii. To determine the threshold water composition for a specific fitness-for-use category. This application is used by water resource managers and users when deliberating on the **setting of water quality requirements** for a given water resource (river stretch or surface or groundwater body)

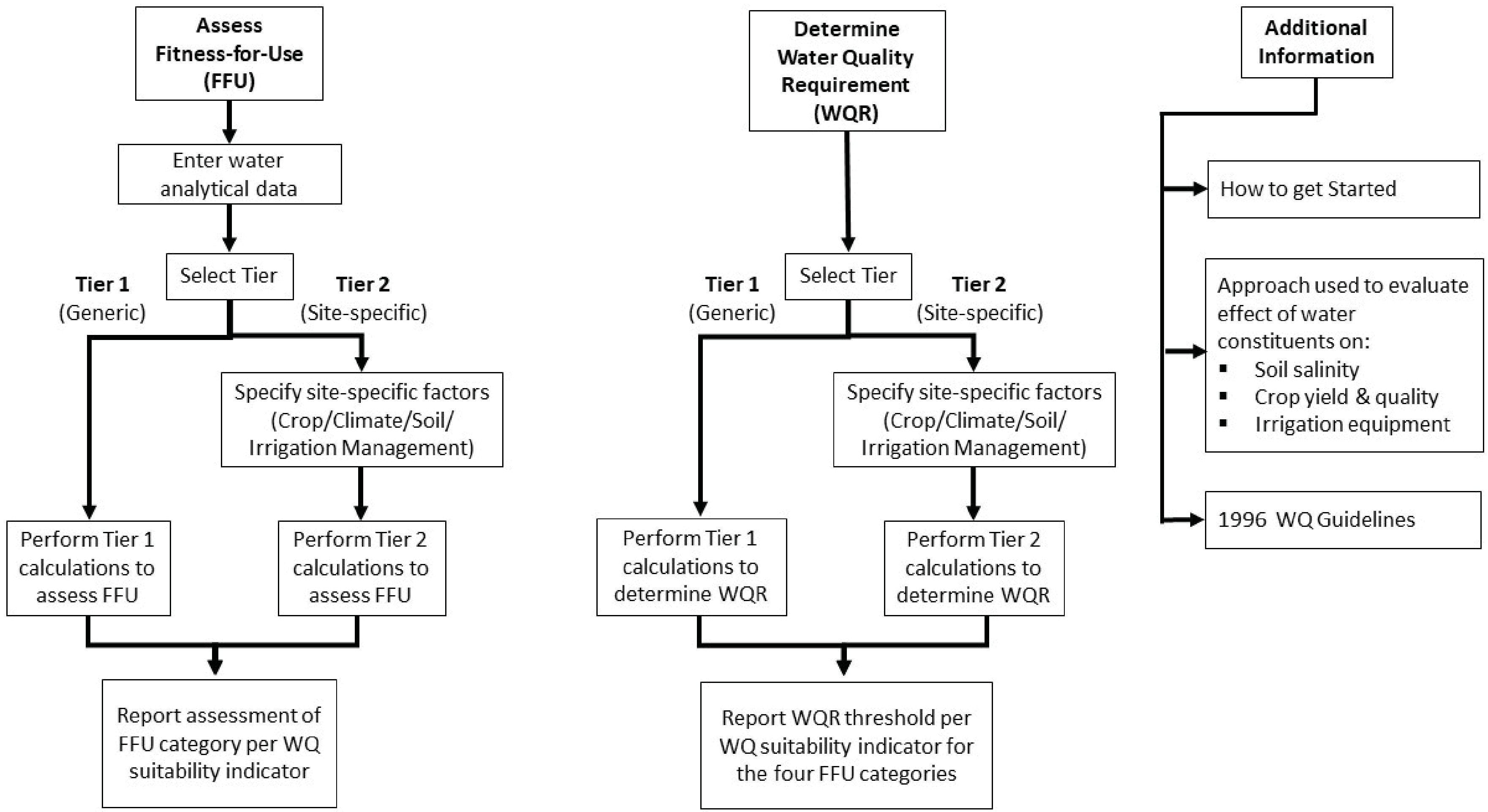


Figure 2-1. Simplified schematic representation of the DSS structure

The input needs, processing procedures and output displays for these two applications are very different. However, the science and calculations that underlie them, are the same. These differences and commonalities are reflected in the structure of the DSS as depicted in Figure 2-1 and Figure 2-2.

At the highest level, a user has to decide whether he or she wants to use the DSS to assist with:

i. assessing the fitness of a water of known composition for irrigation use, or
ii. determining the water quality requirements for irrigation users, or
iii. obtaining additional information.

After selecting the appropriate DSS functionality to access, the user is guided through a decision tree to choose between different options and select the appropriate route in order to process the user's need and provide output in a user friendly format.

In the following Chapters, more information and background are provided concerning:

i. The general approach and calculating procedures employed by the DSS and how they differ for Tier 1 and 2 calculations;
ii. The input requirements of the DSS and how they differ for Tier 1 and 2 calculations;
iii. The specific approaches and calculating procedures adopted for generic (Tier 1) and site-specific (Tier 2) evaluations of the fitness-for-use and determination of water quality requirements related to soil quality, crop yield and quality and irrigation equipment, and
iv. The criteria to assess and graphically display the impact of water constituents on soil quality, crop yield and quality and irrigation equipment.

By selecting the DSS to either assess the fitness-for-use of water of a given composition or to determine water quality requirements, at Tier 1 or 2 levels of site specificity, the DSS will produce output in one of the following four modes:

i. Tier 1 calculations to assess conservative fitness-for-use of irrigation water of a given composition;
ii. Tier 1 calculations to determine conservative water quality requirements for irrigation use;
iii. Tier 2 calculations to assess site-specific fitness-for-use of irrigation water of a given composition, or
iv. Tier 2 calculations to determine site-specific water quality requirements for irrigation use.

The output in each case consists of four to five separate PDF printable output screens displaying either the fitness-for-use assessment or the water quality requirements determined for:

i. Soil quality;
ii. Crop yield and quality, and
iii. Irrigation equipment.

An example of the output for a Tier 1 fitness for use evaluation for growing a double crop is presented in Appendix A.

- The first page contains the analytical data of the water sample the fitness-for-use of which is assessed.
- The second page contains the assessment of how the water composition will affect soil quality.
- The third page contains the assessment of how the water composition will affect crop yield and quality of a generic sensitive crop.
- The fifth page contains the assessment of how irrigation equipment will be affected by the water composition.

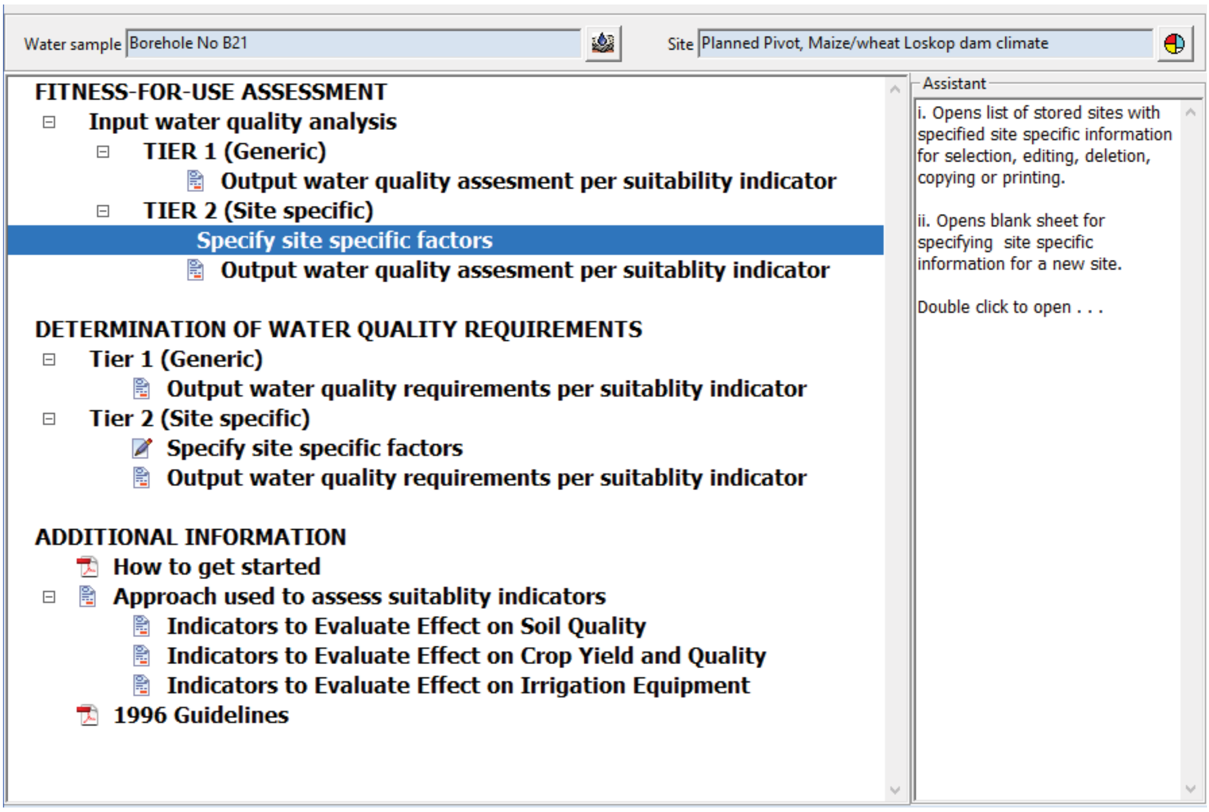


Figure 2-2. The main DSS screen that guides users through the options to perform a fitness-for-use assessment, to determine water quality requirements, or to obtain additional information.

3 THE DEVELOPMENT PLATFORM

3.1 OVERVIEW AND COMPONENTS

One of the important design criteria stipulated in the project Terms of Reference, is that the Decision Support System (DSS) should make use of open source software. This requirement was met.

Lazarus is used for the development of the DSS, as it is an open source Delphi compatible cross-platform integrated development environment (IDE) for Rapid Application Development. It has a variety of components ready for use and a graphical form designer to easily create complex graphical user interfaces. Firebird, which is used for the database, is an open source relational database offering many American National Standards Institute (ANSI) structure query language (SQL) standard features that runs on Linux, Windows, and a variety of Unix platforms. Firebird offers excellent concurrency, high performance, and powerful language support for stored procedures and triggers.

The DSS is an integrated combination of Lazarus computer code linking input data, calculation procedures and data bases to produce output concerning irrigation water quality. It consists of:

i. Calculating 'engines' which simulate crop-soil-climate and other interactions with irrigation water constituents under specified conditions, produce output parameters which are used to estimate the response of soil, crops and irrigation equipment to irrigation water constituents. The main calculation procedures used, are a steady state procedure (see section 4.1) used for Tier 1 calculations, and the SWB model (see section 4.2) for Tier 2 calculations. Some suitability indicators require separate calculations, which in some cases rely on output from the steady state or SWB calculations.

   These calculating procedures were written in Lazarus code and would require reprogramming to update. Care was taken during programming to employ good programming practices such as using a consistent protocol for defining variables, establishing a structured program and copious use of notes and annotation to explain the program coding.

ii. A Firebird database table in which the daily output from SWB simulations and other calculations are stored. The daily data are summarised or integrated to provide seasonal parameter values (annual for soils and growth period for crops) which are used to estimate the response of soils and crops to irrigation water constituents.

iii. Information stored in the Firebird database that is used during simulations, e.g. climatic data from preselected weather stations and water holding characteristics of predefined soil texture classes. These data bases can be expanded upon or deleted by the DSS administrator when required.

iv. Lookup tables within the Firebird database, with soil, crop and irrigation equipment parameters that define their quantitative or qualitative response to output from steady state, SWB and other calculations, e.g. crop yield response relationships. These tables can be updated by the DSS administrator when more appropriate data becomes available.

v. User defined tables containing water analyses and specifications of site-specific conditions as required for Tier 2 simulations.

vi. Output tables which present the assessment of the effect water composition has on soil quality, crop yield and quality and irrigation equipment.

3.2 PROGRAMMING AND RELATED LESSONS LEARNT

The overall planning that preceded the development of the DSS was found to be sound and made a major contribution to the ultimate successful completion of the project. For example, the identification of interim milestones in the form of deliverables that built on each other, helped to ensure that a solid foundation was laid at every stage and before proceeding with the next. It also helped to keep the developers focused on the primary aim.

However, constructing the DSS was a challenging task which often required developing new insights and breaking new programming ground, which took longer than anticipated (e.g. the programming required to develop the user friendly DSS output screens). It was found that all stages of the development process required iterations before an acceptable product was produced. Sometimes it was necessary to compromise. The project team consequently underestimated the magnitude of the task and found the deliverable schedule mostly too tight to adhere to, with the result that they sometimes had to proceed with a next phase without having sufficient opportunity to reflect on what had already been accomplished.

The project team consisted of experts in the field from several different institutions. During the initial information gathering and sharing phase of the project, it was found relatively easy to allocate responsibility and coordinate contributions from team members in different geographic locations. However, this became increasingly difficult during the intensive programming phases when it was necessary for the programmer and researchers to interact on a regular interpersonal basis. It was again possible to involve team members in different geographic locations during the final phase that involved testing whether the DSS performed as expected.

One of the project aims was to maximise synergy with parallel projects on the development of water quality guidelines for other water uses. Synergy with the two parallel projects developing guidelines for domestic and recreational use, was maximised by regular formal and informal interaction with their research teams during which ideas, approaches and completed deliverables were discussed and shared. These interactions between research teams wrestling with similar problems and the implementation of new concepts proved to be beneficial to all concerned.

3.3 RECOMMENDATIONS FOR FUTURE GUIDELINE RELATED PROJECTS

The overall planning and phasing of this project proved to be sound and should thus be used to provide guidance to similar future projects. Much of this project’s planning was scheduled as prescribed by the project Terms of Reference published by the Water Research Commission. Similar Terms of Reference formed the basis for the directed call for project proposals that gave rise to the current two parallel projects developing guidelines for domestic and recreational use. They are thus already being executed following similar planning and phasing as this project.

It is recommended that the other Water Quality Guideline projects consider using the same platform for their software development. Solutions to several of the unique problems encountered with this project, have been found, potentially thereby considerably easing programming in similar future projects.

4 GENERAL APPROACH AND CALCULATING PROCEDURES

A basic premise of the DSS is that the fitness-for-use of water for irrigation is determined by the extent to which water constituents affect those components of an irrigation development which determine its success. The following components of an irrigation development were identified to be affected by water constituents, namely soil quality, crop yield, crop 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. The components were, in turn, subdivided into a number of "suitability indicators", each of which address a different aspect of the success determining components (soil quality, crop yield, crop quality, and irrigation equipment).

For each of the suitability indicators, the current state of knowledge is presented and evaluated in Volume 2 of this report (Technical Support). This is followed by a description of the approach adopted in the DSS to calculate and evaluate the effect the suitability indicator has on soil quality, crop yield, crop quality, or irrigation equipment. The criteria that define fitness-for-use categories for each suitability indicator, are also presented.

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 chapters 6, 7 and 8 of this report. The suitability indicators and the criteria used to define fitness-for-use categories are stated explicitly. The suitability indicators may be expanded or reduced in future updates of the DSS. Similarly, it may in future be found necessary to alter the criteria used to define Fitness-for-Use categories. The same suitability indicators, criteria and calculating procedures are used to determine both Fitness-for-Use and Water Quality Requirements (an inverse calculation is used to calculate Water Quality Requirements)

The fact that suitability indicators and the criteria used to define Fitness-for-Use categories, are stated explicitly, enables DSS users who may wish to use different indicators or criteria, to attach a modified interpretation to DSS output. Should a DSS user consider some suitability indicators as inappropriate or of less concern, the indicator may be ignored or less importance attached to its output. A DSS user may likewise modify the importance attached to the output of a particular suitability indicator when the criteria used in the DSS are considered inappropriate. However, against the background of the current state of knowledge, the project team consider the criteria used in the DSS to represent the most appropriate, currently available.

For Tier 1 assessments, the philosophical approach was adopted to use simplified conservative assumptions requiring no input to determine Water Quality Requirements, and only the irrigation water composition to establish Fitness-for-Use. In this way, a rapid "conservative" irrigation water quality assessment is obtained. 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 water composition problems, a more detailed, site-specific assessment, as provided by a Tier 2 assessment, is indicated.

Tier 2 assessments allow the user to choose between selectable site-specific conditions, in order to provide a significantly enhanced assessment of how the specific water composition can be expected to affect a specific crop, under specific climatic conditions, with defined, selectable, irrigation management when irrigating a soil with a specific, selectable, texture. Tier 2 assessments thus allow the user to assess how the implementation of alternative site-specific management options (e.g. a different crop, soil, irrigation management, etc.), can be expected to modify a fitness-for-use or water quality requirement determination (adopting different management options may reduce or overcome the problematic effects associated with water of a specific composition). Whenever the selectable management options or the modelling procedure provided for in Tier 2, are deemed insufficient or inappropriate for a specific application, a Tier 3 evaluation is called for.

Tier 3 assessments are viewed as specialised in nature. It is anticipated that Tier 3 investigations would focus on specific targeted aspects of water quality assessments. Tier 3 investigations would thus require situation specific on-site investigations and significant expertise. The current DSS does not provide for Tier 3 investigations, although some guidance for conducting Tier 3 investigations using modules of the DSS are provided. It is actually deemed inappropriate to develop a Tier 3 DSS for irrigation water assessment. It is unlikely that the limited use that will be made of a Tier 3 DSS will justify its development cost. It is furthermore deemed unlikely that a formalised DSS will be able to cater for the full range of site-specific considerations associated with Tier 3 investigations. Since Tier 3 investigations should, per definition, often utilise cutting edge procedures and models, a Tier 3 DSS may relatively quickly become outdated. For purposes of this project, the approach was thus adopted that Tier 3 investigations should be undertaken by experts in the field. It is deemed likely that lessons learnt in this way can be incorporated into future Tier 2 updates.

In many cases, the effect that irrigation water constituents have on soil quality, crop yield and quality, and their subcomponent indicators, are indirect, and a consequence of processes taking place within the soil-plant-atmosphere continuum. The effect these constituents have in determining irrigation water fitness-for-use, is thus largely determined by site-specific conditions. When irrigation water is added to soil, the soil acts as a temporary store of water from which plant roots extract water as needed during the period between irrigation applications. The dissolved irrigation water constituents are transported together with the applied water into the soil and interact with soil constituents to affect soil quality. Since most irrigation water constituents are actively excluded from uptake by plants, they tend to accumulate in soil and further affect soil quality and also the availability of water for crop uptake. The effect that the processes operating within the soil-plant-atmosphere continuum have on soil quality and crop yield are largely determined by site-specific factors such as soil texture, soil depth, crop specie, irrigation scheduling, climatic conditions etc. (the selection of which are provided for in Tier 2 assessments). Because of the involved nature of these interactions, they are modelled in the DSS using a simplified dynamic model for Tier 2 applications, while a steady state calculating procedure is used for Tier 1, as described below.

In other cases, the effects of water constituents are more direct. The impacts irrigation water constituents have on irrigation equipment are, for example, generally not site-specific, but determined only by irrigation water constituents, the type of irrigation equipment and the material it is made of. The effect of microbial contaminating and leaf scorching constituents that interact directly with crop foliage to affect crop quality, are likewise largely determined by the composition of irrigation water. These constituents thus require constituent specific calculating procedures to determine their effect on irrigation water fitness-for use.

4.1 TIER 1 CALCULATION PROCEDURES

Tier 1 calculations of the interaction between water constituents, soil and crop water uptake, make simplifying assumptions about the site-specific factors affecting these interactions and use analytical, steady state solutions to calculate the effect. The calculation of soil-crop-water interactions assumes an idealised 4-layer soil in which 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. The steady state (or equilibrium) concentration of soluble constituents in each layer can thus be calculated from the concentration of constituents in the irrigation water and the leaching fraction for the profile as a whole. Further simplifying, conservative assumptions are that water is applied only through irrigation (that is, rain does not dilute the effect of irrigation water constituents) and a 0.1 leaching fraction prevails. Constituent concentrations in the different layers can be summed in different ways to generate indices of e.g. total profile salinity, water uptake weighted root zone salinity etc. The DSS uses the same approach and calculating procedure that was used for the derivation of the 1996 irrigation water quality guidelines (Department of Water Affairs and Forestry, 1996), namely the mean profile concentration, (proposed by Rhoades, 1982, as quoted by Pratt and Suarez, 1990)

A consequence of using steady state calculation procedures and assuming a conservative 0.1 leaching fraction for Tier 1 calculations, is that the calculated output of a fitness-for-use evaluation for a specific water constituent concentration is always the same. This is also the case for constituent specific calculating procedures. Likewise, the threshold concentration of a water constituent for a specific fitness-for-use category, obtained during the determination of water quality requirements, is also always the same.

4.2 Tier 2 calculation procedures using the modified Soil Water Balance (SWB) model

For those water constituents where it is the interaction between the constituent, soil and crop water uptake under different climatic conditions that determine the effect of the particular constituent on soil quality, crop yield or quality, the interactions are modelled using a simplified version of the Soil Water Balance (SWB) model (Annandale et al., 1999) for Tier 2 calculations.

The SWB model is a generic crop model originally developed as an irrigation scheduling tool by the University of Pretoria's Department of Plant Production and Soil Science. Additional capabilities were added over time, including a two-dimensional (2-D) finite difference soil water balance, an FAO based crop factor approach, an ETo calculator and a 2-D radiation balance algorithm for hedgerow crops. A chemical equilibrium routine (Robbins, 1991) was included into a research version of the model (named SWB-Sci) to investigate the feasibility of irrigating crops with neutralised gypsiferous acid mine drainage and the extent of gypsum precipitation. Thereafter, carbon, nitrogen and phosphorus routines were added to investigate use of sewage sludge in agriculture and non-point source nutrient pollution from cropping systems. To date the model has mostly been applied in the research sphere. However, its ability to predict interactions in the crop-soil-atmosphere continuum has been verified extensively, which provides confidence in using it for calculating the parameters that are used to infer the effect water constituents have on soil quality, crop yield and quality (Singels et. al. 2010).

Due to SWB being a relatively mechanistic, plot scale model requiring intensive parameterisation, a simplified version was developed for use in the DSS. For example, in order to estimate crop evapotranspiration, an FAO crop-factor approach is utilised. A number of studies have been done locally to establish these parameters for crops commonly grown under irrigation in South Africa (Annandale et al., 1999). Users are able to specify a summer and winter crop and planting date for each. While the advantage of using a crop-factor approach is user friendliness and easier parameterisation, this does mean that there is no feedback between water or salt stress and crop growth, as is possible when using the more mechanistic crop growth routines of the SWB model.

To estimate soil water content and redistribution, the cascading or 'tipping-bucket' soil water balance approach has been retained. The soil profile is divided into 11 layers, and depth, volumetric field capacity, permanent wilting point and bulk density for each layer is specified. Predefined soil textures (clay, sandy loam, sand and coarse sand) with default parameters have been included to improve user-friendliness. Default values are also provided for the 'drainage rate' and 'drainage fraction' factors, which describe how quickly water and solutes drain through the soil profile. Currently, EC_e is estimated for each layer and an average, root-weighted, profile EC_e is calculated at the end of each growing season to estimate salinity impact on yield.

Simulations are run for several seasons (the number of seasons are user selectable, dependant on the length of the climatic record of the site selected, with a minimum of 10), to obtain a statistically defensible record of yield variability as a result of changes in soil solution composition brought about by climatic variation. This output is used to derive statistical parameters (percentiles) from which the likelihood with which specific yield intervals occur over time, can be calculated.

While users need to specify whether a flood, sprinkler, pivot, micro or drip irrigation system is used, this is only used to simulate whether the crop canopy is wetted by the irrigation water or not, and does not influence how frequently irrigation water is applied to the soil. The frequency of irrigation applications is specified separately as part of the irrigation management options. Weather data for a range of selectable weather stations are provided within the DSS. This option was decided upon, rather than data for representative agricultural climatic zones, in response to feedback from user groups who disputed the value of averaged data associated with climatic zones.

A consequence of using a dynamic soil water balance model such as SWB to simulate interactions in the soil-water-atmosphere continuum in Tier 2, is that several variables influence the output for a specific irrigation water constituent concentration. Since climatic input varies from year to year, the output for a specific irrigation water constituent concentration, also varies from year to year, thereby making it possible to express the effect of irrigation water constituents on yield on a probabilistic basis.

The original SWB code is written in the Delphi programming language, and as part of this study it needed to be converted to the open source Lazarus, which was a time-consuming process. The advantage of this is that Lazarus software can be downloaded free of charge, so any user can download it and access the source code in debug mode, without having to pay for expensive Delphi software.

4.3 CRITERIA USED FOR ASSESSING FITNESS-FOR-USE OR SETTING WATER QUALITY REQUIREMENTS

The same criteria are used to assess the fitness-for-use of water for irrigation and to establish irrigation water quality requirements. However, the procedures to do this and the output differ significantly as described in subsequent paragraphs. The same criteria are, furthermore, used for both Tier 1 and 2 evaluations.

As far as possible, a common four column format is used to present the criteria used to assess water quality for irrigation purposes. The first column identifies the suitability indicator for which criteria are presented, the second column identifies the four fitness-for-use categories, the third specifies the criteria for each of the fitness-for-use categories, while the fourth column provides a qualitative or quantitative description of the effects that are associated with each applicable fitness-for-use category. The description below of the effect that increasing levels of root zone salinity (an indicator of soil quality) can be expected to have on crop growth, is an example of where the effects are described in qualitative terms. Where justified, the effects are described in quantitative terms, such as % relative yield.

	Fitness-for-Use	EC_e interval (mS/m)	Effect on Crop Yield (US Salinity Laboratory Staff, 1954)
Root Zone Salinity	Ideal	0 - 200	Salinity effects mostly negligible
	Acceptable	200 - 400	Yields of very sensitive crops may be restricted
	Tolerable	400 - 800	Yields of many crops restricted
	Unacceptable	>800	Only tolerant crops yield satisfactory

4.3.1 Evaluation of fitness-for-use

A fitness-for-use evaluation is carried out in four steps, namely:

i. The results of a water analysis need to be entered;

ii. Calculate the value of the parameter that is required to evaluate the impact on the suitability indicator that is being assessed (e.g. in order to evaluate the impact on root zone salinity described above, requires the calculation of the value of the soil EC_e parameter). The value of the desired parameter is calculated using the appropriate calculating procedure for either Tier 1 or Tier 2 (See sections 4.1 or 4.2);
iii. The calculated value is compared with the criteria used to assess the effect on the suitability indicator under consideration in order to determine the corresponding fitness-for-use category, and
iv. The fitness-for-use category is highlighted as part of the water quality assessment output.

For Tier 1 evaluations, a single value of the parameter of interest is calculated and the fitness-for-use category identified, as indicated in the example below for the evaluation of the soil quality suitability indicator root zone salinity. Since the value of root zone salinity is displayed (and not only the fitness-for-use category), additional information is conveyed to the user about how close the value is to the boundary of a fitness-for-use category.

	Fitness-for-Use	EC_e interval (mS/m)	Predicted equilibrium root zone salinity (mS/m)
Root Zone Salinity	Ideal	0 - 200	
	Acceptable	200 - 400	**234**
	Tolerable	400 - 800	
	Unacceptable	>800	

For those parameters that are calculated using the SWB model (Tier 2), at least 10 annual mean values are calculated when the SWB model is run for 10 or more years of climatic data. These values are likely to fall into different fitness-for-use categories and are reported as the % of time for which the values fall within a specific fitness-for-use category (as indicated in the example below for the evaluation of the soil quality suitability indicator, root zone salinity). In this way information about the longer term fitness-for-use risk associated with using the water is conveyed to the user.

	Fitness-for-Use	EC_e interval (mS/m)	% of time root zone salinity is predicted to fall within a particular Fitness-for-Use category
Root Zone Salinity	Ideal	0 - 200	**60**
	Acceptable	200 - 400	**30**
	Tolerable	400 - 800	**10**
	Unacceptable	>800	

The output for Tier 3 evaluations are expected to be very similar to those of Tier 2. The main differences are expected to be the result of using highly site-specific soil and climate input parameters and the use of more sophisticated soil-crop-atmosphere chemical equilibrium models to simulate interactions.

4.4 ESTABLISHING WATER QUALITY REQUIREMENTS

Water quality requirements are established in three steps by the DSS, namely:

i. Identify the value of the threshold criterion for each fitness-for-use category of the suitability indicator for which water quality requirements are needed. These values are part of the criteria that are available for the different parameters. In the example below for root zone salinity, the threshold values are 200, 400 and 800 mS/m;

ii. Through iteration or analytical procedure, determine the concentration of the water constituent that will return each threshold concentration, and
iii. Display the concentrations of the water constituent that would return the value of the threshold criterion for each fitness-for-use category.

For Tier 1 water quality requirement determinations, a single value is calculated for each threshold criterion, as indicated in the example below for Root Zone Salinity. An irrigation water EC of 106 mS/m will, for example, return a root zone salinity value of 200 mS/m and an irrigation water EC of 213 mS/m will return a root zone salinity value of 400 mS/m.

	Fitness-for-Use	EC_e interval (mS/m)	EC range that will give rise to the corresponding root zone salinity category (mS/m)
Root Zone Salinity	Ideal	0 - 200	**<106**
	Acceptable	200 - 400	**106 – 213**
	Tolerable	400 - 800	**213 – 426**
	Unacceptable	>800	**>426**

For Tier 2 calculations, variability in climate and other factors give rise to a range of soil EC_e values for a single irrigation water EC. For purposes of the DSS, the 95th percentile EC_e value associated with an irrigation EC is used. The irrigation EC corresponding to a fitness-for-use threshold criterion is obtained through interpolation by running a number of successive SWB simulations, each time with a higher irrigation EC value. In this way, the irrigation water EC requirements that will give rise to corresponding fitness-for-use category EC_e values 95% of the time, as in the example below, are obtained by interpolation.

	Fitness-for-Use	EC_e interval (mS/m)	EC range that will give rise to the corresponding root zone salinity category for 95% of the time (mS/m)
Root Zone Salinity	Ideal	0 - 200	**<90**
	Acceptable	200 - 400	**90 – 180**
	Tolerable	400 - 800	**180 – 360**
	Unacceptable	>800	**>360**

4.5 ADDITIONAL INFORMATION

In addition to fitness-for-use assessments and the setting of water quality requirements, the DSS also provides additional useful information. Currently this consists of a description of the approach used to assess the effect of water constituents on suitability indicators and the text of the 1996 irrigation water quality guidelines.

The description of the approach used to assess the effect water constituents have on suitability indicators, covers:

i. The current state of knowledge related to the suitability indicator
ii. Approach adopted for use in the DSS
iii. The sequence of calculations used in the DSS
iv. References

5 INPUT REQUIREMENTS

The information required by the DSS to perform different calculations depends, on the one hand, on whether it is required to assess the fitness-for-use of a water sample or to determine a water quality requirement, and on the other hand, on whether a Tier 1 or Tier 2 assessment is required, as indicated in Table 5-1

Table 5-1. Information required as input by the DSS to perform an assessment of fitness-for-use or to determine water quality requirements at Tier 1 or 2 levels.

	Information required as Input	
	Fitness-for-use	**Water Quality Requirement Setting**
Tier 1	• Water constituent analytical data (see Figure 5-1)	• Water quality requirement concentrations or values are calculated for all water quality constituents – no input required
Tier 2	• Water constituent analytical data (see Figure 5-1) and site-specific data required (see Figure 5-2)	• Water quality requirement concentrations or values are calculated for all water quality constituents - site-specific data required (see Figure 5-2)

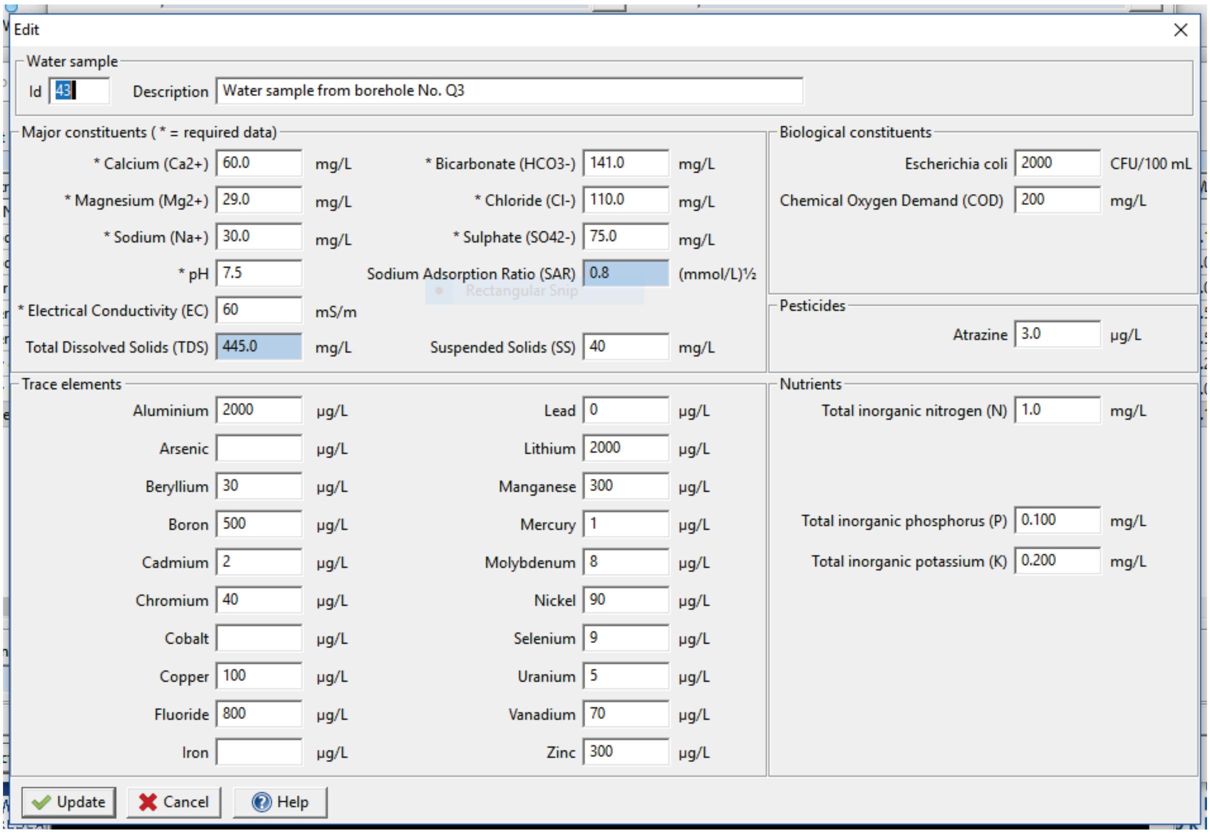


Figure 5-1. Screen for capturing water constituent analytical data.

The results of a water constituent analysis are required for both Tier 1 and 2 assessments of fitness-for-use. Figure 5-1 depicts the DSS screen used to input and edit analytical data. It also serves as a list of the water constituents the DSS considers during the evaluation of the fitness-for-use of a water sample, or when establishing water quality requirements. It is essential to provide data for ***major constituents*** in order to conduct a fitness-for-use assessment. Other constituents are optional, but fitness-for-use will only be assessed for those constituents for which analytical data are available. Analytical data are tested for ionic balance and extreme values to minimise the capturing of faulty data. However, potentially faulty data does not stop the DSS from running. It is the users' responsibility to ensure the accuracy of water analysis data. Captured data are identified and saved for possible later use, before being evaluated by the DSS.

It is necessary to provide site-specific information related to the crops to be grown, climate, soils and irrigation management, as depicted in Figure 5-2, for Tier 2 assessments of both fitness-for-use and water quality requirements. There is no need to select water constituents for establishing water quality requirements. Water quality requirement concentrations or values are automatically calculated for all water constituents in the water quality requirement setting mode.

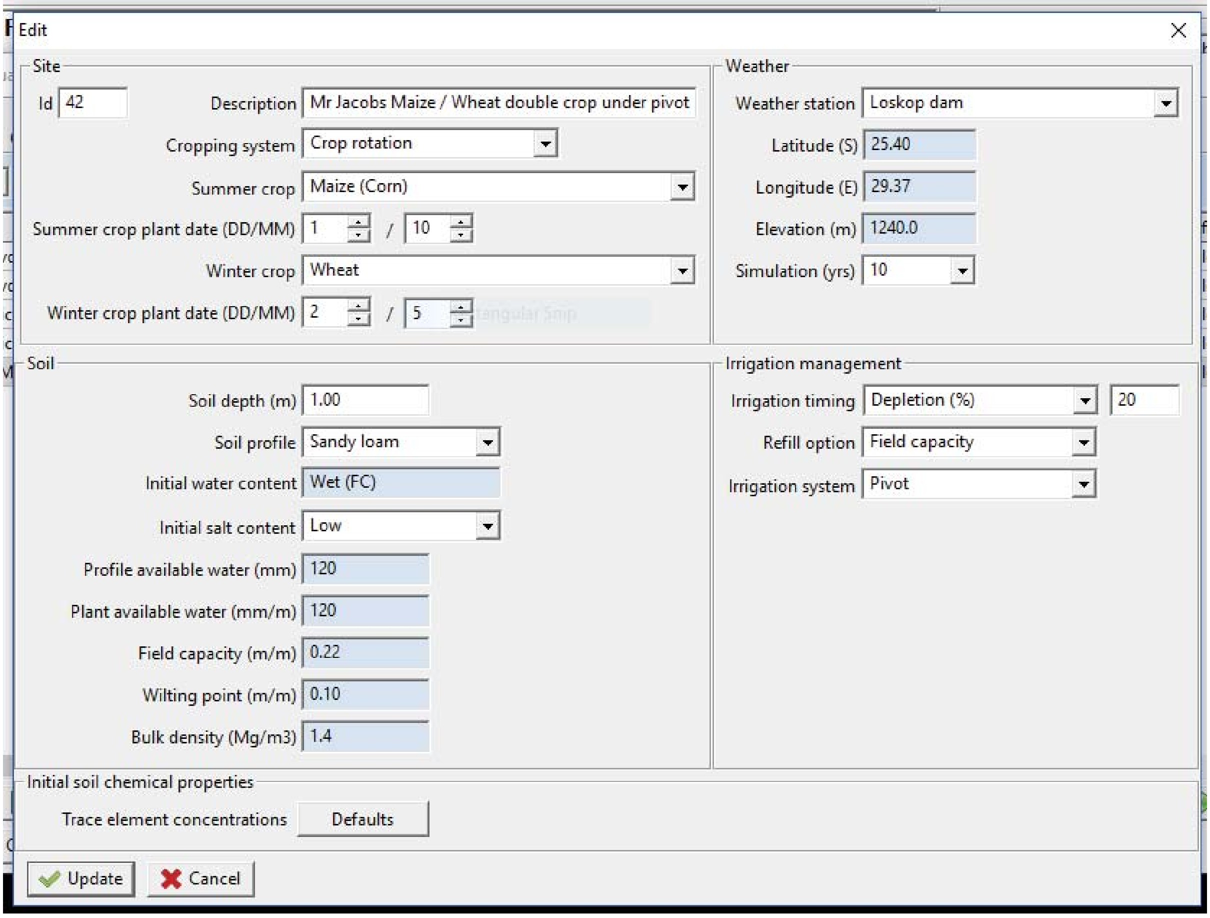


Figure 5-2. DSS screen for capturing site-specific information.

6 PROCEDURES TO CALCULATE AND CRITERIA USED TO ASSESS IMPACT OF WATER CONSTITUENTS ON SOIL QUALITY

The impact of irrigation water constituents on soil quality and its suitability indicators, are largely indirect, and a consequence of processes taking place within the soil. Irrigation water is added to soil, which acts as a temporary store of water from which plant roots extract water as needed during the period in-between irrigation applications. The dissolved irrigation water constituents are transported together with the applied water into the soil and interact with soil constituents to affect soil quality. Since most irrigation water constituents are actively excluded from uptake by plants, usually only a small fraction of the irrigation water constituents is taken up by plants, while the rest tend to accumulate in soil (unless they are soluble and leached during successive irrigation applications). The accumulation of irrigation water constituents within soil, influences soil properties and affects soil quality.

The following suitability indicators have been identified to describe the effects irrigation water constituents have on soil quality:

- i. Root zone salinity
- ii. Soil permeability
- iii. Dissolved carbon loading
- iv. Trace element accumulation

6.1 ROOT ZONE SALINITY

Salinity (salt content) within the root zone reduces crop growth by reducing the ability of plant roots to absorb water from soil. The osmotic effect exerted by soluble ions reduces the availability of water to plants. The availability of soil water to plants is thus not only reduced by the “suction” exerted by soil particles (the so-called matric potential) but also by the osmotic potential exerted by soluble ions. Since plant growth is directly related to water availability, the combined effects of the matric and osmotic potentials over a growing season is a major factor determining crop yield. Evaporation and transpiration by plants remove almost pure water, thereby concentrating the soluble salts in the remaining soil water. As the water content of soil decreases, both its matric and osmotic potential (and the ease with which plants extract water) are also reduced. It is convention to measure and express the root zone salinity of soil as EC_e (EC of a saturated soil extract).

Root zone salinity is thus an important indicator of soil quality under irrigation. Different levels of soil salinity are associated with different effects on crop growth. Low root zone salinity levels do not materially affect crop yield. The criteria used in the DSS to determine the fitness-for-use category as determined by root zone salinity are indicated below. These criteria provide a generic evaluation of how soil quality is affected by increasing root zone salinity. Root zone salinity in turn, determines the range of crops that can be successfully cultivated with the irrigation water. The same criteria are used for both Tier 1 and 2 evaluations.

	Fitness-for-Use	EC_e interval (mS/m)	Effect on Crop Yield (US Salinity Laboratory Staff, 1954)
Root Zone Salinity	Ideal	0 - 200	Salinity effects mostly negligible
	Acceptable	200 - 400	Yields of very sensitive crops may be restricted
	Tolerable	400 - 800	Yields of many crops restricted
	Unacceptable	>800	Only tolerant crops yield satisfactory

6.2 Soil permeability

The suitability of a soil for cropping is to a large degree determined by its ability to conduct water and air (permeability) and on physical properties that control the friability of the seedbed (tilth). Poor permeability and tilth are often major problems in irrigated lands in South Africa. Saline soils generally have normal physical properties. However, in sodic soils, physiochemical reactions cause the slaking of aggregates and the swelling and dispersion of clay minerals, leading to reduced permeability and poor tilth. These undesirable effects associated with sodic (i.e. sodium affected) soils, are counteracted by soil salinity.

Since water entering soil must pass through the soil surface, it is the combined features of water and soil that determine the water-entry rate. Soil permeability to water and tilth problems are thus determined by, and have to be evaluated in terms of, both the salinity of the infiltrating water and the exchangeable sodium percentage (or its equivalent Sodium Adsorption Ratio, SAR[2]) of the topsoil.

Soluble salts move, redistribute and accumulate in soils largely as a result of water movement. Salts in soils are thus largely determined by soil and water management practices which affect water distribution within a soil. Maintaining sufficient permeability is therefore a prerequisite to facilitate salinity control and reclamation of salt-affected soils under irrigation. Since the composition of irrigation water and inherent soil properties regulate soil permeability, it is necessary to establish boundary values above or below which the rate of water movement is significantly restricted (Van der Merwe and Burger, 1973).

For purposes of the DSS, the soil permeability phenomenon was differentiated as consisting of two components, namely infiltrability, operating at the soil surface, and hydraulic conductivity, operating within the bulk soil.

The significance of even low surface sodicity in the reduction of infiltration under rainfall (or low salinity irrigation applications) under South African conditions, was highlighted by du Plessis and Shainberg (1985). The implication is that the infiltrability of irrigated soils can be negatively impacted by rainfall or irrigation (other than flood) with low salinity water during the period of incomplete vegetative cover when rain or overhead irrigation droplets collide with the soil surface. The following table presents the criteria used to obtain a qualitative measure of the degree to which the infiltrability of sensitive soils would be affected by the combination of irrigation water salinity (or rain) and soil sodicity. The same criteria are used for both Tier 1 and 2 evaluations. However, for the Tier 1 evaluation, rainfall (equivalent to an irrigation water EC < 20 mS/m) is assumed. For Tier 2 evaluations, the EC of the actual water application (rain or irrigation water) and the degree of crop cover (which protects the soil surface from crust forming droplets) are used to calculate a seasonal value. Since Tier 2 evaluations cover a series of at least 10 climatic years, with different rainfall distributions that can affect infiltration, it is possible to calculate probabilities for the degree to which the infiltration rate would be affected.

Potential Infiltrability Problems (adapted from 1996 WQ Guidelines)				
Surface SAR $(mmol/L)^{1/2}$	Degree to which infiltration reducing surface crusts develop in sensitive soils (EC of irrigation water, mS/m)			
	None	Slight	Moderate	Severe
<2	> 20	=<20 or rain	-	-
2 – 3	> 60	20 - 60	=<20 or rain	-
3 – 6	>120	90 -120	20 - 90	=<20 or rain
6 – 12	>200	120 - 200	35 - 120	=<35
>12	>300	200 - 300	90 - 200	<90

[2] Sodium adsorption ratio is calculated for irrigation water and the soil saturation extract from the Na, Ca and Mg concentrations in solution.

$SAR = Na/\sqrt{(Ca + Mg)}$ for concentration expressed in mmol/L.

In order to quantify the effects of various combinations of exchangeable cations and total concentration of the soil solution on hydraulic conductivity, Quirk and Schofield (1955) introduced the threshold salt concentration concept, defined as the level to which salt concentration of a soil solution must be decreased to produce a 10-15% reduction of hydraulic conductivity at various values of exchangeable sodium percentage (ESP). These concepts were first applied under local conditions by Van der Merwe and Burger (1973). The following table presents the criteria used to obtain a qualitative measure of the degree to which hydraulic conductivity of sensitive soils would be affected by the combined effects of soil water salinity and soil sodicity. The same criteria are used for both Tier 1 and 2 evaluations, regardless of soil texture selection.

However, with a Tier 1 calculation, a single root zone salinity/sodicity combination is calculated, whereas with a Tier 2 calculation, a series of at least 10 end of year root zone salinity/sodicity combinations are calculated (one for each climatic year) for different soil layers. This enables the calculation of probabilities for the percentage of years during which root zone hydraulic conductivity will fall within different fitness-for-use categories.

Potential Hydraulic Conductivity Problems (adapted from 1996 WQ Guidelines)				
SAR of particular soil layer (mmol/L)$^{1/2}$	Degree to which hydraulic conductivity is reduced in sensitive soils (EC of soil water in particular soil layer, mS/m)			
	None	Slight	Moderate	Severe
<3	>60	40 - 60	20 - 40	<20
3 – 6	>120	80 – 120	30 – 80	<30
6 – 12	>200	125 - 200	50 – 125	<50
>12	>300	180 - 300	130 - 180	<130

6.3 Dissolved organic carbon loading

Although organic matter is a minor soil constituent, it plays a major role in determining soil physical conditions, and greatly affects soil chemistry and soil biology. Cultivation generally leads to a decrease in organic matter content. Adding organic material to soil through irrigation can thus be considered beneficial. However, there are negative effects associated with the addition of excessive quantities.

From a soil quality perspective, the presence of organic carbon in irrigation water is generally considered as advantageous. A high organic matter level in soil is associated with superior soil physical conditions (good soil aggregate stability and permeability, high water holding capacity and easy cultivation), soil chemistry (increased cation exchange capacity and supply of slow release plant nutrients) and soil biology (stimulation of biological activity and diversity). A review of available South African information revealed that all cultivation under dry land conditions resulted in a significant decrease in the organic matter content of soil, with an associated deterioration of soil physical, chemical and biological conditions. The effect of cultivation under irrigation was ambiguous, with an increase of organic matter in some cases, a reduction in others and some with no change (du Preez et al., 2011).

The diversity of the soil microorganism population, enables the microbes to use as energy source and decompose, organic materials from many different sources. Oxygen is consumed during the decomposition process. Should the organic loading become so high that microorganisms consume oxygen at a rate higher than the gaseous exchange capacity of a soil, oxygen will be depleted and anoxic conditions are established (similar to the situation in waterlogged soils). Plant roots require oxygen for their metabolic functions and most plants display reduced growth when their roots are exposed to oxygen stress. Under anoxic conditions, most plants not adapted to these conditions, will die within a few days. Anoxic conditions can also give rise to unpleasant odours. A further potentially complicating factor, is that the addition of carbon-rich compounds to soil may temporarily immobilise dissolved N in the soil solution, that would otherwise be available for uptake by plants (the so-called N-negative period). This is brought about because the bacteria that decompose residues require additional N in order to decompose organic matter with a high C:N ratio and scavenge all available N until decomposition is complete. Therefore, while moderate additions of organic carbon to irrigated land should be considered beneficial, excessive additions may have undesirable consequences.

The water used in irrigation schemes normally has a low organic carbon content. That is probably the reason why organic carbon content is not considered as a potential constituent of concern in water quality guidelines of e.g. Australia, Canada or the FAO (ANZECC, 2000: Canadian Guidelines, 1987; Ayers and Westcot, 1976). However, when wastewater effluents are considered as a source of water for irrigation, organic carbon content would be expected to become an important consideration. In their manual on wastewater irrigation, the FAO warns about the potential oversupply of N, the risks associated with high levels of suspended solids and health risks associated with intestinal nematodes and faecal coliforms (Pescod, 1992) that are associated with wastewater. No mention is, however, made of problems related to the organic carbon loading of wastewaters (probably because the manual focused on municipal wastewaters, which have relatively low COD values). There appears to be a shortage of guidance regarding the use of high organic load waters for irrigation.

The maximum COD allowed for small scale wastewater irrigation (<50 m^3/d) in terms of the DWA (2013) General Authorisation, is 5000 mg/L. The corresponding concentrations for <500 m^3/d and <2000 m^3/d applications, are respectively 400 and 75 mg/L COD. In their guidance for the sustainable use of greywater in small-scale agriculture and gardens in South Africa, Rodda et al. (2010 a and b) propose a COD concentration of <400 mg/L as the target (ideal) concentration. They indicate that because of biological growth, concentrations in the range 400 to 5000 mg/L pose increasing risks to soil and irrigation equipment.

Myburgh and Howell (2014) investigated the effects of irrigating vines with winery wastewater in a four-year field experiment in the Western Cape. They found that irrigation with waters containing up to 3000 mg/L COD had no organic loading related negative effects and minimal negative effects overall. Soil organic matter content was not materially affected in either their field experiment, nor in a parallel pot trial. The maximum COD load they applied amounted to a monthly application of approximately 2400 kg/ha over two to three months of effluent irrigation. They recommended that COD be augmented (diluted) to 3000 mg/L or less, but preferably to less than 2000 mg/L. (For a 2000 mg/L COD concentration, the monthly applied load would have been about 1600 kg/ha). According to the NSW Department of Environment and Conservation (2004) experience indicates an average application of 1500 kg/ha BOD_5 per month to be the maximum organic matter load that can be tolerated by most soils. On the other hand, they consider BOD_5 values of 40, which is typical for secondary treated municipal sewage treatment plant effluent, as low strength.

From the assessment of current knowledge, it transpires that although the organic content of water is an important component determining irrigation water quality, not much guidance is provided in literature on how to assess the fitness for use of water containing organic material. From the available information, it appears important to restrict both the short and longer term organic load that is applied to soil. While it is important to ensure that long term application loads remain within the capacity of soil to decompose organic matter, it is even more important to ensure that short term overload does not occur. The undesirable consequences (plants may die) associated with anoxic conditions which may develop as a result of even short term overload, are such that this must be prevented. It should be noted that the irrigation applications by Myburgh and Howell (2014) were only for periods of two to three months, while the NSW Department of Environment and Conservation (2004) recommendation is specifically for a monthly (and not a longer term) load limit.

The guidance provided by the NSW Department of Environment and Conservation (2004) and Myburgh and Howell (2014) suggests a monthly loading limit in the order of 1500 kg/ha (using BOD_5 as measure) and 1600 kg/ha (using COD as measure). It is important to note that the BOD_5 value equates to a significantly higher COD equivalent (recall that BOD_5 is a measure of the short-term availability of organic material, while COD is a measure of all oxidisable organic material).

For purposes of the DSS, monthly COD applications exceeding 1600 kg/ha, is defined as unacceptable, while applications of less than 400 kg/ha are viewed as ideal (see Table below). In comparison to the NSW Department of Environment and Conservation (2004) threshold, this value must be considered as conservative. However, it is in agreement with recommendations emanating from local research findings.

	Fitness-for-Use	Monthly COD Load (kg/ha)
Oxidisable Carbon Loading	Ideal	<400
	Acceptable	400 - 1000
	Tolerable	1000 - 1600
	Unacceptable	>1600

The same approach and criteria are used for both Tier 1 and 2 evaluations. For Tier 1 evaluations, a generic irrigation application of 1000 mm p.a. is assumed; i.e. a monthly application of 83 mm/ha. For Tier 2 evaluations, the monthly irrigation application as calculated by SWB is used.

6.4 TRACE ELEMENT ACCUMULATION

Soils are complex chemical and biological reactors. It is the interplay between many factors such as soil texture, clay mineralogy, soil organic matter, soil and irrigation water pH, and inorganic constituents etc. that determine and modify the behaviour of trace elements in irrigation water when they are deposited onto soil. For example, the same concentration of metal trace elements tends, on the one hand, to become more toxic at lower soil pH, but on the other hand, less toxic in clayey compared to sandy soil (because clay has a larger sorptive capacity than sand). The predictive models and analyses that are needed to quantify these interactions are of an advanced nature and belong to Tier 3 fitness-for-use assessments. They do thus not form part of this DSS. In order to derive Tier 1 and 2 water quality guidelines for trace elements, a number of simplifying assumptions were made.

Trace elements are mostly strongly sorbed by soil, and when present in irrigation water, tend to accumulate in the top layers of the irrigated soil. While some trace elements are essential plant nutrients at low concentrations, at high concentrations most of them become either toxic to crop growth or to humans or animals consuming the produce grown on such trace element enriched soils. Since trace elements tend to accumulate in soil, there is practically no safe level for sustainable irrigation on a continuous basis. The current approach followed by most countries to derive irrigation water quality guidelines for trace elements, is to back calculate an acceptable irrigation water concentration from protective accumulation levels that have been set for soils.

This approach was first used by the US EPA (US ENVIRONMENTAL PROTECTION AGENCY, 1973) to derive water quality criteria in terms of US legislation to manage water quality in inter- and intra- State streams. The maximum acceptable concentration for a specific trace element in irrigation water was defined as the threshold concentration that would accumulate to an unacceptable concentration in the top 150 mm of irrigated soil over a period of 100 years when applied at a rate of 1000 mm p.a.

An approach similar to that of the US EPA was adopted with minor modifications used in the development of irrigation water quality guidelines for trace elements by the FAO (Ayers and Westcot, 1976 and 1985), Canada (CANADIAN GUIDELINES 1987), Australia (ANZECC 1992 and 2000) and

South Africa (Department of Water Affairs and Forestry, 1993 and 1996) as well as the US agricultural and civil engineering fraternities (Pratt and Suarez, 1990). As a consequence, the trace element water quality guidelines developed by these institutions are very similar or the same. The only differences are relatively minor and occur with fluoride, iron, lead, vanadium and zinc. The current (1996) South African guidelines are presented in Table 6-1 below. In addition to the 100-year threshold concentration, the guidelines also provide for a higher threshold concentration for shorter term (20 year) irrigation of alkaline fine textured soils. In view of the fact that irrigation should be evaluated for longer term sustainability (and not short term disposal) the short-term guidelines for trace elements were not used in this newly developed DSS. The current DSS, however, retained the approach to base criteria for trace element concentrations on the time it would take to accumulate threshold concentrations in irrigated soil. The fitness-for-use criteria for the different categories are depicted below:

	Fitness-for-Use	Number of years of irrigation before Trace Elements reach accumulation threshold in topsoil
Trace Element Accumulation	Ideal	>200 years to reach soil accumulation threshold
	Acceptable	150 to 200 years to reach soil accumulation threshold
	Tolerable	100 to 150 years to reach soil accumulation threshold
	Unacceptable	<100 years to reach soil accumulation threshold

Table 6-1. Maximum acceptable trace element concentrations of irrigation water for short and long term use in South Africa according to the 1996 Guideline, with the corresponding concentrations and loads of trace elements in soil.

Trace element	Irrigation water		Irrigated Soil Concentration		Irrigated Soil Load	
	100 years	20 years	100 years	20 years	100 years	20 years
	mg/L		mg/kg		kg/ha	
Aluminium	5.0	20.0	2500	2000	5000	4000
Arsenic	0.1	2.0	50	200	100	400
Beryllium	0.1	0.5	50	50	100	100
Boron	0.5	vary	250	-	500	-
Cadmium	0.01	0.05	5	5	10	10
Chromium (VI)	0.1	1.0	50	100	100	200
Cobalt	0.05	5.0	25	500	50	1000
Copper	0.2	5.0	100	500	200	1000
Fluoride	2.0	15.0	1000	1500	2000	3000
Iron	5.0	20.0	2500	2000	5000	4000
Lead	0.2	2.0	100	200	200	400
Lithium	2.5	-	1250	-	2500	-
Manganese	0.2	10	100	1000	200	2000
Mercury*	0.002	-	1	-	2	0.4
Molybdenum	0.01	0.05	5	5	10	10
Nickel	0.2	2.0	100	200	200	400
Selenium	0.02	0.05	10	5	20	10
Uranium	0.01	0.1	5	10	10	20
Vanadium	0.1	1.0	50	100	100	200
Zinc	1.0	5.0	500	500	1000	1000

* The 1996 South African guidelines do not list a value for mercury. The value of 0.002 mg/L listed here, was taken over from the Australian guidelines (ANZECC 2000).

The DSS thus calculates the number of years of irrigation it will take to accumulate the specific trace element’s concentration to the 100-year concentration threshold in the top 150 mm of the irrigated soil (the relevant value in the fourth column of Table 6-1). The same criteria are used for both Tier 1 and 2 evaluations. However, for the Tier 1 calculation, an irrigation application of 1000 mm p.a. is assumed, while for Tier 2 calculations, the actual longer term (10 year or more) mean annual irrigation application as calculated with the SWB model is used. Tier 2 also provides for using the actual soil bulk density and residual trace element contents at the start of irrigation.

7 PROCEDURES TO CALCULATE AND CRITERIA USED TO ASSESS IMPACT OF WATER CONSTITUENTS ON CROP YIELD AND QUALITY

The impact irrigation water 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 of soil under irrigation.

The following suitability indicators have been identified to describe the effects irrigation water constituents have on crop yield and crop quality:

i. Root zone effects;
ii. Leaf scorching when wetted;
iii. Contribution to NPK removal by crops;
iv. Microbial contamination, and
v. Qualitative crop damage by atrazine.

7.1 EFFECT OF ROOT ZONE CONCENTRATION ON CROP YIELD

Salinity (salt content) within the root zone reduces crop growth by reducing the ability of plant roots to absorb water from soil. The osmotic effect exerted by soluble ions reduces the availability of water to plants. The availability of soil water to plants is thus not only reduced by the “suction” exerted by soil particles (the so-called matric potential) but also by the osmotic potential exerted by soluble ions. Since plant growth is directly related to water availability, the combined effects of the matric and osmotic potential over a growing season is a major determinant of crop yield. Evaporation and transpiration by plants remove almost pure water, thereby concentrating the soluble salts in the remaining soil water. As the water content of soil decreases, both its matric and osmotic potential (and the ease with which plants extract water) are reduced. The effect of salinity (osmotic potential) on crop yield is calculated using experimental data (as explained in the following pages). It is convention to measure and express the root zone salinity of soil as EC_e (EC of a saturated soil extract).

In addition to EC, crop growth is also affected by the accumulation of B, Cl and Na in the root zone. The effects of the latter three constituents are deemed to be of a toxic nature, since their effect on yield reduction is more pronounced than would be expected from their contribution to soil osmotic potential alone. A large body of data is available that links yield response of different crops to soil EC and concentration of B, Cl and Na in the root zone within which the crop is growing. This body of data is available as crop specific parameters for use by the DSS.

The general approach to deduce the yield response of crops subjected to increasing levels of salinity (EC), boron, chloride or sodium in the root zone, is to:

i. Obtain an estimate of their concentration in the root zone (See chapter 4), and to
ii. Use data linking crop yield response to the concentration of individual constituents in the root zone, in order to estimate how crop yield is affected.

Crops vary in their tolerance to different constituents. Crop response to constituents they are sensitive to, can for practical purposes be divided into two parts:

i. An increasing concentration range within which yield is not affected until a concentration threshold is reached, and
ii. A concentration dependant range within which yield decreases linearly with increasing concentration of the constituent of concern.

This is the generic approach followed in the DSS to calculate crop yield. For concentrations exceeding the concentration threshold for any given crop, the percentage relative yield (Y) is estimated as follows:

$$Y = 100 - b\,(RZC - a) \quad \text{where}$$

b = slope of the yield response curve exceeding the threshold concentration;
RZC = the mean root zone concentration of the constituent of concern; and
a = the threshold concentration of the constituent of concern.

These concepts are diagrammatically illustrated in Figure 7-1. The data identifying the EC threshold (a) and slope of the yield response curve (b) for a large range of crops are stored as parameters in the database of the DSS. Crop response data used in the DSS, the data sources and the interpolation techniques used to generate the data are presented in Volume 2 of this report (Technical Support).

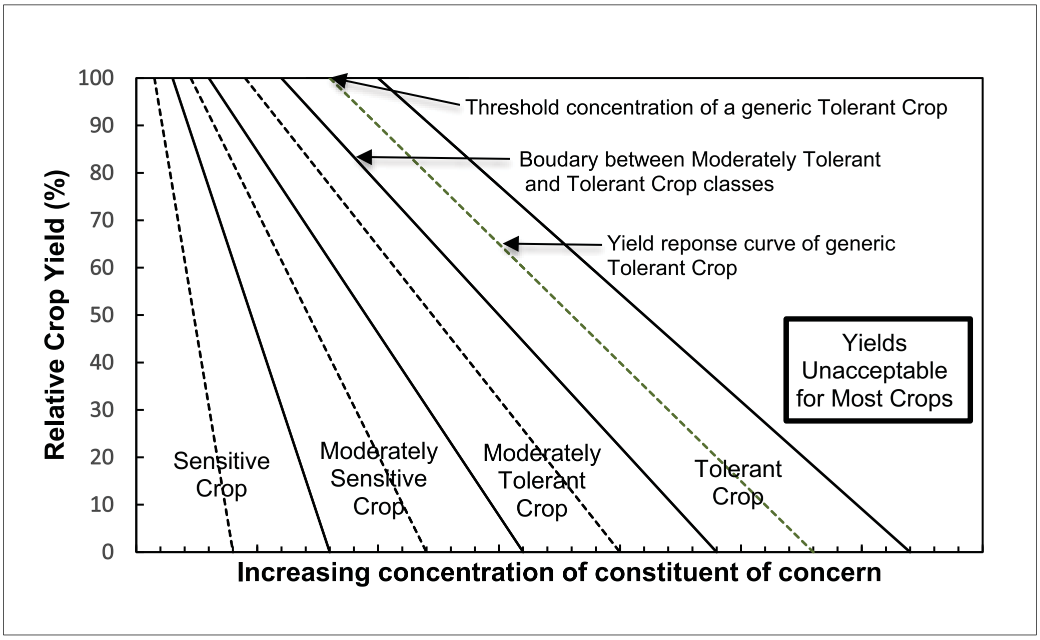


Figure 7-1. Diagrammatic illustration of the concepts around classifying crop response to increasing concentrations of a constituent of concern.

Note that crop yield is expressed in relative not absolute terms. The reason for this, is that many factors in addition to root zone concentration of the constituent of concern, affect the absolute crop yield under a specific set of conditions. The term *Relative Yield* thus represents the yield effects of only the constituent of concern, assuming that other yield determining factors remain constant.

The DSS uses the concentration of salts (EC), B, Cl and Na in the root zone to calculate how the relative yield of crops will be affected. The criteria used in the DSS to determine the fitness-for-use category based on the calculated relative yield are indicated below. The same criteria are used for both Tier 1 and 2 evaluations. However, for Tier 1 calculations, a single relative yield is calculated per constituent (as illustrated below), whereas with Tier 2 calculations, a series of at least 10 relative yields are calculated per constituent per crop (one for each climatic year). This enables the calculation of probabilities of the time that root zone constituent concentration will fall within different fitness-for-use categories.

The project team decided, somewhat arbitrarily, on the yield criteria for the different fitness-for-use categories. Considerations that affected the decision, were to have convenient category interval and a realistic unacceptable yield level. Values of two, five or ten were considered as category intervals. Accepting a 100% yield as ideal, this implies that a four-fold lower unacceptable yield would be defined as a yield lower than 94%, 85% or 70% for the four-category fitness-for-use classification used in the DSS. A 70% relative yield was deemed the more realistic level for an unacceptable yield. User groups that participated in the evaluation and testing of the DSS, concurred with this decision.

	Fitness-for-use	Relative crop yield (%)	%of time yield is within relative crop yield category, as affected by:			
			Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
Root Zone Effects	Ideal	90 – 100			95	
	Acceptable	80 - 90	85			
	Tolerable	70 - 80		75		
	Unacceptable	<70				60

7.2 Leaf scorching

Crops susceptible to foliar damage caused by salts directly absorbed through their leaves display greater yield reductions than when only exposed to root zone effects (as discussed above). However, practically no quantitative data are available to quantify the effect on yield and only limited qualitative data are available to assess the relative susceptibility of crops to foliar injury. The degree of leaf scorching experienced by crops for which data are available, is thus evaluated only in qualitative terms by the DSS, as indicated below. The same criteria are used for both Tier 1 and 2 evaluations. The outcome of the evaluation is also the same, since climatic variability and other site-specific factors considered during Tier 2 evaluations, does not affect the interpretation. In practice, climate may, however, affect the degree of leaf scorching, since leaf scorching is more severe during hot, dry and windy days.

Leaf scorching by Cl and Na when sprinkle irrigated with saline water (modified after Maas, 1990)								
Categories of Crop Susceptibility to Cl and Na	**Cl or Na concentration range (mg/L) associated with the indicated qualitative degree of leaf scorching**							
	None		**Slight**		**Moderate**		**Severe**	
	Cl	**Na**	**Cl**	**Na**	**Cl**	**Na**	**Cl**	**Na**
Sensitive (S)	<70	<50	70 – 135	50 - 83	135 - 180	83 – 115	>180	>115
Moderately Sensitive (MS)	<175	<115	175 – 265	115 - 173	265 - 350	173 - 230	>350	>230
Moderately Tolerant (MT)	<350	<230	350 – 525	230 - 345	525 - 700	345 - 460	>700	>460
Tolerant (T)	<700	<460	700 – 1000	460 – 680	1000 - 1400	680 - 900	>1400	>900

7.3 NUTRIENT EFFECTS ON CROP YIELD AND QUALITY

The presence of plant nutrients in irrigation water is mostly viewed as beneficial by irrigators, since its availability represents a saving in fertiliser costs. High concentrations, however, have undesirable side effects. High N concentrations may stimulate excessive vegetative growth and cause lodging, delayed crop maturity and poor quality. High nutrient concentrations may furthermore complicate fertiliser management, the timing of fertiliser applications and the control of nitrate leaching and P wash off. The presence of plant nutrients in irrigation water thus present both advantages and disadvantages.

The approach adopted for evaluating the presence of plant nutrients in irrigation water is to estimate both the quantity of NPK that will be added through irrigation and the contribution their addition will make to the NPK removed by a specific crop. The assessment of fitness-for-use is based on the contribution that irrigation applications makes towards the estimated NPK removal by crops (indirectly the crop nutrient requirement). When inadvertent nutrient additions through irrigation are relatively low compared to crop requirement, it is relatively easy to accommodate the additional nutrients as part of normal nutrient management practices, and the additional nutrients may be viewed as beneficial. However, as inadvertent nutrient additions increase, it becomes increasingly difficult to manage the negative effects associated with higher fertiliser applications. The rationale for the adopted criteria is that the lower the NPK content of irrigation water, the easier it is to manage crop nutrient requirements. The criteria are indicated in the table below. (The figures used to calculate the mass of NPK removed by crops are based on reasonable assumptions sourced from literature for crop yield and the NPK content of the crop removed at harvest. They are reported on in Volume 2 of this report (Technical Support). The fitness-for-use evaluation table (example listed below) reports not only the percentage removal, on which fitness-for-use is based, but also the NPK application rate. This allows the irrigator to decide whether the higher application rate would be beneficial in specific cases.

The same criteria are used for both Tier 1 and 2 evaluations. However, with Tier 1 calculations, single removal and application values are calculated assuming 1000 mm irrigation p.a. and a generic crop. For Tier 2 calculations, the actual crop(s) and irrigation application during each of 10 or more years are calculated (one for each climatic year). This enables the calculation of probabilities for the percentage of years during which nutrient removal and application values will fall within different fitness-for-use categories.

Contribution to N P K removal by generic sensitive crop	Fitness-for-use	Contribution to estimated N P K removal by crop	% of estimated N P K removal at harvest and amount that is applied through irrigation (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
			Removal (%)	Applied (kg/ha)	Removal (%)	Applied (kg/ha)	Removal (%)	Applied (kg/ha)
	Ideal	<10%			4	2		
	Acceptable	10 – 30%	20	20			17	5
	Tolerable	30 – 50%						
	Unacceptable	>50%						

7.4 MICROBIAL CONTAMINATION OF CROPS

The main concern about the presence of human pathogens in irrigation water is the risk this poses to food safety (crop quality) when crops destined for human consumption are contaminated during irrigation. This also has implications for compliance to food safety regulations. The deposition of pathogens during irrigation is of particular concern for fruits and vegetables which are consumed raw, or with minimal processing (MPF, minimally processed fresh fruit and vegetables) since pathogens may survive to reach the consumer, and upon consumption, cause disease.

The baseline study of a quantitative investigation by Britz and Zigge (2012) into the link between irrigation water quality and food safety in South Africa, found high concentrations of faecal indicators in rivers, with concentrations at times reaching log 7 cell concentrations (or 10 million organisms per 100 mL). In most cases the *E. coli* concentration exceeded the <1000 counts per 100 mL guideline of the World Health Organisation (WHO) and the 1996 Water Quality Guidelines for Irrigation. From further studies, they concluded that there is a high risk of exposure to human pathogens when waters from the rivers they studied are used to irrigate produce that is consumed raw or without any further processing steps. Using phenotypic and genotypic identifications, direct linkages between irrigation water and produce could be made. They concluded that due to the potential for pathogenic organisms to be transferred from irrigation water to the surface of fresh produce, coupled with their ability to survive under these unfavourable conditions, presents the scenario where consumers unknowingly face a high risk of being infected with harmful organisms when consuming fresh produce. However, it is also important to note that no carry-over to produce was observed when the counts of irrigation water were in the 1000 to 10 000 counts per 100 mL range. This could be an indication that these are "safe" concentrations to irrigate fresh produce with and that a minimum number of *E. coli* will be carried over to the fresh produce.

There are two broadly recognized groups of water-transmitted pathogens. One contains viral, bacterial and protozoan pathogens. These are represented by norovirus (virus), Campylobacter (bacterial) and Cryptosporidium (protozoa) (Mara and Bos, 2010). The second group is Ascaris, the most significant helminth parasite associated with soil and crop contamination. If soil or crops become contaminated with viable eggs of Ascaris, this represents a high health risk. However, the likelihood of irrigation water containing sufficient levels of Ascaris to cause such contamination is low, unless the irrigation water contains a high proportion of raw or minimally treated faeces or wastewater. Inclusion of Ascaris in the guidelines would require routine water analysis laboratories to have the facilities and skills to analyse water samples for Ascaris eggs, which is not the case. For this reason, it was decided that Ascaris would not be included as a quantitative measure in the DSS, but that its significance in cases of high wastewater contamination be highlighted in the supporting help files and that the WHO guideline for irrigation with wastewater, excreta or greywater (<1 viable egg per litre or per g settled solids), be stated (WHO, 2006, Vol.4).

It is not feasible to measure the presence and levels of all possible pathogens in irrigation water. Therefore, *E. coli* is used in the DSS as an indicator of microbial pathogens, recognizing that levels of *E. coli* are much higher than those of microbial pathogens. The risk of norovirus infection per person per year is determined in the DSS by comparing the count of *E. coli* per 100 ml to a dose-response function. Next, the risk for an individual dose and the annual risk of infection (risk of infection per person per year) by Campylobacter and Cryptosporidium are calculated by the DSS using appropriate formulae. The annual risk associated with individual exposure is estimated as the sum associated with annual exposures to each of norovirus, Campylobacter and Cryptosporidium. In the absence of data to the contrary, it is assumed that all three micro-organisms contribute equally to the annual risk of infection. The risk of infection is expressed as the number of excess infections per thousand persons p.a. The calculation of the risk of exposure is based on the total annual *E. coli* intake. Annual intake is calculated from the volume of irrigation retained by a crop and how much of it is consumed on an annual basis. Whether a crop is wetted by irrigation is determined by the irrigation system and structure of the crop. The values that were assumed in this regard are published as an Appendix in Volume 2 of this report (Technical Support)

The criteria used in the DSS to determine the fitness-for-use category based on the calculated number of excess infections per thousand persons p.a. are indicated below. The same criteria are used for both Tier 1 and 2 evaluations. However, for Tier 1 calculations, a single number of excess infections per thousand persons p.a. are reported assuming lettuce to be the most sensitive crop, whereas with Tier 2 calculations, the parameters for the actual irrigated crop are used.

	Fitness-for-Use	Excess infections per 1000 people p.a.
Microbial contamination	Ideal	<1
	Acceptable	1 - 3
	Tolerable	3 - 10
	Unacceptable	>10

7.5 EFFECT OF PESTICIDES ON CROP YIELD

From the overview of the current state of knowledge in Volume 2 of this report (Technical Support), it is clear that the measured pesticide concentrations in water resources are low and that the likelihood is small for irrigation water to be the source of unacceptable pesticide residues on produce (i.e. exceeding the Maximum Residue Limits (MRLs) set for consumer protection and complying with export regulations). Using results of Dabrowski (2015), it was calculated what the required concentration of pesticides in irrigation water would have to be to deliver a quantity of pesticide equal to the rate typically applied by farmers (while still conforming to MRLs). The pesticide concentrations that would be required in irrigation water to equal the rate typically applied by farmers, were significantly higher than peak concentrations measured in typical river water samples, indicating that it is highly unlikely that MRLs will be exceeded because of crop irrigation. It was thus deemed unnecessary to develop guidelines for non-herbicide pesticides.

Pesticide studies in South Africa have often focused on human and ecological health and have therefore focused largely on insecticides which pose more significant immediate health risks to this group of organisms. Herbicides are, however, the most widely applied class of pesticides in South Africa and in view of the phytotoxic risk they pose to non-target/sensitive crops, are more likely to be of concern to irrigation farmers. However, they need to be present in concentrations that are toxicologically relevant in order to pose a risk of phytotoxicity. Although this risk also appears to be low based on available evidence, it was decided to consider herbicides as one of the suitability indicators for inclusion in the DSS. After glyphosate, atrazine is the most widely used herbicide in South Africa (see Volume 2 of this report, Technical Support). Since atrazine is highly mobile compared to glyphosates, with a significantly longer half-life, it was selected as the herbicide to consider in the DSS.

Atrazine is used to control pre- and post-emergence broadleaf and grassy weeds in maize, sugarcane and sorghum. It exhibits residual activity in soil for several months and can leach from soil to groundwater. Once in groundwater, it degrades slowly. Atrazine degrades in soil primarily through microbial action and serves as a nitrogen source for aerobic microorganisms. Atrazine is viewed as an endocrine disrupter and its use has been banned in a number of countries, foremost of which is the European Union (https://en.wikipedia.org/wiki/Atrazine accessed 18 April 2017)

A problem associated with atrazine applications (and thus with atrazine applications through irrigation) is that the residual atrazine remaining in the soil may damage follow-on crops. In order to circumvent this, waiting periods are prescribed before the next crop is planted. No waiting period is required for maize or sugarcane as follow-on crops. However, a 12-month waiting period is required for grain sorghum as follow-up crop, 18 months for sunflower, small grains, feed sorghum, dry beans, groundnuts, soybeans and potatoes, and 24 months for other crops. For purposes of the DSS, all crops requiring a waiting period before planting, after atrazine applications (i.e. all crops excluding maize and sugarcane) are viewed as atrazine sensitive crops.

The Australian and Canadian guidelines for atrazine in irrigation water is 10 µg/L. This equates to 100 g/ha a.i. (active ingredient) for every 1000 mm irrigation applied. This value was adopted as the unacceptable fitness-for-use threshold for Tier 1 evaluations in the DSS, with the other ranges as indicated below. These application rates (as modified to incorporate the effect of soil texture) are also used to assess the Tier 2 fitness-for-use for atrazine sensitive crops.

Fitness-for-Use	Atrazine concentration (a.i.) (µg/L)	Atrazine load (g/ha)
Ideal	<5	<50
Acceptable	5 – 7.5	50 – 75
Tolerable	7.5 – 10	75 – 100
Unacceptable	>10	>100

In South Africa atrazine is registered for the control of annual broadleaf weeds and certain grasses in maize, grain sorghum and sugarcane, as a pre- and/or post-emergence application. In view of the faster degradation at higher clay and organic matter content, higher dosages are recommended for soils with a higher clay and organic matter content (According to label of Atrazine 500 SC, Registration No. L6431, under South African Act No. 36 of 1947). The recommended dosages (rounded down to round numbers) were used to determine dosage rates that consider soil texture, for Tier 2 assessments, as indicated below. Dosages exceeding the recommended rates are deemed to be unacceptable and half the recommended rate, as ideal. The dosage rates for sugarcane and maize planted on coarse sand happen to be ten times the dosage rates (load) for atrazine sensitive crops. This ratio was used to extrapolate and obtain dosage rates for sensitive crops that consider soil texture for Tier 2 assessments.

Fitness-for-Use	Dosage (g a.i./ha) per Texture Class			
	Coarse Sand	Sand	Sandy Loam	Clay
Maize				
Ideal	<500	<750	<900	<1000
Acceptable	500 - 750	750 - 1100	900 – 1300	1000 - 1500
Tolerable	750 - 1000	1100 - 1500	1300 – 1800	1500 - 2000
Unacceptable	>1000	>1500	>1800	>2000
Sugarcane				
Ideal	<500	<500	<500	Not Recommended
Acceptable	500 - 750	500 - 750	500 – 750	
Tolerable	750 - 1000	750 - 1000	750 – 1000	
Unacceptable	>1000	>1000	>1000	
Atrazine Sensitive Crops				
Ideal	<50	<75	<90	<100
Acceptable	50 – 75	75 - 110	90 – 130	100 - 150
Tolerable	75 - 100	110 - 150	130 – 180	150 - 200
Unacceptable	>100	>150	>180	>200

8 PROCEDURES TO CALCULATE AND CRITERIA USED TO ASSESS IMPACT OF WATER CONSTITUENTS ON IRRIGATION EQUIPMENT

The irrigation scheduling approach and system which are selected to apply irrigation water form part of the site-specific options that are provided for in the DSS. It is also often the case that site-specific considerations play a determining role in the choice of a scheduling approach and irrigation system. However, the impact that irrigation water constituents have on the irrigation equipment used to distribute and apply water, is for the larger part, not site-specific, and rather a direct result of the interaction between water constituents and components of the irrigation system. This interaction is determined primarily by the material irrigation equipment is made of, or the type of equipment used. Uncommon site-specific factors that are encountered, but not considered in the DSS, include extreme temperatures, bacteria and external electric currents.

The following suitability indicators have been identified to assess the effects irrigation water constituents have on the irrigation system:

i. Corrosion or scaling of irrigation equipment.
ii. Clogging of drippers.

Irrigation water is normally supplied untreated. It is thus not chemically stabilised to control the potential for corrosion or encrustation (precipitation) of irrigation equipment, or filtered so that it can be used directly for drip irrigation. Corrosion and scaling of irrigation equipment and structures are arguably the primary water quality problems associated with on-farm irrigation infrastructure. Either can necessitate the early replacement of expensive irrigation equipment. Both corrosion and scaling are the result of waters having chemical imbalances. A secondary problem associated with water constituents is the clogging of drippers, which can be of either a chemical or physical nature.

8.1 Scaling and corrosion

The prediction of corrosion and scaling is a complex phenomenon with several factors determining its outcome, some of which are very site-specific. Metal, concrete and plastics can all deteriorate over time due to contact with irrigation water. The conversion from pure metal to metal oxides or sulphides is spontaneous. Metal corrosion is influenced by the presence of electrical fields, the conjunction of dissimilar metals, bacteriological activity and physical processes. Organic contaminants in groundwater are primarily responsible for the degradation of synthetic materials like plastics and PVC. Concrete is eroded by water that is under-saturated with regard to calcium carbonate.

Although minor scaling which forms a protective layer against corrosion inside pipes is normally considered beneficial, excessive scaling reduce flow rates and damages water systems, necessitating repair or replacement. The most common cause of scaling is the precipitation of calcium carbonate when saturation is exceeded. Although less frequent, gypsum precipitation also occurs in irrigation equipment when water high in calcium and sulphate is used.

There are several indices with which corrosion and scaling can be predicted. The most commonly used is the Langelier Saturation Index (LI), which was developed by Wilfred Langelier in 1936. The LI is an approximate measure of the degree of saturation of calcium carbonate in water. It is widely used to indicate the likelihood of corrosion and scaling, and is calculated as the difference between actual measured pH of water (pH_a) and the hypothetical saturation pH of the water (pH_s). pH_s is the calculated theoretical pH at which water with a given bicarbonate and calcium ion concentration, and total dissolved solids content at a given temperature, would be in equilibrium with solid calcium carbonate

$$LI = pH_a - pH_s$$

A positive LI indicates that water is over-saturated and scaling is likely, while a negative LI indicates water that is under-saturated with respect to calcium carbonate, and potentially corrosive. The DSS uses the following fitness-for-use categories, based on the LI, to determine the corrosion or scaling potential of a water sample. When interpreting results, it should e.g. be borne in mind that the LI caters primarily for carbonate rather than sulphate rich waters and that the LI was calculated for a temperature of 25°C. There is no difference between the Tier 1 and Tier 2 calculations and interpretation of LI.

Fitness-for-Use	Langelier Index	
	Corrosion	Scaling
Ideal	> -0.5	<+0.5
Acceptable	-0.5 to -1.0	+0.5 to +1.0
Tolerable	-1.0 to -2.0	+1.0 to +2.0
Unacceptable	< -2.0	>+2.0

8.2 Clogging of drippers

The low flow rates in drip emitters are conducive to clogging problems. While it is relatively easy to spot blocked openings, it is very difficult to distinguish one that is partially blocked. Both alter the hydraulics of the entire system, result in a decrease in the uniformity of application and give rise to reduced yields. Ayers and Westcot (1985) cover the topic of clogging in drip irrigation systems in quite some detail while Nakayama and Bucks (1991) provide an overview of the body of research that deals with the contribution water constituents make to emitter clogging, as well as the treatment options that are available to address its causes.

Often clogging of drippers is not a result of the irrigation water composition *per se*, but as a result of fertigation (phosphorous fertilizers precipitate at relatively low calcium concentrations and anhydrous or liquid ammonia cause increase in pH which can cause precipitation of calcium carbonate) or through biological growth inside dripper lines.

Nakayama and Bucks (1991) presented criteria indicating the potential for clogging problems in drip irrigation systems as a result of irrigation water constituents. These criteria are, with some modifications, used to define the fitness for use categories used in the DSS, indicated below. The interpretation of these numbers is the same for both Tiers 1 and 2.

Potential Clogging of drippers by irrigation water constituents (after Nakayama and Bucks (1991))				
Water Constituent	Fitness for Use Category			
	Ideal	Acceptable	Tolerable	Unacceptable
Suspended Solids (mg/L)	<50	50 - 75	75 - 100	>100
pH	<7.0	7.0 - 7.5	7.5 - 8.0	>8.0
Manganese (mg/L)	<0.1	0.1 - 0.5	0.5 - 1.5	>1.5
Total Iron (mg/L)	<0.2	0.2 - 0.5	0.5 - 1.5	>1.5
E. coli (counts x 10^6 /100 mL)	<1.0	1.0 - 2.0	2.0 - 5.0	>5.0

9 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The general aim of this project was to develop a software-based decision support system (DSS) able to provide both generic and site-specific risk-based irrigation water quality guidelines for South Africa. Specific aims were

1. To develop an intermediate 'technology demonstrator' that demonstrates the most important features.
2. To engage with stakeholders to elicit comment and recommendations.
3. To maximise synergy with parallel projects on the development of water quality guidelines for other water uses.
4. To develop a fully-functioning DSS for irrigation

The first two specific aims were addressed during the execution of the project as part of the development and refinement of the fully functional DSS for irrigation. The synergy with the two parallel projects developing guidelines for domestic and recreational use were maximised by regular formal and informal interaction with their research teams during which ideas, approaches and completed deliverables were discussed and shared.

The general aim to develop a software-based DSS able to provide both generic and site-specific risk-based irrigation water quality guidelines for South Africa, was successfully completed as described in this report. The DSS is a user friendly self-contained system incorporating the data bases, help files and supporting information that are required to run the DSS.

Designing and establishing the DSS was a major undertaking and, as far as could be ascertained, a world first. For a project of this nature and scope it is only to be expected that further refinement and the need for additional features would be identified during the course of the project. The more significant of these are to:

i. Enable the use of time series of water constituent analytical data. (The DSS currently provides only for a single water analysis);
ii. Modify the SWB model to create a feedback loop between water and salt stress so that reduced water uptake is simulated during periods of salt stress;
iii. Develop and display an integrated fitness for use evaluation and/or overview summary
iv. Establish an interface which enable downloading of climate data stored on the internet to the DSS;
v. Establish a facility enabling the import of water constituent analytical data multiples (need of analytical laboratories)
vi. To update the DSS to improve user-friendliness and utility based on extensive feedback from actual users;
vii. Enable additional output displays for fitness for use, such as a graph showing how each suitability indicators change with time, how soil salinity change with depth, where in the soil profile problems with hydraulic conductivity is encountered, how the Langelier Index and its implications change with changing temperature etc.
viii. Update the DSS with intervals of about five years, in order to update its scientific content where necessary to introduce new findings or data.

10 REFERENCES

ANNANDALE JG, BENADE N, JOVANOVIC, NZ, STEYN, JM and DU SAUTOY N 1999 Facilitating irrigation scheduling by means of the Soil Water Balance model. Water Research Commission Report No. 753/1/99, Pretoria, South Africa.

ANZECC 1992 Australian water quality guidelines for fresh and marine waters. National Water Quality Management Strategy Paper No 4, Australian and New Zealand Environment and Conservation Council, Canberra.

ANZECC 2000 The Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand. Canberra, Australia. ISBN 0 9578245 2 1.

AYERS RS and WESTCOT DW 1976 Water quality for agriculture. FAO Irrigation and Drainage Paper No. 29. FAO, Rome.

AYERS RS and WESTCOT DW 1985 Water quality for agriculture. FAO Irrigation and Drainage Paper No. 29. FAO, Rome.

BRITZ TJ and SIGGE GO (editors) 2012. Quantitative Investigation into the Link Between Irrigation Water Quality and Food Safety, Volume 1: Synthesis Report. WRC Report No.1773/1/12 Water Research Commission, Pretoria

CANADIAN GUIDELINES 1987. Canadian Water Quality Guidelines. Prepared by the Task Force on Water Quality Guidelines of the Canadian Council of Resource and Environment Ministers. Canada.

DABROWSKI JM 2015 Investigation of the contamination of water resources by agricultural chemicals and the impact on environmental health. WRC Report No. TT 642/15 Water Research Commission, Pretoria

DEPARTMENT OF WATER AFFAIRS AND FORESTRY 1993. South African Water Quality Guidelines, Volume 4: Agricultural Use.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY 1996. South African Water Quality Guidelines (second edition). Volume 4: Agricultural Use: Irrigation.

DWA 2013. Revision of general authorisations in terms of Section 39 of the National Water Act, 1998 (Act No. 36 of 1998), No. 665. Government Gazette No. 36820, 6 September 2013. Department of Water Affairs, Pretoria, South Africa, 3-31.

DWAF (2008). Development of SA Risk-Based Water Quality Guidelines: Phase 1: Needs Assessment and Philosophy by Ralph Heath (Coordinator), K Murray, J Meyer, P Moodley, K Hodgson, C du Preez, B Genthe, N Muller. July 2008. Department of Water Affairs and Forestry, Pretoria, South Africa.

DU PLESSIS HM and SHAINBERG I 1985 Effect of sodium and phosphogypsum on the hydraulic properties of several South African soils. S Afr J Plant Soil 2, 179 – 186

DU PREEZ CC, VAN HUYSSTEEN CW and MNKENI PNS 2011 Land use and soil organic matter in South Africa 2: A review on the influence of arable crop production. S Afr J Sci. 2011;107(5/6), Art. #358, 8 pages.

MAAS EV and HOFFMAN GJ 1977 Crop salt tolerance-current assessment. Journal of Irrigation and Drainage Divisions ASCE 103, 115-134.

MARA D and BOS R 2010 The 2006 WHO Guidelines for the Safe Use of Wastewater in Agriculture.

MYBURGH PA and HOWELL CL 2014 The impact of wastewater irrigation by wineries on soils, crop growth and product quality. WRC Report No. 1881/1/14.

NAKAYAMA FS and BUCKS DA 1991 Water Quality in Drip/trickle Irrigation: A Review. Irrig. Sci. 12, 187 - 192.

NSW DEPARTMENT OF ENVIRONMENT AND CONSERVATION 2004 Environmental Guidelines: Use of effluent in irrigation. Department of Environment and Conservation (NSW). Sydney, DEC 2004/87

PEACOCK CH, MILLER GL and MAARTIN MC 2012 Irrigation water quality problems. North Carolina State University Cooperative Extension Publication No AG-759

PESCOD MB 1992 Wastewater treatment and use in agriculture. FAO Irrigation and Drainage Paper No. 47. FAO, Rome.

PRATT PF and SUAREZ, DL 1990 Irrigation Water Quality Assessments. In: Agricultural Salinity Assessment and Management, TANJI, KK (Ed.). ASCE Manuals and Reports on Engineering Practice No. 71. ASCE New York 1990.

QUIRK JP and SCHOFIELD RK 1955 The effect of electrolyte concentration on soil permeability. J Soil Sci 6, 163 - 178

ROBBINS CH 1991 Solute transport and reactions in salt-affected soils. In: Hanks RJ, Ritchie JT (Eds) Modelling Plant and Soil Systems. Agronomy Monograph No. 31, ASA-CSSA-SSSSA, Madison, Wisconsin, USA, 365-395.

RODDA N, CARDEN K and ARMITAGE N 2010a Sustainable use of greywater in small-scale agriculture and gardens in South Africa. Guidance Report. WRC Report No. TT 469/10

RODDA N, CARDEN K and ARMITAGE N 2010b Sustainable use of greywater in small-scale agriculture and gardens in South Africa. Technical Report. WRC Report No. 1639/1/10

SINGELS, A, ANNANDALE, JG, DE JAGER, JM, SCHULZE, RE, INMAN-BAMBER, NG, DURAND, W, VAN RENSBURG, LD, VAN HEERDEN, PS, CROSBY, CT, GREEN, GC and STEYN, JM, 2010 Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future. *SA Journal Plant and Soil*, 27(1), 49-65.

US ENVIRONMENTAL PROTECTION AGENCY (USEPA) 1973 Proposed Criteria for Water Quality. Volume 1. US Environmental Protection Agency, Washington. DC 20460. (93 pages)

US ENVIRONMENTAL PROTECTION AGENCY (USEPA) 1986 Quality Criteria for Water, 1986. EPA 440/5-86-001. United States Environmental Protection Agency, Office of Water Regulations and Standards, Washington. DC 20460.

US SALINITY LABORATORY STAFF (USSL) 1954 Diagnosis and improvement of saline and alkali soils. Agricultural handbook no. 60. USDA, Washington, DC, United States of America.

VAN DER MERWE AJ 1969 Reclamation of the brack alluvial soils of Riet River using the threshold concentration concept. Agrochemophysica 1, 67 – 72

VAN DER MERWE AJ and BURGER R 1969 The influence of exchangeable cations on certain physical properties of a saline-alkali soil. Agrochemophysica 1, 63 - 66

WHO 2006. Guidelines for the Safe Use of Wastewater, Excreta and Greywater, Volume 4 Excreta and Greywater use in agriculture. World Health Organisation, Geneva.

APPENDIX A

Example of the output produced for a Tier 1 fitness-for-use assessment.

Irrigation Water Fitness-for-Use (Tier 1)

Sample identification:	44: Mr Jacobs Borehole D5
Site description:	41: Planned Pivot, Lettuce/wheat crop rotation

Water Analysis

Major constituents (mg/L)

Calcium	50.0	Bicarbonate	75.0
Magnesium	29.0	Chloride	85.0
Sodium	30.0	Sulphate	120.0
pH	7.5	Total Dissolved solids (TDS)	389.0
Electrical Conductivity (mS/m)	60.0	Suspended solids	40.0
SAR (mol/L)^0.5	0.8		

Biological Constituents

E. coli (counts/100 mL)	1.0E+03
Chemical Oxygen Demand (mg/L)	250

Nutrients (mg/L)

Total inorganic nitrogen (N)	1.2
Total inorganic phosphorous (P)	0.1
Total inorganic potassium (K)	0.2

Pesticides (µg/L)

Atrazine	6.0

Trace Elements in irrigation water (µg/L) and soil (mg/kg)

	Water	Soil		Water	Soil
Aluminium	2000	0	Lead	0	0
Arsenic		0	Lithium	1800	0
Beryllium	30	0	Manganese	300	0
Boron	500	0	Mercury	1	0
Cadmium	2	0	Molybdenum	8	0
Chromium	70	0	Nickel	120	0
Cobalt		0	Selenium	9	0
Copper	100	0	Uranium	5	0
Fluoride	850	0	Vanadium	70	0
Iron		0	Zinc	400	0

Tier 1: Fitness-for-Use
Soil Quality

	Fitness-for-use	Root zone salinity (mS/m)	Predicted equilibrium root zone salinity (mS/m)
Root zone salinity	Ideal	0 - 200	113
	Acceptable	200 - 400	
	Tolerable	400 - 800	
	Unacceptable	> 800	

	Fitness-for-use	Degree of reduced Permeability	Qualitative indication of the impact on soil permeability as manifested by reduced:	
			Surface Infiltrability	Soil Hydraulic Conductivity
Soil Permeability	Ideal	None		None
	Acceptable	Slight	Slight	
	Tolerable	Moderate		
	Unacceptable	Severe		

	Fitness-for-use	COD Load (kg/ha per month)	Chemical Oxygen Demand (COD) Load (kg/ha per month)
Oxidisable Carbon Loading	Ideal	0 - 400	208
	Acceptable	400 - 1000	
	Tolerable	1000 - 1600	
	Unacceptable	>1600	

	Fitness-for-use		Number of years of 1000 mm irrigation before Trace Elements reach accumulation threshold in topsoil			
Trace Element Accumulation	Ideal		> 200 years to reach soil accumulation threshold			
	Acceptable		150 to 200 years to reach soil accumulation threshold			
	Tolerable		100 to 150 years to reach soil accumulation threshold			
	Unacceptable		< 100 years to reach soil accumulation threshold			
	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold
	Al	2500	250	Li	1250	139
	As	50	No data	Mn	100	67
	Ba	50	333	Hg	1	200
	Cd	5	500	Mo	5	125
	Cr	50	143	Ni	100	167
	Co	25	No data	Se	10	222
	Cu	100	200	U	5	200
	F	1000	235	Va	50	143
	Fe	2500	No data	Zn	500	250
	Pb	100	Infinite			

Tier 1: Fitness-for-Use

Yield and Quality of a Generic Sensitive Crop with 1000 mm irrigation p.a.

	Fitness-for-use	Relative crop yield (%)	Predicted relative crop yield (%) as affected by:			
			Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
Root Zone Effects	Ideal	90 - 100			100	100
	Acceptable	80 - 90	88	86		
	Tolerable	70 - 80				
	Unacceptable	<70				

	Fitness-for-use	Degree of leaf scorching	Degree of leaf scorching under sprinkler irrigation caused by:	
			Chloride (Cl)	Sodium (Na)
Leaf scorching when wetted	Ideal	None		None
	Acceptable	Slight	Slight	
	Tolerable	Moderate		
	Unacceptable	Severe		

	Fitness-for-use	Contribution to estimated N P K Removal by crop	% of estimated N P K removal at harvest and amount that is applied through irrigation (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
			Removal (%)	Applied (kg/ha)	Removal (%)	Applied (kg/ha)	Removal (%)	Applied (kg/ha)
Contribution to NPK removal by generic sensitive crop	Ideal	0 - 10%			5	1		
	Acceptable	10 - 30%	24	12			20	2
	Tolerable	30 - 50%						
	Unacceptable	>50%						

	Fitness-for-use	Excess infections per 1000 persons p.a.	Predicted excess infections per 1000 people p.a.
Microbial Contamination	Ideal	<1	
	Acceptable	1 - 3	2.9
	Tolerable	3 - 10	
	Unacceptable	>10	

	Fitness-for-use	Atrazine load (g/ha)	Estimated Atrazine load (g/ha)
Qualitative Atrazine Damage	Ideal	<50	
	Acceptable	50 - 75	60
	Tolerable	75 - 100	
	Unacceptable	>100	

Tier 1: Fitness-for-Use
Irrigation Equipment

Corrosion or Scaling of Irrigation Equipment

Fitness-for-use	Fitness for Use Category determined by the corrosion or scaling potential indicated by the Langelier Index			
	Corrosion (Langelier Index)		Scaling (Langelier Index)	
Ideal	-0.5 to 0		0 to +0.5	Not Scaling
Acceptable	-0.5 to -1.0	-0.56	+0.5 to +1.0	
Tolerable	-1.0 to -2.0		+1.0 to +2.0	
Unacceptable	<-2.0		>+2.0	

Clogging of Drippers

Fitness-for-use	Fitness for Use Category determined by the potential of a constituent to cause clogging of drippers									
	Suspended Solids (mg/L)		pH		Manganese (Mn) (mg/L)		Total Iron (Fe) (mg/L)		*E.coli* (10^6 per 100 mL)	
Ideal	<50	40	<7.0		<0.1		<0.2	No data	<1	0.001
Acceptable	50 - 75		7.0 - 7.5		0.1 - 0.5	0.3	0.2 - 0.5		1 - 2	
Tolerable	75 - 100		7.5 - 8.0	7.5	0.5 - 1.5		0.5 - 1.5		2 - 5	
Unacceptable	>100		>8.0		>1.5		>1.5		>5	

9781431209101