Maintenance of, and training in the application of the site-specific, risk-based decision support system for assessing irrigation water quality

Report
to the Water Research Commission

by

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EXECUTIVE SUMMARY

The South African Water Quality Guidelines comprise one of the most widely used tools in water quality management. In response to a request by the Department of Water and Sanitation (DWS), the Water Research Commission (WRC) initiated a series of research projects aimed at a substantial revision of the 1996 guidelines for different water user groups. The development of the Irrigation Water Quality (IrrigWQ) Decision Support System (DSS) was the first of these projects to be completed. Since its development, two important impediments to the future sustainability and deployment of IrrigWQ have been identified:

i. the fact that a custodian that will take responsibility for its maintenance and upkeep has not yet been identified, and

ii. the lack of training of potential users in its use and functionality, that was brought about as a secondary effect of the COVID pandemic.

Another potential hindrance to the utility of the IrrigWQ DSS, was the fact that the risk that trace element constituents pose to the fitness-for-use (FFU) of water, is determined by the period over which these elements accumulate in soil before exceeding an internationally set accumulation threshold. The issue becomes especially problematic when assessing the FFU of mine waters for irrigation. Often a high risk to using such waters is indicated because of the aluminium, iron, or manganese contents of these waters. The accumulation threshold value used in the DSS is questioned as inappropriate, because these trace elements are abundant in soils and occur naturally at very high concentrations without causing problems. There is thus also a need to review the approach followed in the DSS to identify the risk associated with irrigation water rich in aluminium (Al), iron (Fe), and manganese (Mn), and if justified, to propose an alternative approach to follow.

This project was aimed at addressing the impediments identified as follows:

i. Function as custodian of the IrrigWQ DSS by accepting responsibility for its maintenance and upkeep until a permanent custodian is identified and takes over the responsibility. Identify potential enhancements to the DSS to improve utility and user-friendliness.

ii. Promote the use of the IrrigWQ DSS through the presentation of in-person training courses.

iii. Develop virtual training material that covers the principles behind the algorithms used, the operation of the DSS, and the interpretation of the output for the different suitability indicators.

iv. Conduct preliminary studies to review the approach used in the DSS to identify the risk associated with Al, Fe and Mn in irrigation waters, and if justified, to propose an alternative approach.

This report details the approach used to meet the project aims, as well as the activities completed. Chapter 1 provides background and context of the project, and Chapter 2 details the approach used to meet project aims.

Chapter 3 details the activities completed as interim custodians of the DSS which included maintenance of the host website, software error fixes and user support. As part of the maintenance, the DSS was allocated a dedicated page on the host website and ensuring that the most recent version of the software is accessible. The software fixes and enhancements made, included the addition of a function to print output graphs for water and salt balances, a function to generate statistical output and developing a ‘hack” to import bulk water quality input data.

Chapter 4 details the activities completed to promote the use of the DSS which included presenting introductory training courses, presenting at conferences and as well as publishing articles about the utility of the DSS. Five dedicated training courses were presented, and three publications were produced as part of the initiative to promote the use of the DSS. The DSS was also presented in three conferences. The use of the DSS has also been indirectly promoted at forums, conferences, as well as industry meetings and workshops that the project team has been involved in outside of this project.

Chapter 5 describes the virtual training materials that have been developed. These training materials are presented in short format narrated PowerPoint presentations, as well as demonstration videos. The training materials are divided into three modules. The first module is titled “Genesis of and philosophy behind IrrigWQ” and it is aimed at providing general information that will help users understand what the DSS is and what it does. The second module is titled “Software demonstrations” and it is aimed at giving users hands-on experience of the DSS functionality. The third module is titled “Technical talks” and is aimed at aiding users understand the technical aspects of how the DSS works.

Chapter 6 presents the findings of the studies conducted to review the approach used in the DSS to identify the risk associated with Al, Fe, and Mn in irrigation waters, and proposes an alternative approach. The studies indicated that the risk associated with Al and Fe does not depend on the total concentrations due to increased loading, but rather on pH and redox condition of the soils. Under normal crop production conditions, circumneutral soil pH and well aerated soils, the accumulation of Al and Fe do not pose a risk as the elements have limited mobility and bioavailability. Mn, on the other hand, can be mobile in some circumneutral soils and the risk associated with the accumulation of this metal in soils is expected to be highly influenced by factors such as soil type.

This project was successful in addressing all of the aims set for it, with the exception of identifying a suitable custodian. This aim proved to be extremely challenging. In light of this, the Project Reference Group recommended that it would be most beneficial if UP, with support from the WRC, continue taking responsibility for the DSS until a permanent custodian capable of maintaining and promoting the use of the tool is identified.

The studies conducted to assess whether soil loading limits are essential in assessing the risk associated with Al, Fe, and Mn in irrigation waters provided great insights into the dynamics of these elements in soils. The results indicated that the plant availability of Al and Fe does not depend on total soil concentrations. Therefore, it is recommended that soil loading limits for these elements be excluded from DSS assessments. Mn dynamics in soils were found to be more complex than those of Al and Fe and require further investigations that focus on site-specificity. However, Fe and Mn should be retained in the DSS for assessing water quality effects on irrigation equipment. It is also recommended that the effect of foliar application of Al, Fe and Mn on crop quality be investigated, specifically to assess if foliar absorption of these elements poses a food safety risk, as this mode of uptake which may be of great importance under overhead irrigation that wets the canopy, is not considered in any irrigation water quality guidelines.

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ACRONYMS & ABBREVIATIONS

ANZECC	Australian and New Zealand Environment Conservation Council
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$CaCO_3$	Calcium carbonate (Limestone)
DALRRD	Department of Agriculture Land Reform and Rural Development
DSS	Decision Support System
DWS	Department of Water and Sanitation
EC	Electrical conductivity
ECe	Soil saturated paste electrical conductivity
FFU	Fitness-for-use
ICP-AES	Inductively coupled plasma atomic emission spectroscopy
IrrigWQ	Irrigation Water Quality Decision Support System
LDARD	Limpopo Department of Agriculture and Rural Development
LDH	Layered double hydroxide
PTE	Potentially toxic elements
RE	Removal efficiency
SABI	South African Irrigation Institute
SANCID	South African National Committee on Irrigation and Drainage
SE	Sorption efficiency
UP	University of Pretoria
USEPA	United States Environmental Protection Agency
WRC	Water Research Commission
WRO	Water Research Observatory

CHAPTER 1: INTRODUCTION

The South African Water Quality Guidelines comprise one of the most widely used tools in water quality management. In response to a request by the Department of Water and Sanitation, the Water Research Commission initiated a series of research projects aimed at a substantial revision of the 1996 guidelines for different water user groups. The development of the Irrigation Water Quality (IrrigWQ) Decision Support System (DSS), formerly referred to as SAWQI (South African Water Quality Guidelines for Irrigation), was the first of these projects to be completed. During a follow-on project, several enhancements to the IrrigWQ DSS software were introduced, and included correcting programming and other errors that had been identified. Although several further potential enhancements were also identified, they were not deemed essential for the use and functioning of the IrrigWQ DSS, and were considered to be best left in abeyance until the need for their incorporation was more clearly confirmed through feedback by the user community. At the time of initiating this project, the two most important impediments to the future sustainability and deployment of IrrigWQ were considered to be:

i. the fact that a custodian to take responsibility for maintenance and upkeep of the DSS had not been identified, and
ii. the lack of training of potential users in the use and functionality of the DSS, that was brought about as a secondary effect of the COVID pandemic.

Another potential hindrance to the utility of the IrrigWQ DSS, was the fact that the risk that trace element constituents pose to the fitness-for-use of water, is determined by the period over which these elements accumulate in soil before exceeding an internationally set accumulation threshold. This is especially problematic when assessing the fitness-for-use of mine waters for irrigation. Often, a high risk of using such waters is indicated because of the aluminium, iron, or manganese contents of these waters. The accumulation threshold values used in the DSS were questioned because these trace elements are naturally abundant in soils at very high concentrations without adverse effects. There was thus also a need to review the approach followed in the DSS to identify the risk associated with irrigation water rich in aluminium, iron, and manganese and, if justified, to propose an alternative approach to follow.

A program with the complexity of IrrigWQ will always require some maintenance. It is only to be expected that users will continue to identify minor coding errors or desirable enhancements to improve utility and user-friendliness. These should be attended to as part of the normal maintenance and upkeep of the program. The problem is that an organization to take on the role of custodian of the DSS and be responsible for maintaining, improving and supporting it has not yet been identified. This may result in reduced user confidence in the DSS due to a concern that no provision has been made to provide them with support.

The COVID pandemic made it practically impossible to present in-person training courses, with the result that a backlog in demand for training developed. With no custodian or sustained research initiative that can provide resources to fulfil this need into the future, the decision was made to explore alternative training options. A promising approach that was identified, was the development of virtual training material, as this proved very effective for remote lecturing by universities during the COVID pandemic. This training material would, ideally, cover aspects of operating the DSS and explain the rationale behind and interpretation of the different irrigation water suitability indicators used in the DSS. The availability of this training material would enable users to have access to this valuable information at their convenience even if the developers had retired and were no longer research active. The availability of such training material would additionally serve as an online refresher course, which users could consult at any time, and as lecturing material for irrigation courses at tertiary institutions.

The following were the aims of the project:

i. Function as custodian of the IrrigWQ DSS by accepting responsibility for its maintenance and upkeep until a permanent custodian is identified and takes over the responsibility.
ii. Promote the use of the IrrigWQ DSS through the presentation of in-person training courses.
iii. Develop virtual training material that covers the principles behind the algorithms used, the operation of the DSS, and the interpretation of the output for the different suitability indicators.
iv. Conduct preliminary studies to review the approach used in the DSS to identify the risk associated with aluminium, iron, and manganese in irrigation waters, and if justified, to propose an alternative approach.

This report details the activities completed as custodian of the DSS (now called IrrigWQ), the training courses and narrated training modules developed, and recommends an alternate approach to estimate trace element risk.

CHAPTER 2: PROJECT APPROACH

The methodology adopted for this project was aimed at ensuring that the activities normally expected of the custodian of a Decision Support System (DSS), such as IrrigWQ, are assumed by the Project Team for the duration of this project or until these responsibilities are taken over by a permanent custodian. In addition, awareness-raising introductory training courses were presented, and self-help training material was developed to promote the use of IrrigWQ.

The approach used by the Project Team to address the project aims was as follows:

i. Acting as transitionary custodian of IrrigWQ.

   A program with the complexity of IrrigWQ will always require some maintenance. It is thus only to be expected that users will continue to identify minor programming errors or desirable enhancements to improve its utility and user-friendliness. The Project Team took care of the normal maintenance and upkeep of the program.

   For the duration of the project term, the project team acted as custodian of IrrigWQ and was responsible for the following:

   - Maintaining a website from which the most recent version of IrrigWQ can be downloaded
   - Attending to minor programming errors or desirable enhancements that were identified to improve the utility and user-friendliness of IrrigWQ
   - Available to assist users with problems they encounter
   - Assisted the WRC in the search for a suitable custodian and
   - Identify younger researcher(s) who can take over the scientific leadership for maintaining and developing IrrigWQ.

ii. Presentation of introductory in-person training courses.

   The COVID-19 pandemic made it practically impossible to present in-person training courses during the previous project, with the result that a backlog in demand for training developed. In-person introductory training courses were presented to the user community to increase their awareness of the availability of IrrigWQ and to familiarise them with its operation and functionality. Training consisted of presentations on the background to the development of the DSS and the criteria used to assess how water composition and site-specific characteristics affect soil quality, crop yield, crop quality, and irrigation equipment. This was followed by interactive demonstrations of setting up and executing Fitness-for-Use assessments and Water Quality Requirement determinations using IrrigWQ. The training was concluded with interactive, hands-on demonstrations using IrrigWQ to assess the Fitness-for-Use of waters of interest to attendees using their own water sample analyses and site-specific conditions of their choice. Similar interactive, hands-on demonstrations of how to perform Water Quality Requirement determinations were conducted when requested.

iii. Development of virtual training material.

   Several short, narrated PowerPoint training modules (similar to those developed for lectures by universities during the COVID pandemic), as well as demonstration videos, were developed. The narrated PowerPoints will serve as training modules on the principles of assessment of irrigation water quality, and the demonstration videos will train users on how to operate the DSS and interpret results. Users and potential users will be able to access the training modules at a time convenient to them. The training material will also serve as online refresher courses, which users can consult at any time.

This training material covers the following topics:

- How to capture, modify, export and import the composition of irrigation water samples and site-specific attributes
- The concerns addressed by each of the suitability indicators used by IrrigWQ to assess the effect of irrigation water constituents on soil quality, crop yield, crop quality and irrigation equipment
- How to interpret the results of an assessment of the Fitness-for-Use of a water sample for each of the suitability indicators
- How to interpret the results of a Water Quality Requirement determination for each of the suitability indicators and
- Other aspects of IrrigWQ (such as conversion between concentration units for water constituents) that require clarification for users who are not familiar with certain technical aspects.

iv. Review the approach used in IrrigWQ to determine the risk associated with aluminium, iron, and manganese in irrigation waters.

The approach used in IrrigWQ to determine the risk posed by trace element accumulation in soil is conservative and is based on the calculated time it would take a given trace element to accumulate to an internationally predetermined threshold concentration. The longer it takes the trace element to reach its threshold concentration, the less the risk posed by trace element accumulation. The outcome of these assessments of risk posed by trace element concentration becomes especially problematic when considering irrigation with mine waters, as the risk posed by aluminium, iron and manganese is often calculated to be unacceptable. The accumulation threshold value approach for these elements is questioned, because these trace elements are abundant in soils and occur naturally at very high concentrations without causing crop growth or other problems. This is due to chemical conditions that limit the mobility and/or bioavailability of these elements.

In the South African context, the fitness-for-use of mine waters for irrigation is often assessed as posing an unacceptable risk because of their aluminium, iron, or manganese contents. It would be unfortunate if an otherwise promising mine water irrigation project, was prevented from going ahead, because of an ‘unacceptable’ evaluation by IrrigWQ, which may, in fact, be incorrect. There was thus a need to review the approach followed in IrrigWQ, to identify the risk associated with irrigation water containing aluminium, iron, and manganese, and if justified, to propose an alternative approach. Studies were conducted to investigate the conditions that influence the bioavailability of these trace elements, and how this relates to the threshold concentrations set in IrrigWQ. This was done to guide the assessment of the risk associated with the introduction of these trace elements through irrigation.

CHAPTER 3: ACTIVITIES COMPLETED AS INTERIM CUSTODIANS OF THE IRRIGWQ DSS

It is generally accepted that computer programs such as IrrigWQ will require some maintenance and upkeep throughout their life cycle. This responsibility is normally accepted to be part and parcel of the function of a program's custodian. The functions of the interim custodian of IrrigWQ involved, inter alia:

i. Maintaining the IrrigWQ website from which the most recent version of the DSS could be downloaded;
ii. Attending to identified minor programming errors or desirable enhancements to improve the utility and user-friendliness of the DSS;
iii. Providing basic assistance to users who encountered problems running the program.

When the WRC initiated the development of the series of water quality guidelines for different users in response to requests by the Department of Water and Sanitation, it was understood that the Department would assume the responsibility as custodian of the guidelines that were to be developed. However, this did not materialise, with the result that IrrigWQ does not yet have a permanent custodian. Should the interim period until a custodian is found, not be taken care of, there is the risk that it will be very difficult to restart activities associated with this model at a later stage, and much of the investment in the DSS may be lost. User confidence in the program is also likely to suffer when users become aware that no provision has been made to support them. In addition to the need for a committed custodian, it is equally important to identify a committed and knowledgeable "champion" of the DSS. This is particularly important considering the age of the senior researchers who developed the tool.

Recognising the importance of maintaining the DSS until a long-term custodian and champion is identified, the WRC decided to support this maintenance type project with actions that would help to ensure its longer-term sustainability, as well as the mentorship of a candidate champion for the DSS. The Project Team achieved this by carrying out the following tasks:

- Maintain the IrrigWQ website from which the most recent version of the DSS could be downloaded
- Attend to minor programming errors or desirable enhancements to improve the utility and user-friendliness of the DSS
- Be available to assist users with problems they may encounter
- Assist the WRC in the search for a suitable custodian
- Actively mentor a promising candidate to become the IrrigWQ champion

A summary of the progress made with the listed tasks is presented in the subsections that follow.

3.1 MAINTENANCE OF THE IRRIGWQ HOST WEBSITE

The IrrigWQ DSS is hosted by the software developer, NB Systems, on their website. As part of the maintenance, the link to download the software was changed to ensure that IrrigWQ DSS has a dedicated page. The link was previously https://www.nbsystems.co.za/downloads.html and has now been changed to https://www.wateradmin.co.za/IrrigWQ.html. The page that was previously used to host the download link for IrrigWQ also had links to other software which was confusing to users.

3.2 SOFTWARE ERROR FIXES AND ENHANCEMENTS

3.2.1 Help facility to identify if most recent version is used

The software is updated frequently (at least twice a year) to improve functionality while addressing existing issues, such as "bugs" and "crashes". The most recent update was performed in October 2024. A screenshot of the opening screen showing the current version of the software is presented (circled in red in Figure 3-1). Users are able to check for updates in the software by following the software update link in the help tab on IrrigWQ's opening page (circled in blue in Figure 3-1). The link directs users to the software download page. This provides the user with an easy check to confirm that he/she is using the most recent version.

DISCLAIMER
This decision support system (DSS) was developed to provide guidance on the effect of irrigation water quality on soil quality, crop yield and quality, and irrigation equipment.
Great attention to detail has been taken to ensure that calculation procedures in this model are sound. Nevertheless, the authors, the University of Pretoria, the Department of Agriculture and the Water Research Commission will not accept liability for any damage nor loss suffered as a result of the use of this DSS.

Figure 3-1: Screenshot of software version circled in red, and the help facility to check for updates circled in blue.

3.2.2 Adding the facility to print graphs

IrrigWQ provides for the generation of a large number of graphs for use by more advanced users to view graphs depicting, e.g., water balance components, seasonal salt balance components, seasonal irrigation, transpiration, etc. These graphs were originally developed to provide advanced users with an opportunity to observe the effect of the interaction of different components of IrrigWQ. For this reason, graphs were initially only developed as screen display output. Should a user wish to store a graph they had to take a screenshot. These graphs and the need to store them proved to be so popular that it was decided to develop the facility to print and store them.

3.2.3 Statistical analysis of results

During the simulation of the effect irrigation water composition has on the various indicators of water quality, a very large amount of data is generated and temporarily stored on a daily basis. The stored data are processed to generate the values of the various suitability indicators, which is the main output of IrrigWQ. However, for advanced users, the opportunity to further mine the generated data is an attractive proposition. To this end, the data is statistically analyzed, and the user is provided with the sum, standard deviation and average of the results grouped by year, season, month or week for the variable(s) of interest.

3.2.4 "Hack" to upload data for multiple water quality samples

IrrigWQ was designed to process a combination of one water sample and one site-specific situation at a time. The need was expressed by analytical laboratories to be able to upload and process a number of samples in batches. At the time the potential benefit was not considered to justify the effort that would be required to introduce such a facility. However, Ms Madiseng recently developed a "hack" which enables the user to simultaneously upload a number of water sample analyses into the water quality database. This technique is explained in one of the virtual training modules.

3.2.5 Replacement of Department of Agriculture, Land Reform and Rural Development logo

The name and logo of the Department of Agriculture, Land Reform and Rural Development, formerly known as the Department of Agriculture, Forestry and Fisheries, were updated to reflect the name change.

3.3 SEARCH FOR A SUITABLE CUSTODIAN

There are two components to ensuring the long-term sustainability and success of IrrigWQ. One is the need for a committed long-term custodian, and the other is to identify a committed, knowledgeable and long-term champion of IrrigWQ. The Project Team believe that they have identified the desired long-term champion in the person of Ms Lesego Madiseng. Identifying the correct champion is particularly important considering the age of the senior researchers who developed the DSS. Finding a suitable custodian has proved elusive. Possible custodians that were identified included the Department of Water and Sanitation (DWS), the WRC through the Water Research Observatory (WRO), and the Department of Agriculture Land Reform and Rural Development (DALRRD). During the "Penultimate Reference Group Meeting" of this project, the matter of custodianship was discussed at great length, and the general consensus was that it would to be beneficial for UP, with research support from the WRC, to continue taking responsibility of the DSS until a permanent custodian capable of maintaining and promoting the usage of the tool had been identified.

CHAPTER 4: ACTIVITIES COMPLETED TO PROMOTE THE USE OF THE IRRIGWQ DSS

4.1 PRESENTATION OF INTRODUCTORY TRAINING COURSES

During the first of the two preceding DSS projects, members of the Project Team made several presentations to user groups and interested parties to introduce them to the DSS and raise awareness of its availability and functionality. Several one-day introductory training courses were also presented in centra across the country to train potential users in its use. However, travel and other restrictions imposed during the COVID 19 pandemic made it practically impossible to present in-person training courses during the previous project. In this project, several in-person introductory training courses were presented, as determined by demand, to the user community to increase their awareness of the availability of the DSS, on the one hand, and to familiarise them with its operation and functionality, on the other hand. The training courses were presented as follows:

i. On the 11 May 2022, the DSS was presented as part of their practicum, to 25 students of the Irrigation Management and Soil Physics course offered by the Department of Plant and Soil Sciences, University of Pretoria. The presentation consisted of an introduction to the DSS by Prof Annandale and Mr du Plessis, followed by a practical demonstration and actual use of the DSS under the guidance of Ms. Madiseng. The demonstration was concluded by giving the students a practical assignment consisting of a water quality problem they had to investigate and report on, by making use of the DSS.

ii. On request of the Department of Agriculture, Land Reform and Rural Development (DALRRD), the WRC arranged a training workshop entitled *Site-specific, Risk based DSS for Assessing Irrigation Water Quality,* that was held on 14 June 2022 at the CSIR Conference Centre. The training session was attended by approximately 30 participants, mainly officials of DALRRD. A copy of the workshop flyer and programme is attached in Appendix A. Dr Samkelisiwe Hlophe-Ginindza acted as facilitator during the training workshop. Prof. Annandale presented the background and introduction to the DSS, while Ms Madiseng coached participants in the use of the DSS by running hands-on examples, using their own computers. The WRC provided participants who could not download the program prior to the training session, with pre-loaded memory sticks containing the software.

iv. On the 24 May 2023, the DSS was presented as part of their practicum, to students of the Irrigation Management and Soil Physics course offered by the Department of Plant and Soil Sciences in the University of Pretoria (Figure 4-1). The presentation consisted of an introduction to the DSS by Mr du Plessis, followed by a practical demonstration and actual use of the DSS under the guidance of Ms. Madiseng. The demonstration was concluded by giving the students a practical assignment consisting of a water quality problem they had to investigate and report on, by making use of the DSS.

v. On request of the Limpopo Department of Agriculture and Rural Development (LDARD), the WRC arranged a training workshop entitled *Site-specific, Risk-based DSS for Assessing Irrigation Water Quality,* that was held on 13 June 2023 in Tzaneen. The training session was attended by approximately 30 participants, mainly officials of LDARD. A copy of the workshop flyer and programme is attached in Appendix A. Ms Nomvuso Mjadu acted as facilitator during the training workshop, Prof. Annandale presented the background and introduction to the DSS, while Ms Madiseng coached participants in the use of the DSS by running hands-on examples demonstrating the use of the IrrigWQ, using their own computers. The WRC provided participants who could not download the software prior to the training session, with pre-loaded memory sticks containing the DSS.

vi. On the 8 May 2024, the DSS was presented as part of their practicum, to students of the Irrigation Management and Soil Physics course offered by the Department of Plant and Soil Sciences in the University of Pretoria (Figure 4-2). The presentation consisted of an introduction to the DSS, followed by a practical demonstration and actual use of the DSS, both led by Ms. Madiseng. The demonstration was concluded by giving the students a practical assignment consisting of a water quality problem they had to investigate and report on, by making use of the DSS.

Figure 4-1: Presentation of the IrrigWQ DSS to students at the University of Pretoria, 24 May 2023.

Figure 4-2: Presentation of the IrrigWQ DSS to students at the University of Pretoria, 8 May 2024.

4.2 PUBLICATIONS

In addition to the virtual training modules, the project team has been promoting the use of the DSS through presentations to learned societies and through publications.

Early in 2023 the DSS was presented at the International Society of Horticultural Sciences Symposium. The presentation was accompanied by a paper which was published in the Acta Horticulturae journal. The paper is titled “An Electronic Decision Support System to Asses Risk-Based, Site-Specific Fitness for Use of Irrigation Water: Application to Horticultural Crops” and was authored by J.G. Annandale, H.M. du Plessis, N. Benadé and N.J. Taylor and can be accessed from: https://doi.org/10.17660/ActaHortic.2024.1409.30.

At the end of 2023, the project team published a peer-reviewed paper on the DSS in the Applied Sciences Journal titled “A Decision Support System that Considers Risk and Site Specificity in the Assessment of Irrigation Water Quality (IrrigWQ)”. The paper was authored by Heinrich M. du Plessis, John G. Annandale and Nico Benadé and can be accessed from: https://doi.org/10.3390/app132312625.

Members of the project team also published an article in the journal Mine Water and the Environment, titled “Irrigation Should be Explored as a Sustainable Management Solution to the Acid Mine Drainage

Legacy of the Witwatersrand Goldfields". The paper was authored by John Annandale, Meiring du Plessis, Phil Tanner, Sarah Heuer and Lesego Madiseng and can be accessed from: https://doi.org/10.1007/s10230-023-00961-3.

Abstracts for the articles are presented in the sections below and the first page of the manuscripts are attached as Appendix B.

4.2.1 An electronic decision support system to assess risk-based, site-specific fitness for use of irrigation water: Application to horticultural crops

Increased demands on available irrigation water supplies necessitate increased production with less water, often of a poorer quality and from unconventional sources. An electronic Decision Support System (DSS) which models soil-plant-atmosphere interactions has been developed to assess the fitness for use (FFU) of irrigation waters under site-specific conditions that may influence the assessment. The DSS operates at two tiers to assess the effect that water quality constituents may have on soil quality, crop yield and quality, and irrigation infrastructure. 'Suitability Indicators' divide these effects further into sub-components. User-friendly colour-coded Tier 2 output displays the risk associated with using the water under specific conditions, as 'ideal', 'acceptable', 'tolerable' or 'unacceptable'. Tier 1 assessments provide generic, conservative guidance, assuming no dilution of irrigation water by rain, instant equilibrium between water constituents and soil, and crops that are generally sensitive to water quality constituents. This resembles currently published international guidelines. Tier 2 assessments are more rigorous and are used to determine whether the assessed FFU of a water could improve when site-specific conditions are considered. These assessments use the Soil Water Balance (SWB) model to dynamically simulate the interactions between irrigation water constituents and the soil-crop-atmosphere system over 10 to 45 years, to quantify the probability and severity of a specific effect occurring. Default model parameters enable selection of an appropriate weather station, soil texture, crop species, irrigation management approach, and irrigation system. DSS predicted yield response to salinity is demonstrated for three horticultural crops to be comparable to that of international irrigation water quality guidelines, under similar conditions and assumptions. Examples are given to illustrate how FFU of irrigation water is affected by site-specific conditions. This illustrates how the DSS can be used to identify conditions under which a particular water can be used most beneficially.

4.2.2 A decision support system that considers risk and site specificity in the assessment of irrigation water quality (IrrigWQ)

Irrigators are increasingly challenged to maintain or even increase production using less water, sometimes of poorer quality, and often from unconventional sources. This paper describes the main features of a newly developed software-based Decision Support System (DSS), with which the fitness for use (FFU) of water for irrigation (IrrigWQ) can be assessed. The assessment considers site-specific factors, several non-traditional water constituents, and the risk of negative effects. The water balance components of a cropping system and the redistribution of solutes within a soil profile are assessed with a simplified soil water balance and chemistry model. User-friendly, colour-coded output highlights the expected effects of water constituents on soil quality, crop yield and quality, and irrigation infrastructure. Because IrrigWQ uses mainly internationally accepted cause–effect relationships to assess the effect of water quality constituents, it is expected to find universal acceptance and application among users. IrrigWQ also caters for calculating so-called Water Quality Requirements (WQRs). WQRs indicate the threshold levels of water quality constituents for irrigation at specified levels of acceptability or risk. WQRs assist water resource managers in setting site-specific maximum threshold levels of water quality constituents that can be tolerated in a water source before impacting negatively on successful irrigation.

4.2.3 Irrigation should be explored as a sustainable management solution to the acid mine drainage legacy of the Witwatersrand Goldfields

Mine closure in the Witwatersrand Goldfields of South Africa has resulted in an acid mine drainage (AMD) legacy that is difficult to manage and costly to address. As a short-term measure, three large high-density sludge (HDS) plants were erected that treat 185 megalitres of AMD per day (ML/day), at great cost to taxpayers. Longer-term solutions are sought, as the salt load to the Vaal River System is unacceptable. Long-term modelling was used to assess whether the untreated and HDS treated AMD could be used for irrigation, and to determine the scale of the potential opportunity. The Goldfields waters are not very acidic, and simulations indicate it should be feasible to utilise even the untreated water for irrigation, especially if growers commit to applying limestone to their fields. HDS treatment lowers the corrosivity and trace element concentrations, and because the water is gypsiferous, double cropping will precipitate more than a third of the salts in solution as gypsum in the soil profile, thereby reducing salt load to the water environment. The potential irrigated area depends on the cropping system; it is about 9000 ha for rotational cropping and 30,000 ha for supplemental maize irrigation. It is prudent to seriously consider irrigation as a potential long-term water management option for the Goldfields AMD.

4.3 PRESENTATIONS AT CONFERENCES

The Project Team presented the DSS during the Demonstration Workshop Session at the South African National Committee on Irrigation and Drainage (SANCID) Symposium from 21 to 23 February 2023. This workshop showcased the latest tools that have been developed for the SA Irrigation and Drainage industry. An abstract of the presentation for the workshop as well as extracts of the symposium programme are attached as Appendix C.

In 2024, Prof Annandale was invited to give a presentation on the DSS at the SABI Technical Forum, and Dr du Plessis was invited to present the DSS at the Soilborne Plant Diseases Symposium in October of 2024. A copy of the forum and symposium programmes, as well as the SABI Technical Forum flyer are presented in Appendix C, In addition to these initiatives, the project team has indirectly promoted the use of the DSS at forums, conferences, as well as industry meetings and workshops outside the scope of this project.

CHAPTER 5: DEVELOPMENT OF VIRTUAL TRAINING MATERIALS

While the COVID pandemic made it practically impossible to present in-person lectures at centres of higher learning, it forced lecturers to explore and develop alternative options to teach and convey information. A promising option that was identified and employed at the University of Pretoria, is the development and use of short, narrated PowerPoint training modules to supplement or replace formal lectures. Similar material was developed in this project, to assist with the training of potential users of the DSS in its use and operation. It is envisaged that the virtual training material developed will teach users how to operate the DSS and explain to them the rationale behind the different irrigation water suitability indicators used by the DSS, as well as how to interpret them. This should enable users to learn how to operate the DSS at their own pace and to the level of sophistication they wish to achieve. It would also enable them to take a 'refresher course' whenever they wish. A big advantage of this material is that even if the developers of the DSS have retired and are no longer research active, users would be able to access this material at their convenience. The availability of such training material will additionally serve as online refresher courses, which users can consult at any time. The training material is also expected to serve as lecturing material for irrigation courses at other tertiary institutions.

The electronic training material, which forms part of the virtual course, is presented in short format narrated PowerPoint presentations, as well as demonstration videos. The narrated presentations cover a wide range of general and technical topics. A brief discussion of the themes and modules that have been covered is presented in the subsections that follow. Samples of the narrated presentations and demonstration videos are presented in Appendix D. The training materials can be accessed from the Irrigation@UP webpage, https://www.up.ac.za/irrigation.

5.1 GENESIS OF AND PHILOSOPHY BEHIND IRRIGWQ

This theme provides general information that introduces users to the DSS, its functionality and its capabilities. This module includes the following sections:

5.1.1 Background to guideline development

This module provides some background on the development of IrrigWQ and covers the following topics:

- A brief history of the South African Water Quality Guidelines
- The need for revised water quality guidelines
- The approach taken to revise the South African Irrigation Water Quality Guidelines and the outputs from that endeavor

5.1.2 Water quality perspectives

This module presents water quality perspectives and covers the following topics:

- Water related challenges in South Africa, specifically in the context of irrigation
- Important factors contributing to successful development of irrigation
- Importance of site-specific approaches to assessing irrigation water quality

5.1.3 Unique features

This module discusses the unique features of the DSS. Part three focusses on the risk-based and site-specific approach used to assess water quality in the DSS. Part four focusses on the types of assessments that IrrigWQ can perform.

5.2 SOFTWARE DEMONSTRATIONS

The software demonstrations are instructional videos on how to use the DSS and they include the following modules:

5.2.1 Getting started

The DSS was designed to be user-friendly and in many ways it is. However, experience with in-person training courses has indicated that some guidance is needed on navigating the software upon first use. This module provides this guidance and covers the following topics:

- Navigating the opening screen
- Registering the software
- Navigating the main screen

5.2.2 Tier 1 simulations

In this module users are shown how to run a Tier 1 FFU assessment and the following topics are covered:

- Description of the Tier 1 assessment and input requirements
- Inserting water quality data
- How to use the unit conversion calculator
- Description of assessment output

5.2.3 Tier 2 simulations

In this module users are shown how to run a Tier 2 FFU assessment and the following topics are covered:

- Importance of site specificity
- Setting up site-specific conditions
- How to use the map tool
- How to download weather data

5.3 TECHNICAL TALKS

This theme aids users in understanding the technical aspects of how the DSS works. The following modules are available:

5.3.1 Understanding the soil quality output

This module aids the user in interpreting the DSS output results for soil quality. The module discusses soil profile salinity as an indicator of soil quality, soil permeability, and trace element accumulation.

5.3.2 Understanding the crop yield and quality output

This module aids the user in interpreting the DSS output results for crop yield and quality. The module covers rootzone effects on crop yield, and how sodium and chloride contribute to leaf scorching.

5.3.3 Understanding the irrigation equipment output

This module assists users in interpreting DSS output regarding the effect of irrigation water quality on irrigation infrastructure. It addresses topics concerning the effects of water quality constituents on corrosion or scaling of irrigation equipment and the clogging of drippers.

CHAPTER 6: REVIEW OF THE APPROACH USED IN THE DSS TO DETERMINE THE RISK ASSOCIATED WITH ALUMINIUM, IRON AND MANGANESE IN IRRIGATION WATERS

6.1 BACKGROUND

The approach used in the DSS to determine the risk posed by trace elements is conservative and is based on the calculated time it would take a given trace element to accumulate to an internationally predetermined threshold soil concentration. The longer it takes for a trace element to reach its threshold soil concentration, the lower the risk highlighted by the DSS. The outcomes of these assessments become especially problematic when the risk posed by aluminium, iron and manganese is calculated to be unacceptable, considering that these trace elements are often abundant in natural soils. The accumulation threshold approach used in the model is questioned for these elements. Most mine waters are often highlighted as posing an unacceptable risk when irrigation fitness-for-use (FFU) assessments are conducted because of their aluminium, iron, or manganese contents. It would be unfortunate if an otherwise promising mine water irrigation project is prevented from going ahead because of an ‘unacceptable’ evaluation by the DSS, which may, in fact, be incorrect. There is thus a need to review the approach followed by the DSS to identify the risk associated with trace elements in irrigation water, and if justified, to propose alternatives. In this project, attention is focused on aluminium, iron and manganese. However, contemporary perspectives on the risks posed by the other trace elements in irrigation waters is also discussed.

6.2 CONTEXT

Guidelines for assessing the quality of irrigation water have been developed by various organizations, including the Food and Agriculture Organization (FAO) (Ayers and Westcot, 1985), World Health Organization (WHO) (WHO, 2006), United States Environmental Protection Agency (USEPA) (USEPA, 2012, NAS-NAE, 1973), Australian and New Zealand Environment Conservation Council (ANZECC) (ANZECC, 2000), and the Republic of South Africa (RSA) through the Department of Water and Sanitation (DWS), formerly the Department of Water Affairs and Forestry (DWAF) (DWAF, 1996, du Plessis, et al., 2017). These guidelines aim to establish critical limits based on scientific evidence to prevent adverse effects on crops, soils, irrigation equipment and human health.

Most of these guidelines, for instance, USEPA (1972) and Ayers and Westcot (1985), highlight that the suggested maximum concentrations of trace element constituents in irrigation water were derived for long-term use (100 years) on all soils and were established conservatively by assuming the worst-case scenario of irrigating the most sensitive crops in sandy soils (soils expected to have a limited sorption capacity). These generic guideline values are set below the levels that would be expected to cause toxicity problems in all soil-plant-systems and also aim to minimise negative effects on irrigation equipment. The approach was first used by the USEPA (1972), which is widely generic, but has been adopted by many countries across the world (du Plessis, et al., 2017).

Du Plessis et al. (2017) developed “IrrigWQ”, an irrigation water quality model, in the form of an electronic Decision Support System (DSS) that assesses the site-specific effect of irrigation water quality on soil and crop resources, as well as on irrigation infrastructure. In addition, the DSS follows a risk-based approach and operates at two tiers or levels of detail (du Plessis, et al., 2023).

The approach that IrrigWQ follows for trace elements, however, is fundamentally similar to that of the other international guidelines, which may render some FFU assessments unduly restrictive. With this approach, because most trace elements applied through irrigation accumulate in soils, soil loading limits were set. The thresholds used for Al, Fe and Mn may be inappropriate as these elements are recognized as major elements in soils owing to their very high natural abundance (Sposito, 2008). The negative effects of irrigation waters high in these elements on other protection targets, such as irrigation infrastructure and produce quality, may be evaluated on a case-by-case and site-specific basis by IrrigWQ.

There are foreseeable advantages of enhancing the model to improve its site-specificity in the approach it follows for trace elements. Firstly, the model already has site-specific capabilities in assessing the impact of some water quality constituents on crops, soils and irrigation infrastructure. Secondly, its use is expected to make site-specific evaluations less arduous, as it is a user-friendly electronic system, further enhanced by colour-coded outputs (Du Plessis et al. 2017; Annandale et al. 2018).

As a first step towards the development of site-specific guidelines, there is a need to identify the most important 'specifics' that are paramount to determining the suitability of waters for irrigation. The selection of such essential ‘specifics’ requires the realisation of the fact that the determination of the FFU of irrigation water is a multi-faceted problem, dependent on the identified receptor protection targets and the presence of risk mitigating factors. Protection targets include crops, the health of animals and humans consuming the produce, irrigation infrastructure and the soil resource; while mitigating factors include factors such as the capacity of soils to sequester potentially toxic elements as well as crop selection.

If too many site-specifics are essential to conduct a FFU analysis, the DSS may increasingly become too complex to be of any use. A rational solution will require a good balance between the simplicity of the selected factors and the robustness of the designed system. A number of factors may undeniably be important but ideally, not all will be essential.

6.3 LITERATURE REVIEW

As mentioned, the quality of irrigation water with regards to trace elements has traditionally been assessed by following a generic and conservative approach, with the main aim of limiting excessive accumulation of trace elements in soils. Site-specific factors that may influence the suitability of water, like crop choice (based on food safety considerations and plant tolerance), soil factors and irrigation management are often not considered. Hence, a discussion of such factors that indicate the need for a site-specific approach in the assessment of trace elements in irrigation waters, forms an important part of this study.

6.3.1 The abundance of trace elements in soils and their associated risks

The abundance of trace elements is of major interest mainly in the fields of soil science, environmental science, and other geological sciences. Studies have shown that some Potentially Toxic Elements (PTEs), such as Pb, Cd, Hg, and As, can have detrimental effects if they find their way into the food chain (Rafique, et al., 2022). In many cases, the first point of entry into the food chain is plant absorption, followed by the subsequent transfer to animals and humans. However, it should be pointed out that the total abundance of trace elements in soils is not normally proportional to the risk that they pose to ecosystems. In fact, the most abundant metals in soils (Al and Fe) are perhaps in the group of the least concerning elements (Underwood, 2012). Real threats posed by trace elements in soils depends on their nature and bioavailability (Harmsen, 2007, Kim, et al., 2015, Merrington, et al., 2016). The total abundance of all the trace elements assessed by IrrigWQ is given in Table 6-1 (Sposito, 2008, McLean, 1992). In addition, the international recommended soil threshold values used by the DSS are also presented. The discrepancy between natural soil abundance and soil loading limits for Al, Fe and Mn are clear. This served as a motivation for this study.

In reviewing the risks posed by each of the 20 trace elements assessed by the DSS, a wide number of articles, research papers and previous guidelines were reviewed to identify the contemporary perspectives of the major risks posed by trace elements in irrigation water. The findings are summarised in Table 6-2. These issues may need to be considered in irrigation FFU assessment of water containing these trace elements.

Table 6-1: The range and mean background concentrations of trace elements in natural soils (total concentrations)[1].

Trace element	Range (mg/kg)	Mean (mg/kg)	Soil loading limits (IrrigWQ)
Al	10 000 – 300 000	71 000	2500
As	1 - 50	5	50
Be	< 1 - 15	0.6	50
B	< 20 - 30	< 20	250
Cd	0.01 – 0.7	0.06	5
Cr	1 - 1000	100	50
Co	< 3 – 70	7	25
Cu	2 - 100	30	100
F	<10 – 3700	635	1000
Fe	7 000 – 550 000	38 000	2500
Pb	2 - 200	10	100
Li	< 5 - 140	< 20	1250
Mn	20 - 3000	600	100
Hg	0.01 – 0.3	0.03	1
Mo	< 3 - 15	0.6	5
Ni	5 - 500	40	100
Se	0.1 - 2	0.3	10
U	-	2.3	5
V	<7 - 500	58	50
Zn	10 - 300	50	500

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[1] Data for Al, Fe, Mn, Cu, Cr, Cd, Zn, As, Se, Ni, Pb and Hg is obtained from McLean (1992) Data for the other elements is taken from Sposito (2008)

Table 6-2: A summary of the key issues influencing contemporary perspectives in the assessment of irrigation water quality with regard to trace element composition

Trace element	Key Issues (Foliar absorption risks not included)	References
Al	Precipitation induces fixation of P and acid generating potential, soil accumulation not a concern in non-acidic soils.	(Gupta, et al., 2013, ANZECC, 2000)
As	Phytotoxicity and phyto-accumulation risk (leading to zoo-toxicity) stemming directly from irrigation water before As can be immobilised. Soil accumulation also a big concern. High risk in sandy soils.	(Hughes, et al., 2011, ANZECC, 2000)
Be	Soil build-up of concern, but not much is known about Be risks in the soil-plant system.	(Shah, et al., 2016, WHO, 2006)
B	Phytotoxic and sensitivity varies widely with plant species. See ANZECC reference for list of plant species and their tolerance levels.	(ANZECC, 2000, Brdar-Jokanović, 2020, WHO, 2006)
Cd	Both phyto and zootoxic. Plants may take up Cd beyond food and feed safety limits. High risk in acidic, saline soils. Interaction with Cl may be significant.	(Suhani, et al., 2021, WHO, 2006, ANZECC, 2000)
Cr (VI)	Soil build-up and phytotoxicity concerns, minimal zootoxic risk as translocation to above ground biomass not expected (Caution with root crops e.g., carrot). Reduction to immobile Cr(III) is possible.	(Ao, et al., 2022, ANZECC, 2000)
Cr (III)	Immobile in soils such that plants are unable to absorb it. Oxidation to the mobile Cr(VI) highly unlikely under agricultural soil conditions, but Mn oxides may play a central role.	(ANZECC, 2000, Ao, et al., 2022)
Co	Phyto and zootoxic concerns directly from irrigation water before it can be immobilised by the soil.	(Banerjee and Bhattacharya, 2021)
Cu	Direct irrigation effects followed by long term soil build-up.	(Rooney, et al., 2006, ANZECC, 2000)
F	Contamination of stock water through irrigation water. Minimal soil build-up risk. Direct phytotoxic risks minimal.	(ANZECC, 2000, Chatterjee, et al., 2020)

Trace element	Key Issues (Foliar absorption risks not included)	References
Fe	Clogging of drippers, unsightly precipitates on fresh produce, induces soil P fixing, acid generating potential. Negligible phyto and zoo toxicity risk. Soil accumulation not expected to be of concern.	(Drakatos, et al., 2002, Almeida, et al., 2022)
Pb	Direct phytotoxic effects of irrigation water as well as soil accumulation.	(Bui, et al., 2016, Hong, et al., 2008)
Li	Direct phytotoxic effects on crops before immobilization, soil build-up risk high in acidic, saline soils.	(Shakoor, et al., 2023)
Mn	Direct phytotoxic risks before immobilization. Soil accumulation risks are controversial and highly dependent on soil environmental factors.	(Millaleo, et al., 2010, ANZECC, 2000)
Hg	Food safety risks, mainly vegetable phyto-accumulation. Strongly retained in organic matter rich soils.	(Shahid, et al., 2020, ANZECC, 2000)
Mo	Both phyto and zoo-toxic concerns, but mainly fodder safety risks. Many plants may accumulate Mo to pose zoo-toxic risks before it becomes phytotoxic.	(ANZECC, 2000, Tallkvist and Oskarsson, 2015)
Ni	Direct and soil build-up concerns. High phytotoxic concerns at pH < 6 in sandy soils.	(Bogusz and Oleszczuk, 2018, ANZECC, 2000)
Se	Considerably large amounts can phyto-accumulate to zoo-toxic levels before phytotoxicity can be observed.	(Dhillon and Dhillon, 2015)
U	Can be both phytotoxic and may phyto-accumulate to zoo-toxic levels. Soil build-up concerns. Accumulates in roots.	(Chen, et al., 2021a, Cui, et al., 2023)
V	Soil build-up concerns as high V in soils may pose food safety risks.	(Chen, et al., 2021b, WHO, 2006)
Zn	Largely deficient in many soils but can also be phytotoxic at high soil concentrations. Highly available when pH < 6.	(Kachenko and Singh, 2006, Liščáková, et al., 2022)

6.3.2 The basis for focusing on Al, Fe and Mn

In South Africa, research into the use of mine-affected waters for irrigation has been conducted for four decades and remains an active pursuit (Annandale, et al., 2018, Grewar, 2019, Heuer, et al., 2021, Mabuza, et al., 2023, Madiseng, 2018, Sukati, 2020, van der Laan, et al., 2014, du Preez, 2022, Du Plessis, 1983, Jovanovic, et al., 1998). Depending on the pH of the mine waters, Al, Fe and Mn levels have been of concern (Annandale, et al., 2018). Although the conservative approach that was employed in the derivation of existing guidelines for most trace elements is thought to be protective in most situations and for many crops, Pratt and Suarez (1990) argued against establishing restrictions for Al and Fe in irrigation water. They refrained from stipulating any limits due to their natural abundance and behaviour in soils. In support of this argument, experience gained through irrigating with coalfield mine-affected waters has suggested that the limits set for Al, Fe and Mn may be unduly restrictive (Annandale, et al., 2018). It has been established that their availability in soils depends heavily on soil conditions such as pH and redox potential (Van Groeningen, 2020, Pratt and Suarez, 1990, Gupta, et al., 2013, Zhang, et al., 2020).

Thus, it is thought that irrigating crops with effluents rich in these trace elements may neither have major negative effects on the soil, nor result in unacceptable yield penalties as the elements tend to precipitate as insoluble secondary minerals (e.g. oxides and hydroxides) under soil conditions that are ideal for crop production (well drained and circumneutral soils) (Pratt and Suarez, 1990, Annandale, et al., 2018). Nevertheless, the overall 'Fitness for Use' (FFU) of waters rich in Al and Fe (and Mn) will further depend on a number of additional site and context-specific factors. Such factors include the effects on, inter alia, yield quality (if overhead irrigation is used, unsightly Fe/Mn precipitates may deposit on horticultural produce) and potential blockages of micro-irrigation equipment (ANZECC, 2000). Such factors may be evaluated on a case-by-case basis.

6.3.3 The need for a refined site-specific approach in the assessment of Al, Fe and Mn

The most important fundamental control of trace element phytotoxicity in soils is plant 'availability' (Kim, et al., 2015, Merrington, et al., 2016). The available fractions are a result of a balance governed by mass transfer, sorption and solubility in soils (Nordstrom and Ball, 1986, Hass, et al., 2011, Kim, et al., 2015). It is now established that the dynamics of soluble and insoluble forms of Al, Fe and Mn are mainly dependent on soil conditions (Hass, et al., 2011). According to Watzlaf, et al. (2004) Al, solubility is pH controlled. It is very low at pH > 5.3 and will be infinitesimal as the pH approaches neutral values, while becoming considerably soluble again at pH > 8 (Dube, et al., 2022, Watzlaf, et al., 2004). Hence, proper management of soil pH at circum-neutral levels by applying lime if soils tend to be acidic, will be expected to eliminate Al toxicity problems (Moir and Moot, 2014). In soils with pH > 8, the soil may be acidified with either irrigation water, fertilisers or other amendments to lower the pH.

Similarly, the solubility of Fe in soils is controlled by the availability of oxygen and the pH (Audebert and Sahrawat, 2000, Becker and Asch, 2005). At circum-neutral pH, ferrous iron oxidises rapidly to ferric iron when oxygen levels are not limiting (Watzlaf, et al., 2004). According to Watzlaf, et al. (2004), the kinetics of oxidation at neutral to slightly alkaline conditions (pH levels > 8) are so rapid that it is measured in seconds. The rates slow down a hundredfold for every unit decrease in pH and rates become considerably slow at pH levels < 5, with rates measured in days. In irrigated fields, this is still thought to be sufficiently quick. When oxidized, the solubility of the ferric hydroxide solid is very low and little dissolved ferric iron (< 1 mg/ℓ) is predicted to exist at pH > 4. The highest concentrations of dissolved ferric iron can occur when the pH is less than 3. Hence it appears to be clear that proper management of drainage and aeration in circum-neutral soils will eliminate Fe phytotoxicity problems and phyto-accumulation, as the soluble ferrous iron will rapidly be converted to ferric iron, which precipitates as ferric oxides.

Soluble Mn is notorious for high mobility, and the persistence of soluble forms has been a problem highlighted in many environmental systems when compared to Al and Fe (Johnson and Younger, 2005, Tobiason, et al., 2016). The removal of manganese from the soluble phase is affected by redox potential and pH, but is further considerably dependent on other factors (Sparrow and Uren, 2014, Tebo, et al., 2004). In soils, the propensity and kinetics of Mn oxidation and its immobilization can vary depending on clay mineralogy, the presence of Mn/Fe oxides and the activity of Manganese Oxidizing Bacteria (MOBs) (Sparrow and Uren, 2014, Tebo, et al., 2004). Even though manganese is reported to have more than three oxidation states, Mn (II) is the most stable aqueous oxidation state, while Mn (III) and (IV) compounds are the most common immobile Mn-oxide solids (WHO, 2021).

Microbial activities in the presence of metabolizable organic matter in oxygen deficient environments may reduce Mn-oxides, resulting in the release of soluble Mn (Sparrow and Uren, 2014, Zhang, et al., 2020). The presence of clay minerals and Fe-oxides is expected to mitigate the release of soluble Mn into the soil solution. This is mediated by the adsorption of soluble Mn on these stable minerals and by subsequent surface-catalysed oxidation (Van Groeningen, 2020).

Therefore, it is clear that the chemistry and behaviour of Mn in soils is far more complicated than that of Al and Fe. With the high predictability of the behaviour of Al and Fe in soils, particularly their low availability in circumneutral soils when crops are irrigated following irrigation best practices that maintain a suitable redox potential, a fundamental question that forms the main focus of this project arises: Are soil loading limits for Al and Fe essential in irrigation water quality guidelines? Detailed work, specifically focusing on the biogeochemical behaviour of Mn in different soils to aid in the development of site-specific assessment criteria to be followed by IrrigWQ for Mn, was found to be required. The experimental work reported on here, aimed to contribute to the development of site-specific guidelines for the assessment of Al, Fe and to a certain extent, Mn, in irrigation waters.

6.4 EXPERIMENTAL APPROACH/METHODOLOGY

It was hypothesised that heavily loading soils with Al, Fe and Mn will not result in unacceptably high plant availability under ideal conditions for crop production. Therefore, this study investigated the bioavailability of Al, Mn and Fe by equilibrating soil with several metal loading rates (without compensating for background values) and subjecting them to various lime-oxidation regimes. The first step was to consider the accumulation thresholds set for these elements summarised in Table 6-3 (extracted from Table 6-1).

Table 6-3: Soil accumulation thresholds of Al, Fe and Mn used by IrrigWQ

Trace element	Soil accumulation threshold (mg/kg)
Al	2500
Fe	2500
Mn	100

By loading a sorbent with various metal loading rates (or any solute) and subjecting it to various treatments in batch mode, valuable information about its sorption characteristics can be obtained. Irrigating with poor-quality water relies on the chemical reactivity of the soil and its capacity to attenuate potentially toxic constituents from solution to solid phase. A given irrigated soil, under normal soil conditions for crop production, must have the capacity to immobilise potentially toxic elements to prevent onset of phyto or zoo-toxicity. In this study, potentially toxic elements refer to Al, Fe and Mn which are associated with mine waters.

A soil obtained from the University of Pretoria's experimental farm was used in this study. A basic soil characterisation was conducted, including textural distribution, soil pH, and colour. Understanding a soil's sorption characteristics provides useful information in determining if crop productivity may be hampered by irrigating with metalliferous waters. A batch sorption experiment whereby Al, Fe and Mn were applied in ternary systems to the soil (all three elements added together) was conducted in a constant temperature room (25°C) at the soil science laboratory of the University of Pretoria to better understand sorption characteristics and possibly extrapolate the results to other scenarios.

6.4.1 Metal loading rates

Six metal loading rates were applied to the soil as fractions of guideline thresholds in a geometric sequence of scale factor two from 156.25 to 5000 mg/kg for Fe and Al while it was 6.25 to 200 mg/kg for Mn (Table 6-4). In other words, beginning from the lowest to the highest, each successive load was double the previous load. As it can be noted from Table 6-4, the highest loads for each element were double their guideline thresholds. This is important because it is often recommended to overlap concentration ranges used in sorption experiments with those of concern (McLean and Bledsoe, 1992). Metal loading rates were applied in ternary systems to better mimic real-world scenarios whereby Al, Fe and Mn often exist together in mine effluents.

Metal loading rates were given a code number. For example, loading rates referred to as ½, 1 or 2 represent metal loading rates of half the guideline threshold, the guideline threshold load, and double the guideline threshold, respectively.

Table 6-4: Summary of metal loading rates applied to the soil as a fraction of each metal's guideline threshold together with the target soil loads in mg/kg

Load as fraction of guideline threshold	Target soil load for Fe (mg/kg)	Target soil load for Al (mg/kg)	Target soil load for Mn (mg/kg)
$\frac{1}{16}$	156.25	156.25	6.25
$\frac{1}{8}$	312.5	312.5	12.5
$\frac{1}{4}$	625	625	25
$\frac{1}{2}$	1250	1250	50
1	2500	2500	100
2	5000	5000	200

6.4.2 Lime-oxidation regimes

Since soil pH and redox potential and/or dissolved oxygen levels of a system are probably the most important parameters influencing the bioavailability of trace elements in soils, it is important to consider their role in sorption experiments. It was expected that soil pH will drop as a function of metal load. Oxidation/ hydrolysis reactions of Al, Fe and Mn ions generate acidity by increasing solution concentrations of H^+ (Watzlaf, et al., 2004). It was expected that high metal loading rates will generate more acidity than lower loads. This acidity generated is bound to influence adsorption and precipitation reactions of these solutes. The solubility of redox-active elements is further impacted by the redox potential of a system or, more importantly, the availability of dissolved oxygen. Redox-active elements, Fe and Mn, are more soluble when they exist as divalent ions, Fe(II) and Mn(II), than in their higher valence states, Fe (III) and Mn(III/IV). This is due to a tendency exhibited by these higher valence states to hydrolyse and precipitate as insoluble oxides (Borda and Sparks, 2008). Redox potential is not expected to have a direct influence on Al solubility and sorption (Watzlaf, et al., 2004).

It was necessary to investigate the availability of these elements under different lime-oxidation regimes. Application of variable liming rates depending on metal load was therefore essential to neutralise any acidity generated to maintain an ideal pH range across several metal loading rates. Since a soil: solution ratio of 180 g: 300 mℓ was used, this indicates that soil samples were inundated with water. Submergence of the soil, coupled with sudden loading of the soils with huge quantities of reduced Fe and Mn, was predicted to lower the redox potential of the soil and increase its chemical oxygen demand. Inundating the soil with water, however, ensures that soil chemical reactions occur continuously, as most chemical reactions occur in the solution phase. Aeration was essential to maintain dissolved oxygen at levels that can be expected for well-drained soil profiles. Hence, for all the soil samples, each was subjected to four lime-oxidation regimes on top of receiving variable metal loading rates (Table 6-4). The lime-oxidation regimes were limed and oxidized, limed (only), oxidized (only) and Control (not limed and not oxidized). Lime was, therefore, only applied to these two regimes: “limed + oxidized” and “limed (only)”. Forced aeration using an air pump was applied to the regimes: “limed + oxidized” and “oxidized (only)”.

6.4.3 Chemicals

Fe(II), Mn(II) and Al(III) sulphate salts were selected as the source of metals as sulphates are the dominant anions in most mine waters. The following highly soluble metal sulphates were used; manganese (II) sulphate monohydrate ($MnSO_4 \cdot H_2O$), Aluminium sulphate octa-deca-hydrate ($Al_2(SO_4)_3 \cdot 18H_2O$) and iron (II) sulphate hepta-hydrate ($FeSO_4 \cdot 7H_2O$). Analytical grade calcium carbonate ($CaCO_3$) was used as the liming material for acid neutralisation in the incubation experiments. All other chemicals used for analytical purposes were as listed in standard analytical procedures and are described in this report. All chemicals were obtained from the soil science laboratory at the University of Pretoria.

6.4.4 Experimental layout

The experimental design, which was a combination of metal loading rates as fractions of guideline thresholds as well as lime-oxidation regimes, is shown in Table 6-5. To ensure reproducibility of results and to carry out statistical tests of significance, the whole experimental design was replicated three times.

Table 6-5: Experimental layout depicting six soil metal loading rates, subjected to four lime-oxidation regimes.

Load as fraction of guideline threshold	Limed + oxidized	Limed	Oxidized	Control
$\frac{1}{16}$	☑	☑	☑	☑
$\frac{1}{8}$	☑	☑	☑	☑
$\frac{1}{4}$	☑	☑	☑	☑
$\frac{1}{2}$	☑	☑	☑	☑
1	☑	☑	☑	☑
2	☑	☑	☑	☑

6.4.5 Determination of solution concentrations

The total number of samples per loading rate can be obtained by multiplying the four lime-oxidation regimes by the three replicates, a total of 12 samples per loading rate. By considering that a soil:solution ratio of 180 g:300 mℓ was used, it can be noted that six bulk solutions of 3.6 ℓ (each with appropriate solution concentrations of metals) per load were required for distribution amongst the 12 samples per metal loading rate. Each target soil load, as well as the concentration of each element in the solution applied, are given in Table 6-6.

Table 6-6: Metal loading rates and the applied solution concentrations as fractions of each metal's guideline threshold.[1]

Load as fraction of guideline threshold	Fe		Al		Mn	
	Target soil load (mg/kg)	Applied solution concentration (mg/ℓ)	Target soil load (mg/kg)	Applied solution concentration (mg/ℓ)	Target soil load (mg/kg)	Applied solution concentration (mg/ℓ)
$\frac{1}{16}$	156.25	93.75	156.25	93.75	6.25	3.75
$\frac{1}{8}$	312.5	187.5	312.5	187.5	12.5	7.5
$\frac{1}{4}$	625	375	625	375	25	15
$\frac{1}{2}$	1250	750	1250	750	50	30
1	2500	1500	2500	1500	100	60
2	5000	3000	5000	3000	200	120

[1] Soil:solution ratio =180 g:300 mℓ

A stock solution of 3.6 ℓ, with the following concentrations of the three metals, was made: 240 mg/ℓ of Mn (II), 6000 mg/ℓ of Al (III) and 6000 mg/ℓ of Fe (II) (note the 25-fold difference between Mn and the other two elements). The formula in equation (eq) 1 below was used to calculate the mass of each salt that was required to make the stock solution;

$$\text{Salt mass} = \text{metal stock conc. } \left(\frac{\text{mg}}{\ell}\right) \times \text{stock vol. } (\text{l}) \times \left[\frac{\text{salt molar mass}}{\text{n}\times\text{metal atomic mass}}\right] \quad \text{(eq 1)}$$

The letter 'n' represents number of moles of each metal in the molecular formula of the salt. An example for Mn (II) is given below;

$$\text{Salt mass (mg)} = \text{metal stock conc. } \left(\frac{\text{mg}}{\ell}\right) \times \text{stock vol. } (\ell) \times \left[\frac{\text{salt molar mass}}{\text{n}\times\text{metal atomic mass}}\right]$$

$$\text{Salt mass (mg)} = 240 \left(\frac{\text{mg}}{\ell}\right) \times 3.6\ (\ell) \times \left[\frac{169.02}{1\times54.94}\right]$$

$$\text{Salt mass} = 2\ 658 \text{ mg}$$

Where 'vol.' represents volume and 'conc.' represents concentration.

After adding these salts to a 4 ℓ 'Schott Duran' laboratory container, distilled water was used to make up the volume of the stock solution to 3.6 ℓ. A stirring rod was used to mix the solution thoroughly. Table 6-7 shows the mass of each salt required to make the stock solution.

Table 6-7: Mass of each salt added to make the desired stock solution of 3.6 ℓ volume and the concentration of each metal in the stock solution

Name of salt	Iron sulphate hepta-hydrate	Manganese sulphate monohydrate	Aluminium sulphate octa-deca-hydrate
Mass of salt (mg)	107 530	2 658	266 765
Metal concentration (mg/ℓ)	6000	240	6000

6.4.6 Preparation of bulk sample solutions

Solutions applied to the soil were prepared by making use of the stock solution. To prepare bulk solutions of the desired concentration of the three elements, specific volumes of the stock solution were transferred to clearly labelled 4 ℓ 'Schott Duran' laboratory containers. After which, the solutions were made up to 3.6 ℓ using deionized water. Volumes of the stock solution required to make desired solution concentrations can be determined by using a simple dilution formula (eq 2):

$C_1 \times V_1 = C_2 \times V_2$ (eq 2)

This can be manipulated to give the formula:

$$\text{Required stock vol.} = \frac{\text{target [solution]} \times \text{solution vol.}}{\text{[Stock]}}$$

Since a combined stock solution was made which took into account the 25-fold difference of Mn loads to Al and Fe loads, a calculation for only one element is necessary. An example is given using aluminium at the double guideline threshold load.

$$\text{Required stock vol.} = \frac{3000\frac{\text{mg}}{\ell} \times 3.6\ \text{l}}{6000\frac{\text{mg}}{\ell}} = 1.8\ \text{l}$$

Where ‘vol.’ represents volume.

Stock solution volumes required for other lower successive loads were obtained by halving the preceding stock solution volume, as metal loading rates were applied as fractions of guideline thresholds in a geometric sequence with a scale factor of two. Table 6-8 is a summary of the sample solution concentrations.

Table 6-8: A summary of each trace element solution concentration, the volume of the stock solution that was required to make it and the final volume after adding deionized water across metal loading rates.

Metal load as fraction of guideline threshold	Vol. stock required (ℓ)	Final bulk vol. (ℓ)	[Al] in Sample solution (mg/ℓ)	[Fe] in Sample solution (mg/ℓ)	[Mn] in sample solution (mg/ℓ)
$\frac{1}{16}$	0.05625	3.6	93.75	93.75	3.75
$\frac{1}{8}$	0.1125	3.6	187.5	187.5	7.5
$\frac{1}{4}$	0.225	3.6	375	375	15
$\frac{1}{2}$	0.45	3.6	750	750	30
1	0.9	3.6	1500	1500	60
2	1.8	3.6	3000	3000	120

6.4.7 Determination of lime requirements

Determination of lime requirements to maintain a particular pH range can be a daunting task in sorption experiments. Soil pH is driven and controlled by several parameters and mechanisms. In order to achieve the aim of maintaining an ideal pH range, lime requirements for this incubation trial were determined after considering the theoretical acid generating potential of the metal ions through their oxidation/hydrolytic reactions, in combination with preliminary acid neutralization experiments.

According to Watzlaf et al. (2004), Al, Fe and Mn are considered acidic because they generate acidity. Hydrogen proton acidity is generated via oxidation and hydrolysis reactions that these metals undergo. The stoichiometric equations (eq 3), (eq 4) and (eq 5) for these reactions as reported by Watzlaf, et al. (2004) are:

$Fe^{2+} + 0.25O_2 + 1.5H_2O \rightarrow FeOOH + 2H^+$ (eq 3)

$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$ (eq 4)

$Mn^{2+} + 0.25O_2 + 1.5H_2O \rightarrow MnOOH + 2H^+$ (eq 5)

These reactions can be used to estimate the total proton acidity of a water sample that contains these three metal ions as constituents. By making use of equations (eq 3), (eq 4) and (eq 5), it is possible to calculate the acidity that can potentially be generated by each of these metal ions in each of the bulk solutions. This is done by first converting mass concentrations (mg/ℓ) of each loaded metal to molar concentrations (mol/ℓ). The molar concentrations of H^+ can then be obtained by multiplying those of each metal by the stoichiometric ratio derived from the equations (eq 3), (eq 4) and (eq 5). For every mole of Al, three moles of acidity are generated, and for every mole of each of Fe and Mn, two moles of acidity are generated (see equations (eq 3), (eq 4) and (eq 5). A detailed summary of these molar concentrations of acidity that may be generated by each metal is given in Table 6-9.

Table 6-9: Summary of molar concentrations of acidity that may be generated by each metal across all loading rates

Load	**[Al] mg/ℓ**	**[Al] mol/ℓ**	**Generated $[H^+]$ mol/ℓ**	**[Fe] mg/ℓ**	**[Fe] mol/ℓ**	**Generated $[H^+]$ mol/ℓ**	**[Mn] mg/ℓ**	**[Mn] mol/ℓ**	**Generated $[H^+]$ mol/ℓ**
$\mathbf{\frac{1}{16}}$	93.75	0.003475	0.010424	93.75	0.001679	0.003357	3.75	6.82 x 10^{-5}	0.000137
$\mathbf{\frac{1}{8}}$	187.5	0.00695	0.020849	187.5	0.003357	0.006714	7.5	0.000136513	0.000273
$\mathbf{\frac{1}{4}}$	375	0.013899	0.041698	375	0.006714	0.013429	15	0.000273025	0.000546
$\mathbf{\frac{1}{2}}$	750	0.027798	0.083395	750	0.013429	0.026858	30	0.00054605	0.001092
1	1500	0.055597	0.16679	1500	0.026858	0.053715	60	0.0010921	0.002184
2	3000	0.111193	0.33358	3000	0.053715	0.107431	120	0.002184201	0.004368

Acidity generated per load is the sum of acidity that can be generated by each of the elements (Table 6-9). Generally, according to various literature sources (Taylor, et al., 2005, Ward, et al., 2002), the following reaction (eq 6) occurs with the neutralisation of acidity by calcium carbonate;

$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2 + H_2O$ (eq 6)

It can be noted from the equation that one mole of $CaCO_3$ can theoretically neutralize two moles of hydrogen protons (H^+). Hence, $CaCO_3$ equivalents to neutralize acidity can be calculated by dividing acidity molar concentrations by two. Table 6-10 gives the summary of total potential acidity per load based on oxidation and/or hydrolysis reactions and $CaCO_3$ equivalents as molar and mass concentrations. The mass concentrations of $CaCO_3$ equivalents can be obtained by multiplying its molar concentrations by the molar mass of $CaCO_3$.

Table 6-10: Total acidity that can be generated through oxidation and/or hydrolysis reactions of Al, Fe and Mn per loading rate and the calculated calcium carbonate ($CaCO_3$) equivalents.

Load	Total acidity [H] (mol/ℓ)	$CaCO_3$ equivalent mol (mol/ℓ)	$CaCO_3$ equivalent (g/ℓ)
$\frac{1}{16}$	0.013919	0.006959	0.695938
$\frac{1}{8}$	0.027838	0.013919	1.391875
$\frac{1}{4}$	0.055675	0.027838	2.78375
$\frac{1}{2}$	0.11135	0.055675	5.5675
1	0.2227	0.11135	11.135
2	0.4454	0.2227	22.27

By taking into consideration that only two of the four lime-oxidation regimes required liming (the “limed + oxidized” and the “limed (only)” regimes) and that the experiment had three replications, it can be noted that six samples per load were limed using the appropriate lime quantity for that load. Further, considering the soil-to-solution ratio, the total mass of sorbent for the six samples of each load is 1080 g (depending on the regime, sorbent refers to the soil or soil and calcium carbonate mixture). The mass of the sorbent was targeted to be 180 g for each sample, instead of adding lime on top of 180 g soil which would result in limed samples having a greater sorbent mass. This implies that the mass of each sorbent was the sum of the lime requirement ($CaCO_3$) and that of the “top-up” soil required to make 180 g sorbent mass per sample.

Note that the use of volumetric units such as g/ℓ for $CaCO_3$ requirements is for calculation purposes only. In simple terms, the determined $CaCO_3$ requirements were mixed with soil before applying metalliferous solutions.

To enable better accuracy in terms of making the correct soil and limestone mixtures, bulk soil mixtures (total sorbent mass of limed samples per loading rate) were prepared. Bulk $CaCO_3$ requirements of the limed samples (“limed + oxidized and “limed” only) per loading rate were calculated by multiplying

$CaCO_3$ equivalents to neutralise acidity (g/ℓ) by the bulk volume of the solutions (ℓ). Table 6-11 is a summary of these calculations.

Table 6-11: Summary of predicted lime requirements on a mass basis based on potential acidity generation through oxidation/hydrolysis reactions across all metal loads

Load	$CaCO_3$ Equiv. (g/ℓ)	Vol. bulk solution (ℓ)	$CaCO_3$ requirement (g)	Target sorbent mass (g)	Mass of top-up soil (g)
$\frac{1}{16}$	0.6959375	1.8	1.253	1080	1078.75
$\frac{1}{8}$	1.391875	1.8	2.505	1080	1077.50
$\frac{1}{4}$	2.78375	1.8	5.010	1080	1074.99
$\frac{1}{2}$	5.5675	1.8	10.022	1080	1069.98
1	11.135	1.8	20.043	1080	1059.96
2	22.27	1.8	40.086	1080	1039.91

6.4.8 Oxidation of samples

As indicated before, some samples were subjected to the regimes; “limed + oxidized” and “oxidized only”. Samples were oxidized with a compressor. Dissolved oxygen measurements using a dissolved oxygen probe guided the frequency and intensity of aeration. Daily aeration for a minimum of one and a half minutes up to two minutes was able to saturate the soil solutions across all loads. This was ascertained in preliminary trials to investigate the required intensity of aeration. The preliminary oxidation trials showed that samples did not go below 30 - 40% oxygen saturation, which is at the boundary between hypoxic and oxic conditions. The longer duration was mainly required for samples with a high load of metal ions. It was expected that chemical oxygen demand may decrease over time due to the precipitation of ions as oxides. However, after establishing the intensity of aeration in terms of duration, the longer duration was applied to all the oxidized samples over the course of the experiment. Dissolved oxygen measurements were not taken over time because the dissolved oxygen probe that was available had a very long response time. It was, therefore, not possible to measure dissolved oxygen frequently.

The redox potential of the oxidized systems was monitored over the course of the experiment, and data was recorded. Samples that were not oxidized were not opened, hence, measurements were not taken, to avoid unintended oxidation. Redox measurements were done to observe time-dependent changes in the oxidation-reduction potential of the various systems. An HM Digital ORP200 meter was used in this experiment to measure redox potential. After 30 minutes of daily agitation (a standard procedure for soil sorption experiments that allows for a good mix of the metals and the soil for sufficient sorbate-sorbent interaction), the redox probe was inserted until completely covered by the solution of the system. After the system stabilised, the potential difference reading was transformed into a standardised redox potential value. Redox measurements were recorded on five occasions, after 2, 3, 5, 14 and 21 days, to allow for a good balance between the practical feasibility of taking such measurements and a good spread of data over the experimental period. The measurements were taken before aeration to show changes in the redox potential of the system without being confounded by high dissolved oxygen levels following periods of forced aeration.

6.4.9 pH measurements

Soil pH (H_2O) of the natural, untreated soil was determined before the experiment. It was found that the average pH (H_2O) (averaged using the antilog approach – not arithmetic mean) of three replicates was 6.5. This value falls within ranges cited as ideal for crop production. The aim of liming samples was to neutralise any acidity and maintain the pH of the natural soil.

Measurement of the pH of all the systems was done at the end of the experiment to assess if it was possible to neutralise the acid generation from metals in solution and to maintain the ideal pH range across all loads and lime-oxidation regimes.

6.4.10 Electrical conductivity measurements

In soil science, electrical conductivity (EC) measures the soil's ability to conduct electricity. It is used by soil scientists in soil salinity assessments. EC can be used as an indication of the extent of dissolved ions in the soil solution. The higher the EC, the more the dissolved ions. EC was monitored over the course of the experiment for both oxidized and limed and oxidized samples (other samples were kept closed for the duration of the experiment). Data was collected after the following number of days: 0, 1, 2, 3, 10, 15 and 21, with the intention of observing time-dependent changes of EC.

6.4.11 Solution metal content analysis and the determination of sorption parameters

After carrying out incubation experiments, supernatant solutions were analysed for Al, Fe and Mn using ICP-AES with the help of a laboratory assistant in the Soil Science Laboratory of the University of Pretoria. Supernatants (10 mℓ samples) were transferred to centrifuge tubes to separate the solution phase from soil colloids. This achieved very clear solutions which did not require filtration.

From the ICP analysis, several soil sorption parameters for each element were determined for the different lime-oxidation regimes, including comparing metal sorption efficiencies and assessing plant availability.

The concentration of sorbed metals, q_e (mg/kg), was calculated using the expression (eq 7), which is modified to account for evaporative water loss (Robinson-Lora and Brennan, 2010, Travis and Etnier, 1981):

$$qe = \frac{(C_o{}^* V_1 - C_e{}^* V_2\ )}{m} \qquad \text{(eq 7)}$$

Where C_o is the initial solute concentration in solution (mg/ℓ), C_e is the final solute concentration in solution (mg/ℓ), and V_1 and V_2 are the volumes of the system solutions (mℓ) at the beginning and end of the experiment respectively. The mass of the sorbent used is m (kg). V_2 was determined by weighing samples after the experiment. The decrease in mass from initial mass to final mass was taken as water lost through evaporation during the incubation period.

Sorption efficiency (SE) % was calculated using the modified expression of Elzinga and Sparks (1999), Robinson-Lora and Brennan (2010), Roy (1992) (eq 8) to account for evaporative water loss:

$$SE\ \% = \frac{(C_o{}^* V_1 - C_e{}^* V_2\ ){}^* 100}{C_o{}^* V_1} \qquad \text{(eq 8)}$$

6.5 RESULTS AND DISCUSSION

6.5.1 Characterisation of the untreated soil

The results of soil texture analyses adapted from Bouyoucos (1962) and dry soil colour determined through the Munsell soil colour chart, as well as the measurement of soil pH$_{(water)}$, provided this general characterisation of the soil (Table 6-12).

Table 6-12: General characterisation of the soil: Soil texture, soil colour and soil pH

	Soil texture			**Dry Soil colour**	**Soil pH**
Distribution	Sand	Silt	Clay	Red soil with Munsell soil colour code: 10 R 4/8	6.5
	60 %	10 %	30 %		
Classification	Sandy clay loam				

6.5.2 Soil pH across all loads and lime-oxidation regimes after the incubation period

Soil pH measurements suggest that the liming method was effective in maintaining the pH of the limed systems between roughly 6 -7 (Figure 6-1). The acid-generating potential of the metal ions is evident in the samples that were not limed. System pH decreased as a function of metal loading, in accordance with expectations. The decrease was down to pH levels of around 3.2. The effect of pH on metal ion sorption is, therefore, expected to be dramatic when regimes are compared.

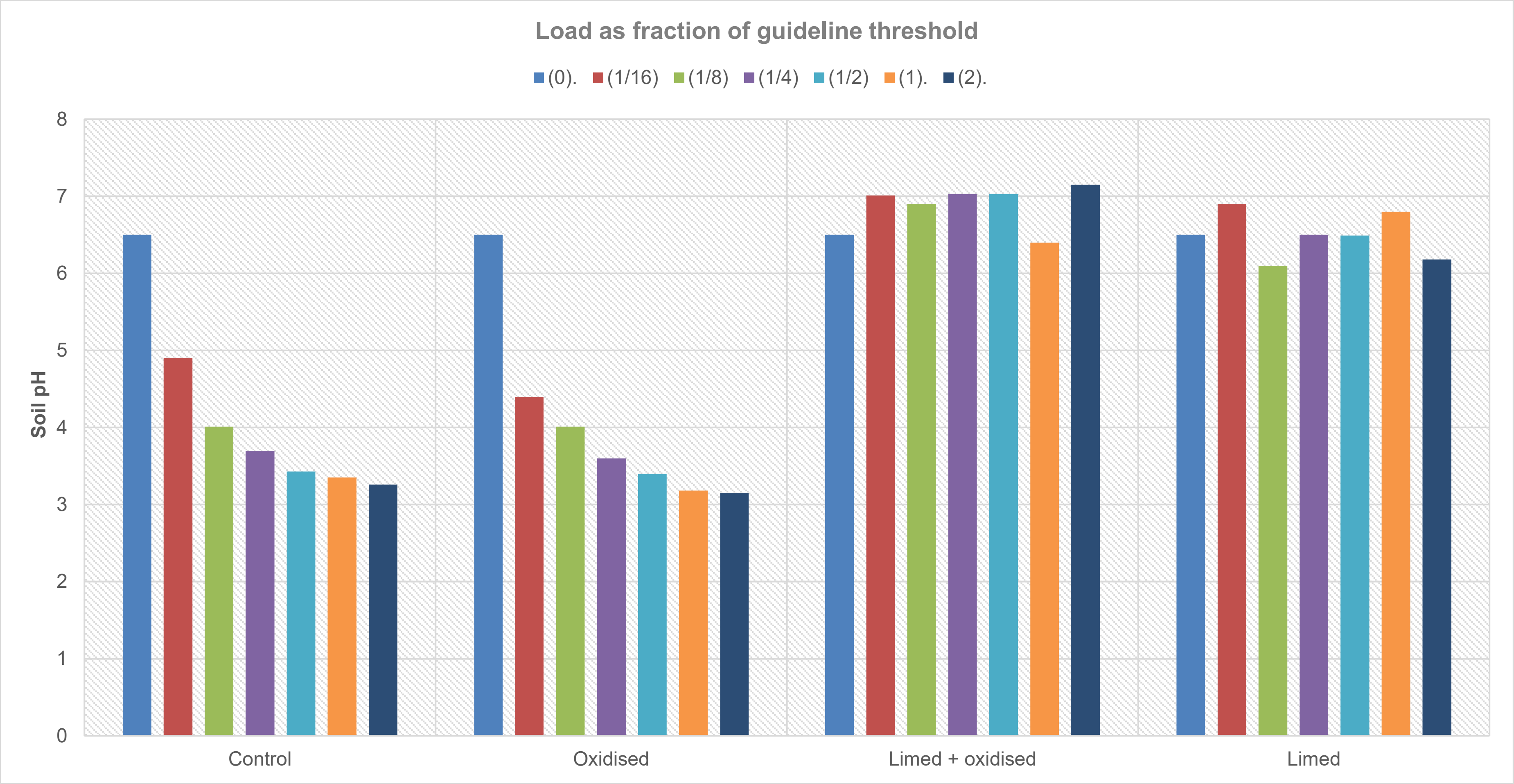

Figure 6-1: System pH of all the lime-oxidation regimes across all loads measured after the incubation period

6.5.3 Redox potential over the incubation period for the “limed + oxidized” and “oxidized” regimes

Initially, the redox potential of limed samples demonstrated vast differences with those of un-limed samples (Figure 6-2). Such dependence of redox potential on lime application was unexpected. However, there are literature sources that report similar results. A study conducted Smayda (1990) on the influence of lime and biological activity on sediment pH, redox potential as well as well as phosphorus dynamics found that in limed sediments, there was a significant decline in redox potential. The maximum differences were readings of -66 mV in limed samples versus 102 mV in un-limed samples. The study suggested that the responsible mechanisms for this were not well understood. However, it concluded that abiotic reactions account for 82 ± 54% of this reduction, and the remainder was attributed to the oxidation of organic matter by bacteria that was favoured in limed samples. The redox potential of the soils steadily increased during the incubation period and was comparable to that of samples that were not limed. Therefore, in the agricultural context, the effects of liming samples on redox potential are expected to be minimal, as the applied quantities of limestone under practical scenarios will likely be less than those applied in this experiment. This is in light of the fact that the applied metal loading rates emulated long-term loading of these elements in soils over many years of irrigation.

6.4.4. Salinity over the incubation period for the “limed + oxidized” and “oxidized” regimes

Salinity differences between limed and un-limed systems suggest that sorption differences may have been substantial between the two treatments (Figure 6-3). This is because a solution with more dissolved ions is expected to have a higher EC. Limed samples had a lower EC as liming was strategically done to maintain a circumneutral pH, which is both ideal for crop production and favours metal precipitation.

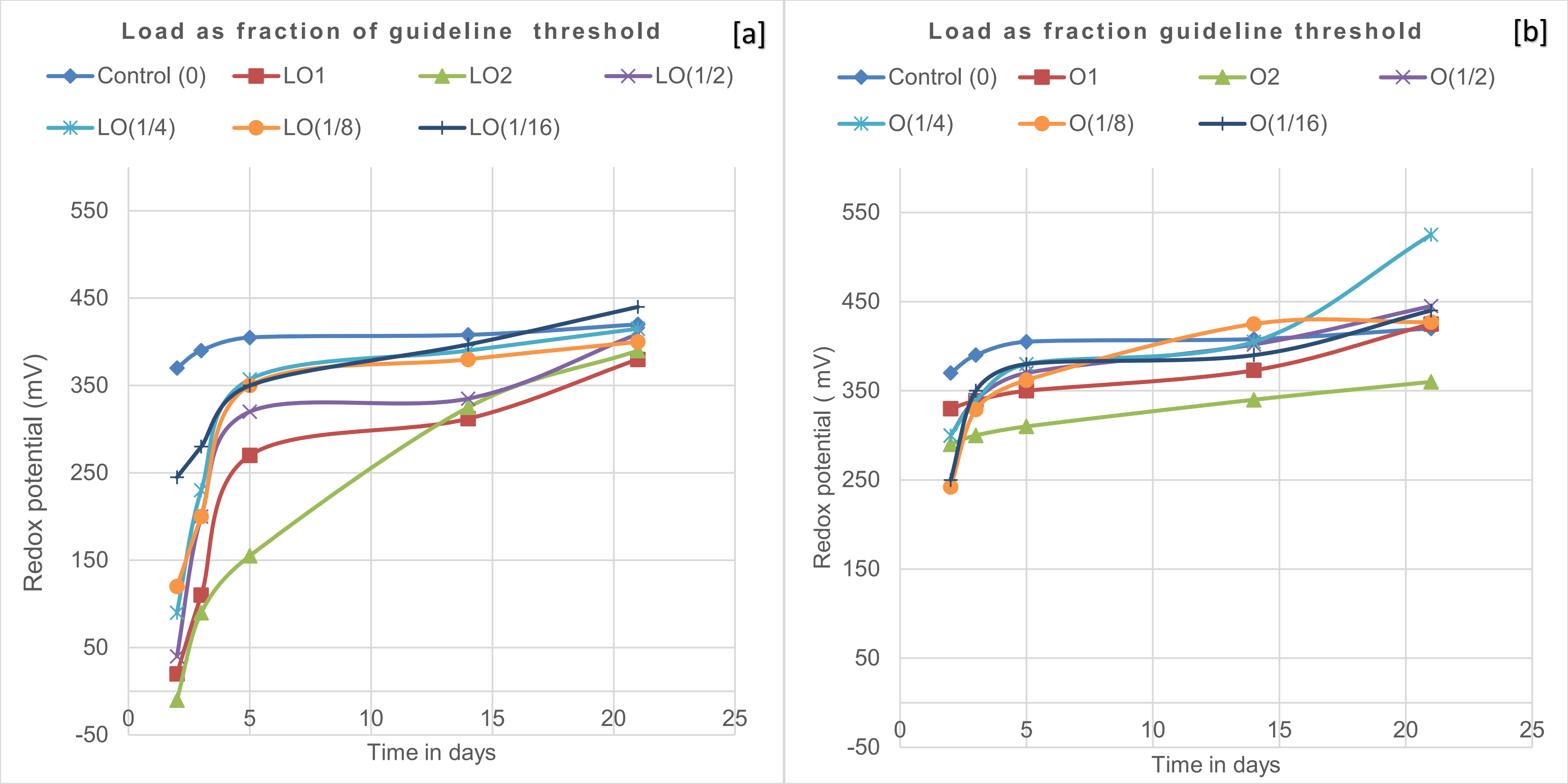

Figure 6-2: Redox potential changes as a function of time in (a) “limed+ oxidized” (LO) regime and (b) “oxidized” (O) regime

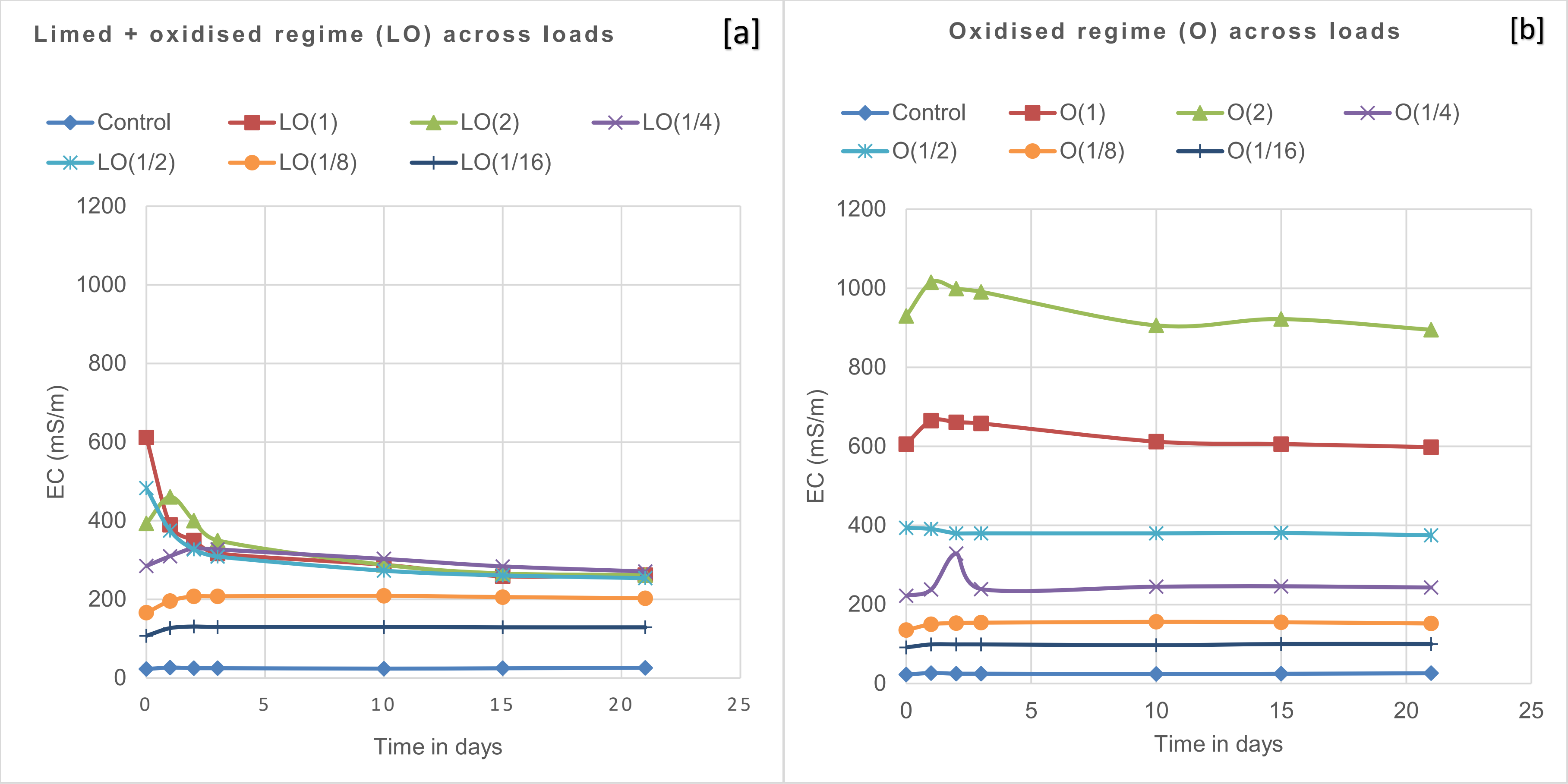

Figure 6-3: Salinity (EC) changes in (a) "limed + oxidized" (LO) regime and (b) "oxidized" (O) regime as a function of time

6.5.4 Iron removal efficiencies and water-soluble fractions

Limed and Limed + oxidized samples had RE of 100 % across all loads for Fe (Figure 6-4). Conversely, Removal Efficiency decreased as a function of load for samples that were not limed when metal loading exceeded ¼ of the guideline threshold, with minimal to no dependence on aeration (Figure 6-4). Poor Fe removal efficiency, which decreased as a function of load under un-limited regimes, is not surprising. The pH of these systems dropped as a function of load (Figure 6-1). Under such acidic conditions, precipitation of Fe is not favoured but rather the dissolution of soil minerals (Watzlaf, et al., 2004). However, results do show that sorption did occur because removal efficiency was still always higher than 45% across all loads. Plant available/water-soluble fractions were lower than what was applied to all treatment regimens (Figure 6-5). Nevertheless, the water-soluble fractions did increase significantly with two treatment regimens, “oxidized only” and “control”, as a function of the applied loads.

Removal of Fe from solution to solid phase through sorption was very efficient under ideal conditions, as hypothesised (see Figure 6-4). Water soluble fractions of Fe did not differ significantly from that of the natural soil and did not increase as a function of load for two regimes; “limed + oxidized” and “limed (only)” (Figure 6-5). This confirms the assertion that there is a very low likelihood of Fe causing phytotoxicity problems in crop production, even after long-term accumulation via irrigation water due to the high propensity for sorption that Fe exhibits. Under such ideal conditions for crop production (pH 6-7 and aerated), many studies have established that Fe will exist as insoluble minerals and mainly as oxyhydroxides or mixed minerals (van der Laan, et al., 2014, Sposito, 2008, Taylor, et al., 2005, Watzlaf, et al., 2004). There were also very high removal rates of the added divalent Fe in samples that were only limed and not oxidized (RE > 97 %) across all loads (Figure 6-4). Since redox potential measurements or dissolved oxygen levels of un-oxidized samples were not taken (because attempting to take measurements may unintentionally aerate samples), one may assume the systems were not sufficiently under reducing conditions to keep Fe in the ferrous state, which often remains in the solution phase unless they become adsorbed on mineral surfaces or precipitated in the divalent state to form Fe(II) minerals. Under reducing conditions, siderite ($FeCO_3$) may form in the presence of carbonate ions. This possible sink for Fe is, however, not the most likely for limed samples, even though $CaCO_3$ was present, which dissociates into calcium and carbonate ions. Furthermore, upon exposure to oxidising conditions, siderite is oxidized to form iron oxyhydroxides (Sposito, 2008).

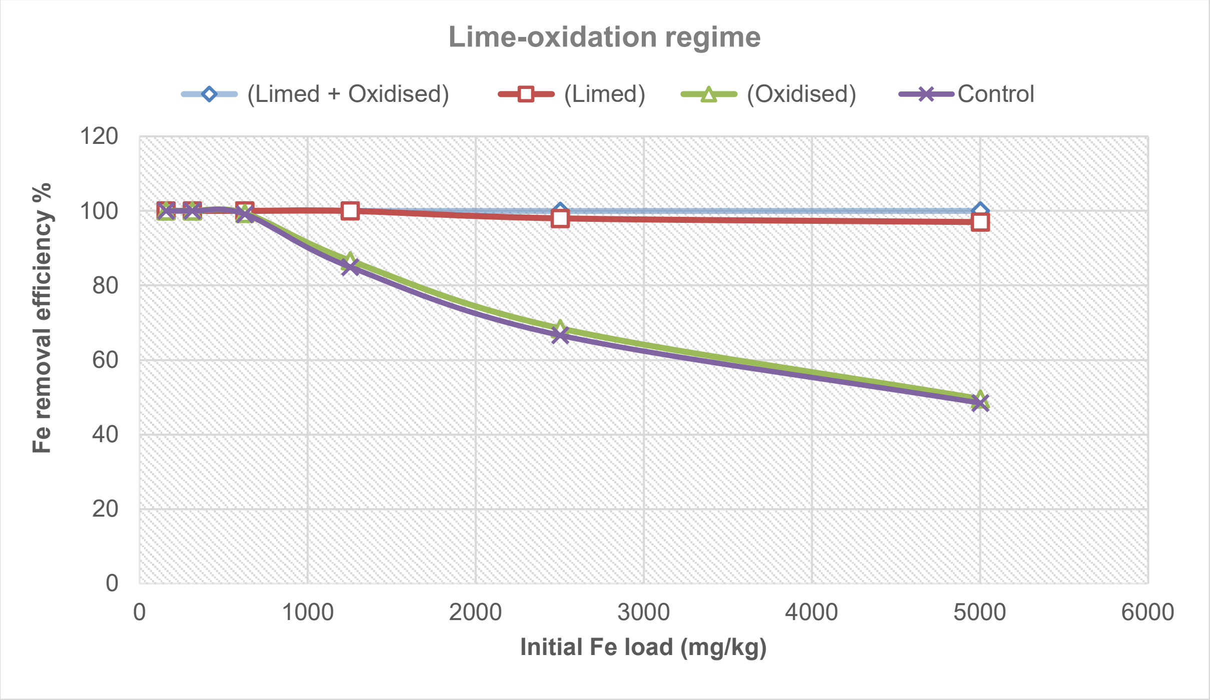

Figure 6-4: Fe removal efficiency as a function of initial Fe load after the incubation period for the four lime-oxidation regimes

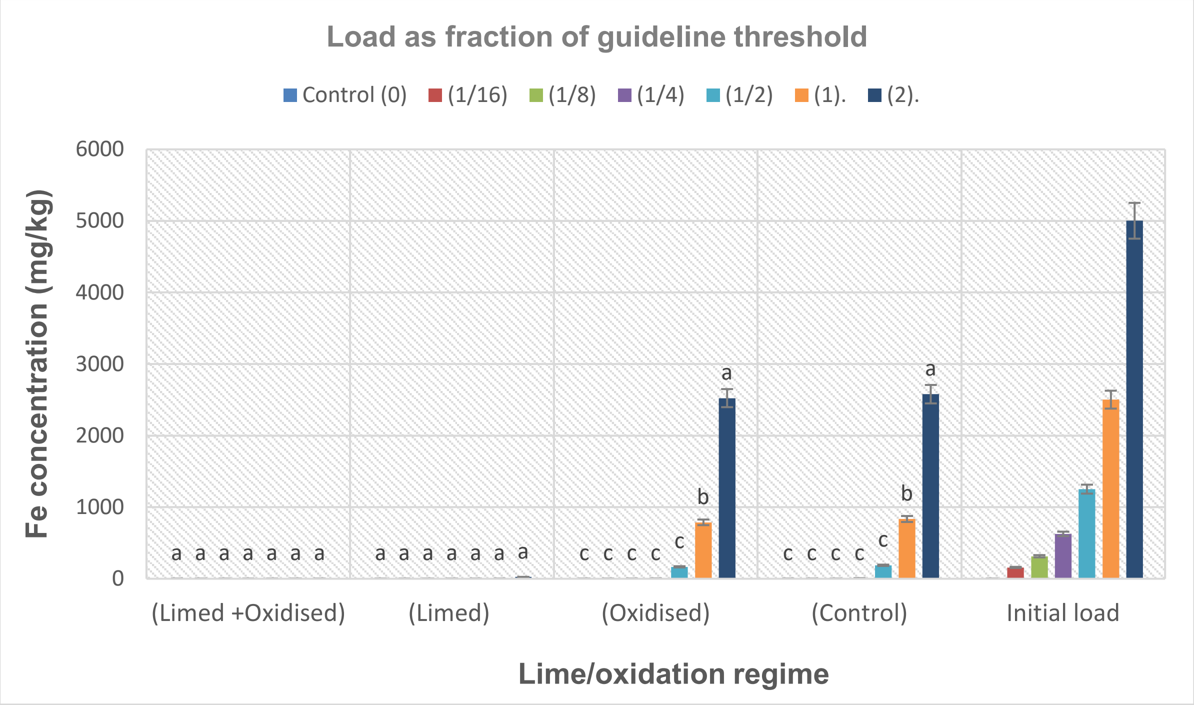

Figure 6-5: Water soluble/plant available Fe across loads after the incubation period for the four lime-oxidation regimes. (The initial water-soluble fraction is also presented on the far right). Letters of significance indicate the statistical significance of differences within lime-oxidation regimes.

There is a more interesting mechanism whereby divalent ions, such as Fe(II), co-precipitate in the divalent state under neutral or alkaline conditions as double-layered hydroxides with a trivalent cation such as aluminium (Al). Aluminium precipitation is directly affected by soil pH, and hence, alkaline co-precipitation of Al with Fe(II) is possible. This involves the formation of layered double hydroxide-type compounds (LDH). A study by van der Laan, et al. (2014) discussed the favourable possibility of ferrous Fe co-precipitating with trivalent metals (Al and/or oxidized trivalent Fe) to form a mixed hydroxide in which the trivalent metal substitutes for the divalent cation in brucite-like compounds. Compounds such as ettringite, hydrotalcite, pyroaurite and a variety of others are formed this way (van der Laan, et al., 2014). Hence, multi-metal, multi-ligand precipitates can form in multicomponent systems, such as the ternary system of this study. This allows for the sorption or removal of an element from solution outside the established formation conditions of single systems (sorption experiments or situations with a single type of solute). In theory, this suggests a possible sink for soluble divalent metals such as Fe(II), whereby mobile reduced cations precipitate without requiring prior oxidation at pH values which are nearer to neutral than would have been expected.

6.4.6: Aluminium removal efficiencies and water-soluble fractions

"Limed" and "limed + oxidized" samples had aluminium RE values of 100 % across all loads (Figure 6-6). On the other hand, as expected, RE decreased dramatically as a function of load for samples that were not limed (oxidized and Control) and approached zero towards the highest loads for these regimes. Such low Al removal efficiency, which decreased as a function of load for the un-limed regimes, was also not surprising. The pH of these systems dropped as a function of load (Figure 6-1). Under such acidic conditions, aluminium minerals are highly soluble and precipitation under such acidic conditions is rare, if not impossible (Watzlaf, et al., 2004, Sposito, 2008, Tyagi, et al., 2020).

Minimal effects of aeration for samples that were not limed, with no obvious dramatic dependence, were observed, as would be expected. RE of "oxidized (only)" samples were almost always equal to or higher than those of samples that were neither limed nor oxidized (Figure 6-6). According to Watzlaf, et al. (2004) and van der Laan, et al. (2014), this is due to the possibility of co-precipitation with Fe, which can be oxidized biotically in acidic soils, albeit to a lesser degree, and precipitate as impure iron oxides in the presence of Al to form mixed minerals as discussed in the previous sections. Aluminium has only one oxidation state in natural systems (+3) (Nordstrom and Ball, 1986, Tyagi, et al., 2020). Hence, oxidation and reduction processes, which complicate iron and manganese chemistry, do not directly affect concentrations of dissolved aluminium. Al naturally forms complexes with other elements, to form insoluble minerals such as aluminosilicates and the solubility of Al is often controlled by $Al(OH)_3$ (gibbsite) in soil environments (Nordstrom and Ball, 1986).

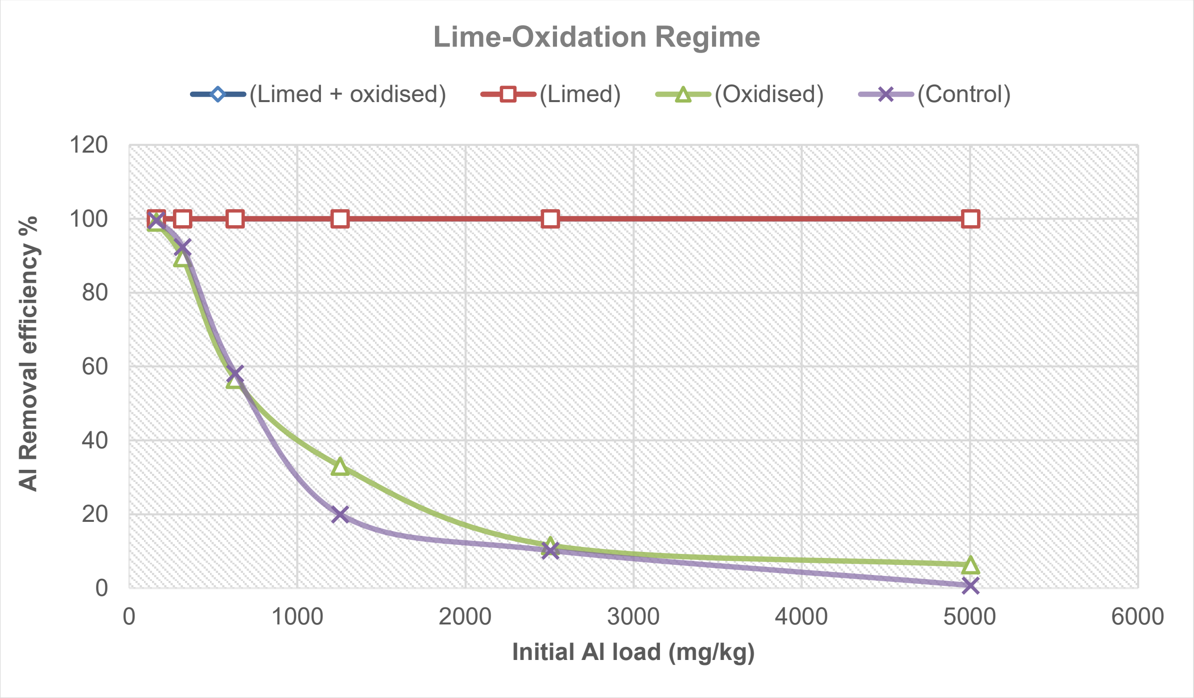

Figure 6-6: Al removal efficiency as a function of initial load after the incubation period for the four lime-oxidation regimes ('limed + oxidized' and 'limed only' lines are superimposed)

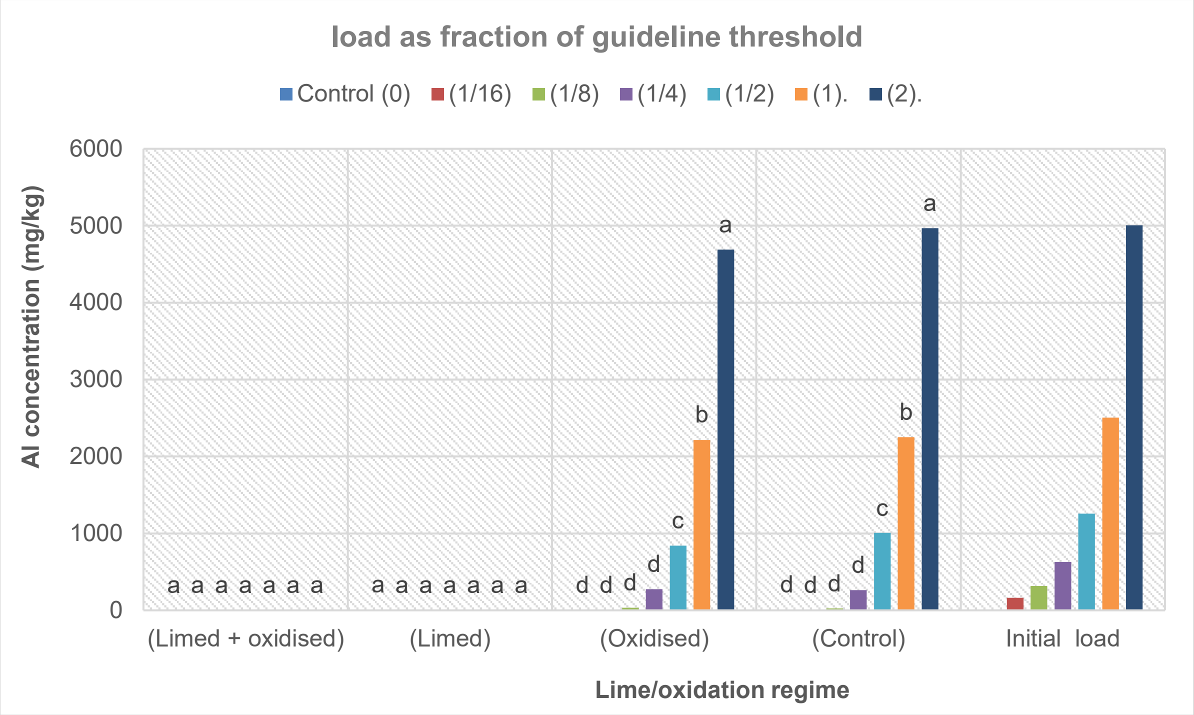

Figure 6-7: Water soluble/plant available Al as a function of initial load after the incubation period for the four lime-oxidation regimes. (The initial water-soluble fraction is also presented on the far right). Letters of significance indicate the statistical significance of differences within lime-oxidation regimes.

The high removal efficiencies of Al under the two regimes that received lime are explained by the established phenomenon that at pH levels between 5 and 8, $Al(OH)_3$ is insoluble, and concentrations of dissolved aluminium are usually less than 1 mg/ℓ (Watzlaf, et al., 2004). However, at pH values less than 4, $Al(OH)_3$ is highly soluble (Nordstrom and Ball, 1986), and it was not surprising that the water-soluble fractions of the samples that were not limed did increase as a function of load and differed significantly with that of the natural soil (control) in the same regimes when aluminium loading rate was equal to or greater than half the guideline threshold (Figure 6-7).

As a result of these observations and discussion, the hypothesis that states that the plant availability of Al is not a function of loading rate under ideal soil conditions was accepted, as Al water-soluble fractions across all loads were not significantly different from the natural soils (control) and from each other, both under optimum conditions, designated as “limed + oxidized” (pH 6-7, aerated) as well as in “limed (only)” samples (Figure 6-7).

6.4.7: Manganese removal efficiencies and water-soluble fractions

According to Robinson-Lora and Brennan (2010), divalent manganese is notoriously difficult to remove from solution in many environmental systems. A popular mechanism for Mn removal, similar to Fe, is by its oxidation followed by precipitation as a manganese oxide. This is often achieved reasonably quickly under highly alkaline conditions since the oxidation kinetics of Mn(II) by molecular oxygen (O_2) are very slow when $pH < 9$. The estimated half-life of Mn(II) oxidation by O_2 is in the order of years according to Watzlaf, et al. (2004). In addition, according to Johnson and Younger (2005) Mn, oxidation can be inhibited by the presence of ferrous iron. If pH falls below 6, Mn(II) oxidation virtually ceases according to Watzlaf, et al. (2004).

The conditions (see Figure 6-1) of this experiment were below the thresholds for efficient and rapid manganese oxidation (Watzlaf, et al., 2004), even for limed samples, which were at pH levels in the region of 6 to 7. It is not surprising that removal efficiency for Mn decreased with load across all regimes (see Figure 6-9). It began to increase, however, under optimum conditions (limed + oxidized) as the load was increased further. This may be due to the autocatalytic nature of manganese oxidation. Once manganese oxide precipitates form, their presence increases the rate of manganese removal (Johnson and Younger, 2005, Watzlaf, et al., 2004). RE was only 56% at the double guideline threshold loading rates under optimum conditions (Figure 6-8).

Abiotic oxidation of Mn (II) does not seem to be the most common pathway of manganese sorption. The role of microorganisms in manganese removal has been demonstrated to be of great importance. Oxidation of Mn by manganese-oxidizing organisms is a well-known phenomenon that may speed up the oxidation and sorption process. Manganese-oxidizing organisms use Mn (II) as an electron donor and oxygen as an electron acceptor. Any factor in a manganese sorption experiment that negatively affects manganese oxidizing micro-organisms will indirectly also negatively affect Mn sorption. Hence, the role microorganisms played in this sorption experiment was not directly considered and may need future investigation.

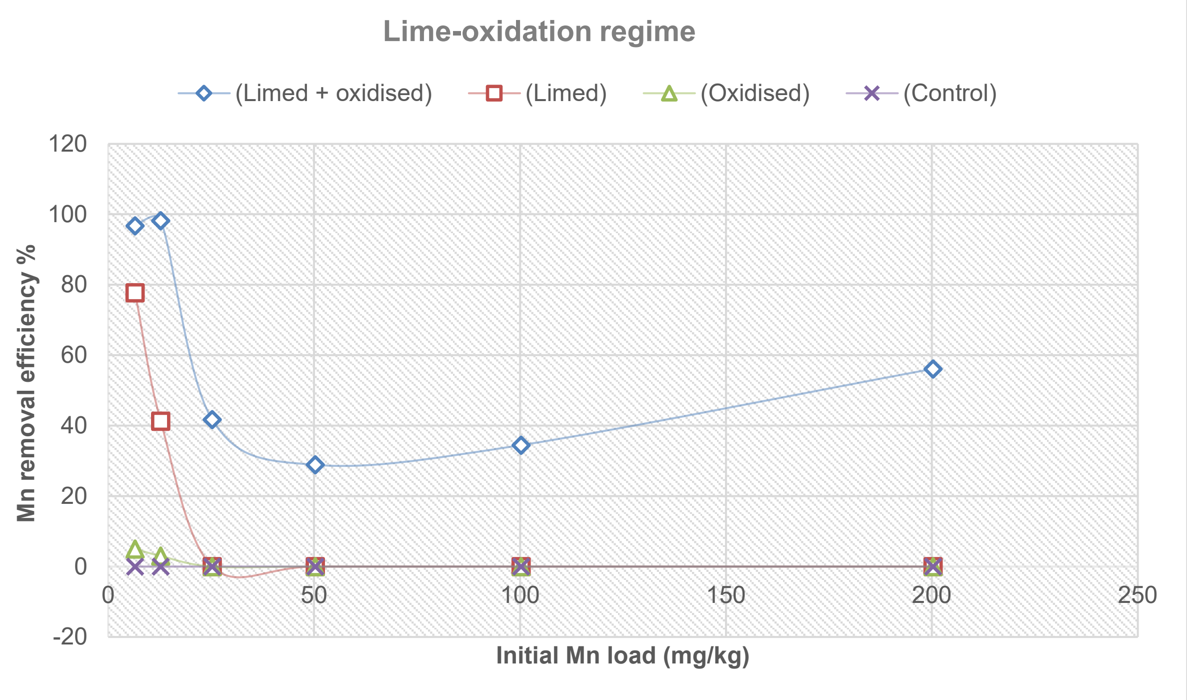

Figure 6-8: Mn removal efficiency as a function of initial load after the incubation period for the four lime-oxidation regimes.

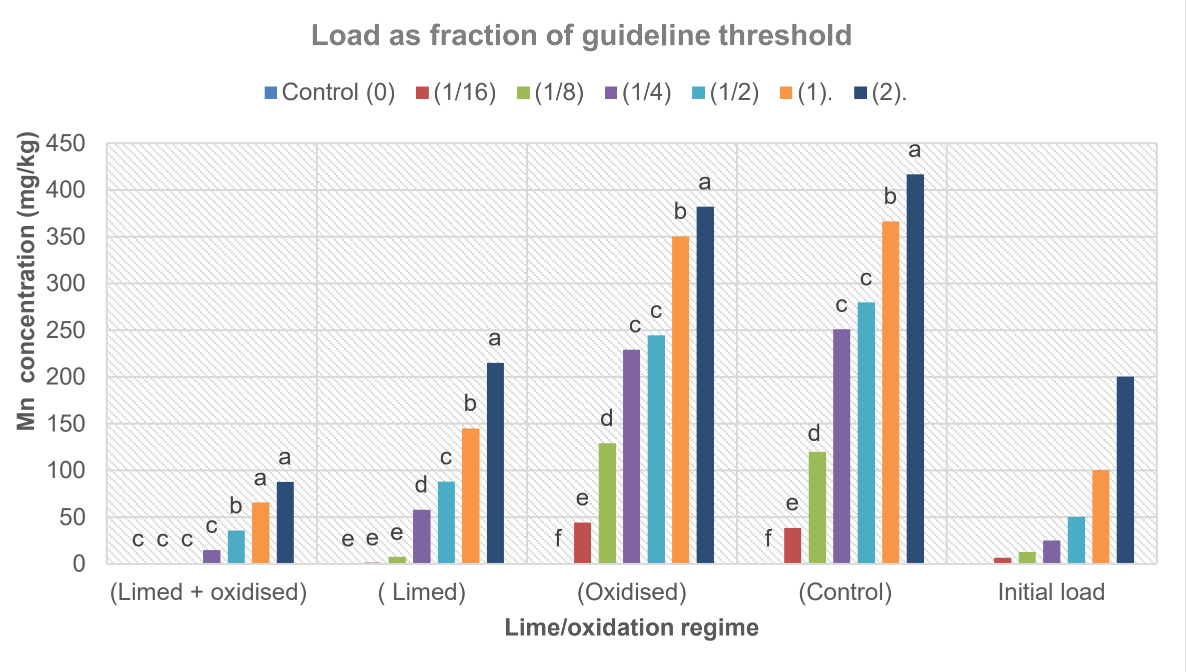

Figure 6-9: Water soluble/plant available Mn as a function of initial load after the incubation period for the four lime-oxidation regimes. Letters of significance indicate statistical significance of differences within lime-oxidation regimes.

With the exception of the ideal regime (limed + oxidized), manganese water-soluble fractions for all the other regimes were higher than the initial water-soluble load (Figure 6-9). Depending on each system's conditions, this is attributed to acidity and reductive dissolution of natural soil Mn oxides (Essington, 2015, Watzlaf, et al., 2004, Johnson and Younger, 2005). Furthermore, for all regimes, the water-soluble fraction of manganese increased as a function of load, hence, rejecting the hypothesis that manganese plant availability is not a function of load in well aerated circum-neutral soils. Sorption of manganese did occur under these optimum conditions, albeit, with very low efficiency (Figure 6-8).

6.6 RECOMMENDATIONS

The results of this study suggest that mine effluents and potentially other water sources containing Al and Fe may be unnecessarily deemed unacceptable for irrigation by IrrigWQ due to a projected exceedance of preset soil accumulation thresholds. Such waters may not pose a phytotoxic risk because of the very high propensity for precipitation that these elements exhibit under ideal conditions for crop production.

It was hypothesized that the availability of these metals will not depend on total soil concentrations and, therefore, will not increase over time in well-drained, circumneutral soils. This proved to be correct for aluminium and iron. It was also demonstrated that Mn can indeed be mobile in some circumneutral soils. Therefore, it is recommended that IrrigWQ refrain from using soil loading limits for Al and Fe to assess irrigation water quality but continue to assess the impacts of these elements on other protection targets, such as crop quality and effects on irrigation infrastructure. It is also concluded that it is necessary to conduct further research on Mn to determine whether site-specific factors such as soil type and crop choice should influence the assessment of fitness for use of waters for irrigation for this element.

CHAPTER 7: CONCLUSIONS & RECOMMENDATIONS

This project was successful in addressing all of the aims set for it, with the exception of identifying a suitable custodian. This aim proved to be extremely challenging. In light of this, the Project Reference Group has recommended that it would be most beneficial if UP, with research support from the WRC, continued taking responsibility for the DSS until a permanent custodian capable of maintaining and promoting the usage of the tool has been identified.

As interim custodians, the project team ensured that IrrigWQ was maintained and kept up to date. The use of IrrigWQ was promoted extensively by the team through peer-reviewed publications and presentations at scholarly society conferences and industry engagements. Virtual training materials in the form of narrated PowerPoint presentations and demonstration videos were successfully developed, but it is likely that these will require updating in future based on user feedback. Users may also request that additional topics be covered in future.

The studies conducted to assess whether loading limits are essential in assessing the risk associated with Al, Fe, and Mn in irrigation waters provided great insights into the dynamics of these elements in soils. The results indicated that the plant availability of Al and Fe does not depend on total concentrations. Therefore, it is recommended that soil loading limits for these elements be excluded from the DSS assessments. Mn dynamics in soils were found to be more complex than those of Al and Fe and require further investigations that focus on site-specificity. This will aid in determining if factors such as soil type and crop choice should influence the assessment of fitness for use of waters for irrigation for this element. However, Fe and Mn should be retained in the DSS for assessing water quality effects on irrigation equipment. It is also recommended that the effect of foliar application of Al, Fe and Mn on crop quality be investigated, specifically to assess if foliar absorption of these elements poses a food safety risk, as this mode of uptake which may be of great importance under overhead irrigation that wets the canopy, is not considered in any irrigation water quality guidelines.

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APPENDIX A: WORKSHOPS

DALRRD Training workshop

Workshop Flyer

agriculture, land reform
& rural development
Department:
Agriculture, Land Reform & Rural Development
REPUBLIC OF SOUTH AFRICA

WATER
RESEARCH
COMMISSION

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Training workshop: Site-specific, Risk based DSS for Assessing Irrigation Water Quality

Date: 14 June 2022

Time: 0900 – 1400 hrs

Venue: Water Research Commission (WRC)

The Site-specific, risk-based Decision Support Tool (DSS) for assessing irrigation water quality is based on the South African Water Quality Guidelines published in 1996. The WRC has developed new guidelines that are risk-based – a fundamental change in philosophy from earlier text-based guidelines. Secondly, they allow for much greater site-specificity – a widely recognised limitation of the generic 1996 guidelines. These guidelines are available primarily as a software-based Decision Support System.

The Site-specific, Risk-based DSS for Assessing Irrigation Water Quality does not only consider risk, but it also allows for water quality to be assessed at different levels of sophistication and caters for evaluation of both the fitness-for-use and the setting of water quality requirement. The DSS has been extensively used to assess suitability of mine affected waters for irrigation and forms an integral part of the Technical Guidelines for mine water irrigation.

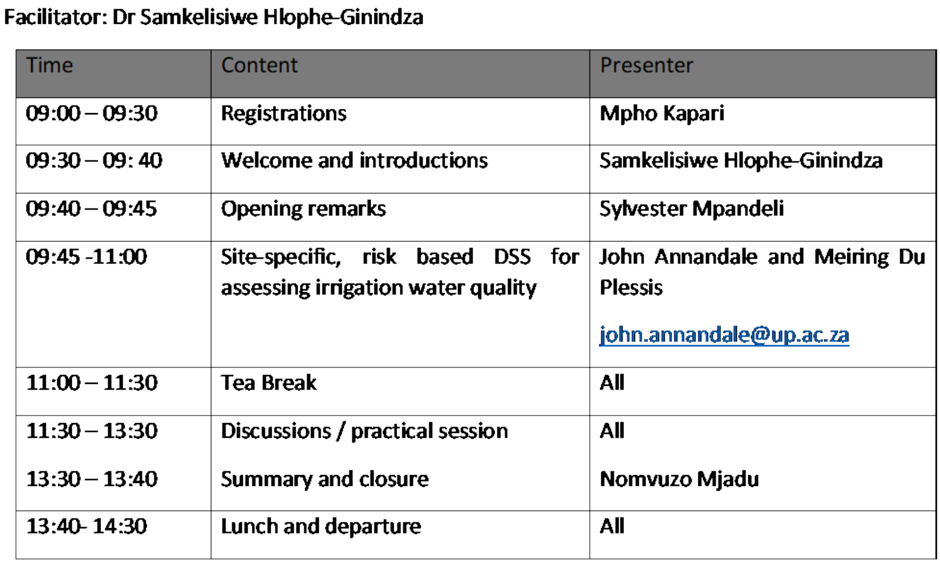
The DSS for assessing irrigation water quality has been designed to cater for two diverging applications, namely:

i. To assess the fitness-for-use of a water of known composition (water analysis) by determining its fitness-for-use category.

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 user of a water resource (river stretch or surface or groundwater body).

The workshop intends to provide practical training on the use and applicability of the DSS to accelerate adoption to officials from the Department of Agriculture Land Reform and Rural Development.

Workshop Programme



Facilitator: Dr Samkelisiwe Hlophe-Ginindza

Time	Content	Presenter
09:00 – 09:30	Registrations	Mpho Kapari
09:30 – 09: 40	Welcome and introductions	Samkelisiwe Hlophe-Ginindza
09:40 – 09:45	Opening remarks	Sylvester Mpandeli
09:45 -11:00	Site-specific, risk based DSS for assessing irrigation water quality	John Annandale and Meiring Du Plessis john.annandale@up.ac.za
11:00 – 11:30	Tea Break	All
11:30 – 13:30 13:30 – 13:40	Discussions / practical session Summary and closure	All Nomvuzo Mjadu
13:40- 14:30	Lunch and departure	All

TZANEEN TRAINING WORKSHOP

Flyer

agriculture, land reform
& rural development
Department:
Agriculture, Land Reform and Rural Development
REPUBLIC OF SOUTH AFRICA

WATER
RESEARCH
COMMISSION

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Training workshop: Site-specific, Risk based DSS for Assessing Irrigation Water Quality.

Date: 13 June 2023

Time: 0900 – 1430 hrs.

Venue: Tzaneen, Limpopo (Exact venue TBC).

The Site-specific, risk-based Decision Support Tool (DSS) for assessing irrigation water quality is based on the South African Water Quality Guidelines published in 1996. The Water Research Commission (WRC) has developed new guidelines that are risk-based – a fundamental change in philosophy from earlier text-based guidelines. Secondly, they allow for much greater site-specificity – a widely recognised limitation of the generic 1996 guidelines. These guidelines are available primarily as a software-based Decision Support System.

The Site-specific, Risk-based DSS for Assessing Irrigation Water Quality does not only consider risk, but it also allows for water quality to be assessed at different levels of sophistication and caters for evaluation of both the fitness-for-use and the setting of water quality requirement. The DSS has been extensively used to assess suitability of mine affected waters for irrigation and forms an integral part of the Technical Guidelines for mine water irrigation.

The DSS for assessing irrigation water quality has been designed to cater for two diverging applications, namely:

i. To assess the fitness-for-use of a water of known composition (water analysis) by determining its fitness-for-use category.

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 user of a water resource (river stretch or surface or groundwater body).

Programme

The workshop intends to provide practical training on the use and applicability of the DSS to accelerate adoption to officials from the Department of Agriculture Land Reform and Rural Development.

Facilitator: Dr Samkelisiwe Hlophe-Ginindza

Time	Content	Presenter
09:00 – 09:30	Registrations	Mpho Kapari
09:30 – 09: 40	Welcome and introductions	Samkelisiwe Hlophe-Ginindza
09:40 – 09:45	Opening remarks	Nomvuzo Mjadu
09:45 -11:00	Site-specific, risk based DSS for assessing irrigation water quality	John Annandale and Meiring Du Plessis john.annandale@up.ac.za
11:00 – 11:30	Tea Break	All
11:30 – 13:30	Discussions / practical session	All
13:30 – 13:40	Summary and closure	Luxon Nhamo
13:40- 14:30	Lunch and departure	All

APPENDIX B: PUBLICATIONS

ACTA HORTICULTURAE PUBLICATION

AN ELECTRONIC DECISION SUPPORT SYSTEM TO ASSESS RISK-BASED, SITE-SPECIFIC FITNESS FOR USE OF IRRIGATION WATER: APPLICATION TO HORTICULTURAL CROPS

*J.G. Annandale[1], H.M. du Plessis[1], N. Benade[2] and N.J. Taylor[1]

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[2]NB Systems, 33 Dr van der Merwe Road, Montana, Pretoria, 0182, South Africa

Abstract

Increased demands on available irrigation water supplies necessitate increased production with less water, often of a poorer quality and from unconventional sources. An electronic Decision Support System (DSS) which models soil-plant-atmosphere interactions has been developed to assess the fitness for use (FFU) of irrigation waters under site-specific conditions that may influence the assessment. The DSS operates at two tiers to assess the effect that water quality constituents may have on soil quality, crop yield and quality, and irrigation infrastructure. 'Suitability Indicators' divide these effects further into sub-components. User-friendly colour coded Tier 2 output displays the risk associated with using the water under specific conditions, as 'ideal', 'acceptable', 'tolerable' or 'unacceptable'. Tier 1 assessments provide generic, conservative guidance, assuming no dilution of irrigation water by rain, instant equilibrium between water constituents and soil, and crops that are generally sensitive to water quality constituents. This resembles currently published international guidelines. Tier 2 assessments are more rigorous and used to determine whether the assessed FFU of a water could improve when site-specific conditions are considered. These assessments use the Soil Water Balance (SWB) model to dynamically simulate the interactions between irrigation water constituents and the soil-crop-atmosphere system over 10 to 45 years, to quantify the probability and severity of a specific effect occurring. Default model parameters enable selection of an appropriate weather station, soil texture, crop species, irrigation management approach, and irrigation system. DSS predicted yield response to salinity is demonstrated for three horticultural crops to be comparable to that of international irrigation water quality guidelines, under similar conditions and assumptions. Examples are given to illustrate how FFU of irrigation water is affected by site-specific conditions. This illustrates how the DSS can be used to identify conditions under which a particular water can be used most beneficially.

Keywords: Irrigation water quality guidelines, crop quality, crop yield, soil quality, corrosion and scaling of irrigation infrastructure, salinity, sodicity

INTRODUCTION

In a fast-changing world where increased demands are being made on the available water supply, complicated by the uncertainties introduced by the impacts of climate change and variability, irrigated agriculture is increasingly challenged to increase production using less water, often of a poorer quality from unconventional sources. Several classification systems have been developed to assess the suitability of water for irrigation. Arguably the best known of these

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PUBLICATION IN APPLIED SCIENCES

applied
sciences

MDPI

Citation: du Plessis, H.M.; Annandale, J.G.; Benadé, N. A Decision Support System That Considers Risk and Site Specificity in the Assessment of Irrigation Water Quality (IrrigWQ). *Appl. Sci.* **2023**, *13*, 12625. https://doi.org/10.3390/app132312625

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Published: 23 November 2023

tps://www.mdpi.com/journal/applsci

MINE WATER AND THE ENVIRONMENT PUBLICATION

Mine Water and the Environment
https://doi.org/10.1007/s10230-023-00961-3

TECHNICAL ARTICLE

0028, South Africa

APPENDIX C: PRESENTATIONS

SANCID SYMPOSIUM

Abstract

SAWQI: South African Water Quality Guidelines for Irrigation Decision Support System

Irrigation water quality has traditionally been assessed assuming that irrigation is the main or only source of water for plant use. Site-specific factors that may influence the suitability of water, like crop choice, climate, soil factors and irrigation management, were not considered. Assessments of the Fitness for Use (FFU) of a water, furthermore, focused primarily on the effects of constituents that occur naturally in waters, while the degree of risk associated with using a particular water was not considered. However, irrigators are increasingly challenged to maintain or even increase production using less water, sometimes of a poorer quality, and often from unconventional sources. This demonstration will highlight the main features of the newly developed software-based Decision Support System (DSS), with which to assess the FFU of water for irrigation, that was developed with financial support of the Water Research Commission and the Department of Agriculture, Land Reform and Rural Development. The DSS generates user-friendly, colour-coded output, which highlights expected effects that water constituents will have on soil quality, crop yield and quality, and on irrigation equipment.

SANCID SYMPOSIUM: Research and innovation towards meeting new challenges and a thriving irrigation sector”

Programme

Date: 21-23 February 2023

Venue: Fairview Hotels, Spa & Golf Resort, Tzaneen

Day 1

Time	Topic	Person Responsible
10:00 – 11:00	**Registration**	**Ms Kapari & Mr Motsoko**
11:00 – 12:30	Session 1	Chair: Ms Palo Kgasago
11:00 –11:05	Opening Address	Prof. Sylvester Mpandeli - SANCID Chairman
11:05 –11:30	Welcome, Address	Ms Maisela – HOD: Limpopo Department of Agriculture and Rural Development
11:30 –12:00	Keynote Address	Mr Ramasodi – DG: Department of Agriculture, Land Reform and Rural Development
12:00 – 12:30	Water-energy-food nexus innovations and practices under the impact of water scarcity in Vhembe district, Limpopo province, South Africa.	*EJ Mwendera, K Nephawe, R Makungo, DK Musetsho, T Madzivhandila, NS Mamphweli, and T Volenzo*
12:30 – 13:00	Lunch	
13:00 – 15:00	**Session 2: Integrated Water Resource Management**	**Chair: Mr Jan Potgieter**
13:00 – 13:20	Water resource planning and management practices in a mature water economy: lessons from South Africa	*P Mlilo*

Day 2,Wednesday 22 February 2023

Time	Topic	Person Responsible
08:00 – 10:00	**Session 4: Demonstration workshop**	**Chair: Dr Khumbulani Dhavu**
08:00 – 08:40	DECAL: Economic management of conjunctive use of irrigation water and shallow groundwater.	*B Grove*
08:40 – 09:20	SAWQI: South African Water Quality Guidelines for Irrigation Decision Support System.	*L Madiseng*
09:20 – 10:00	The Water Research Observatory: Discovering and uploading data for hydrological modelling and big data analytics.	*M van der Laan, S Maseko, and A Thompson*
10:00 – 10:30	**Refreshment break**	
10:30 – 12:00	**Session 5**	**Chair: Ms Nomvuzo Mjadu**
10:30 – 10:50	The value of incorporating tribal communities in water resource allocation to improve productivity in South Africa.	*TE Manungufala, ZE Mashimbye, W De Clercq, S Williams*
10:50 – 11:10	Science communication and digital literacy in undergraduate agricultural science education.	*R van Wyk, D Reynhardt, J de Jager, R Hay*
10:10 – 11:30	ARC Presentation.	*N Masekwana*
11:30 – 12:00	Question and answer session.	
12:00 – 13:00	Lunch	
13:00-17:00	Technical tour	*P Kgasago*

SABI TECHNICAL FORUM

SABI

SOUTH AFRICAN IRRIGATION INSTITUTE
SUID AFRIKAANSE BESPROEIINGSINSTITUUT

PROGRAMME

Technical Forum

"Creative Irrigation changes the World"
13 - 15 August 2024
Indaba Hotel, Spa & Conference Centre, Fourways - Gauteng - South Africa

Rivulis	MACSTEEL FLUID CONTROL	GRUNDFOS	NETAFIM™ An Orbia business.	IrriGator PRODUCTS	C.R.I. PUMPS Pumping trust...Worldwide.
Platinum	Gold	Gold	Silver	Bronze	Bronze

PROGRAMME

Tuesday, 13 August 2024

- 08:00 – 11:00 Build-up of Exhibitions
- 11:00 – 12:00 Registration
- 12:00 – 13:00 Lunch and viewing of exhibits
- 13:00 – 13:15 **Welcome Address: Albertus Burger, SABI President**
- 13:15 – 13:45 **Platinum Sponsor: Rivulis**
- 13:45 – 14:45 **Keynote Speaker: Wandile Sihlobo**
- 14:45 – 15:00 Question & Answer
- 15:00 – 15:30 Refreshment break and viewing of exhibits

Start of Programme - Facilitator Michael Esmeraldo

Session 1: BUSINESS
Facilitator of Session: Hein van Graan

- 15:30 – 16:00 Business – How to build a Legacy
  Ronald King
- 16:00 – 16:30 Management strategies for agribusinesses in times of uncertainty
  Dr Lindie von Maltitz
- 16:30 – 17:00 Discussion
- 19:00 **Dinner** (Chefs Boma)

Wednesday, 14 August 2024

- 07:00 – 08:00 Breakfast
- 07:30 – 07:55 Registration Day Delegates (Viewing of exhibits)

Session 2: AGRONOMY
Facilitator of Session: Dr Ashiel Jumman

- 08:00 – 08:45 Crop factor methodology
  Stephan Schoeman
- 08:45 – 09:30 Irrigation water quility guidelines
  Prof John Annandale
- 09:30 – 10:30 Refreshment break and viewing of exhibits

Session 2: Continue

- 10:30 – 11:15 What does years of irrigating and fertilizing do to our soil
  Dr Rian van Antwerpen
- 11:15 – 12:00 Working Discussion
- 12:00 – 13:00 Lunch and viewing of exhibits

SOILBORNE PLANT DISEASES SYMPOSIUM

22–24 OCTOBER 2024

IMPROVING SOIL HEALTH AND SOILBORNE PLANT DISEASES

PROGRAMME

22 October 2024

13:00–13:45	**Arrival and Tea**
13:45–16:00	Discussion: Measuring soil health
16:00–16:30	**Tea**

23 October 2024

08:30–09:00	**Arrival and Tea**
09:00–09:40	Opening *Dr. Willem Hoffman (Stellenbosch University, Stellenbosch)*
09:40–09:50	Acknowledgements and Announcements *Prof. Sandra Lamprecht (ARC Plant Health and Protection, Stellenbosch)*
09:50–10:35	On Health *Prof. Erik Holm (Saartjiesnek, Hartebeespoort)*
10:35–10:45	Discussion
10:45–11:35	**Tea and group photograph**

15:55–16:15	Two decades of soil health – A practical case study *Mr. Hendrik Pohl (Holistic Horticulture Pty Ltd, Ceres)*
16:15–16:25	Discussion
16:25–16:45	Sponsor sessions (2 sponsors)
18:30 for 19:00	**Dinner**

24 October 2024

08:30–09:00	**Arrival and Tea**

Session 3

Chairperson: Dr. Jacques van Zyl

09:00–09:20	IrrigWQ – A decision support system to assess the fitness for use of irrigation water *Dr. Meiring du Plessis (University of Pretoria, Pretoria)*
09:20–09:30	Discussion
09:30–09:50	Soil and water management for sustainable production *Prof. Martin Steyn (University of Pretoria, Pretoria)*
09:50–10:00	Discussion
10:00–10:20	Innovative sensor and spectral methods for assessing plant health *Mr. Arie van Ravenswaay (Department of Agriculture, Western Cape Government, Elsenburg)*
10:20–10:30	Discussion
10:30–11:00	**Tea**

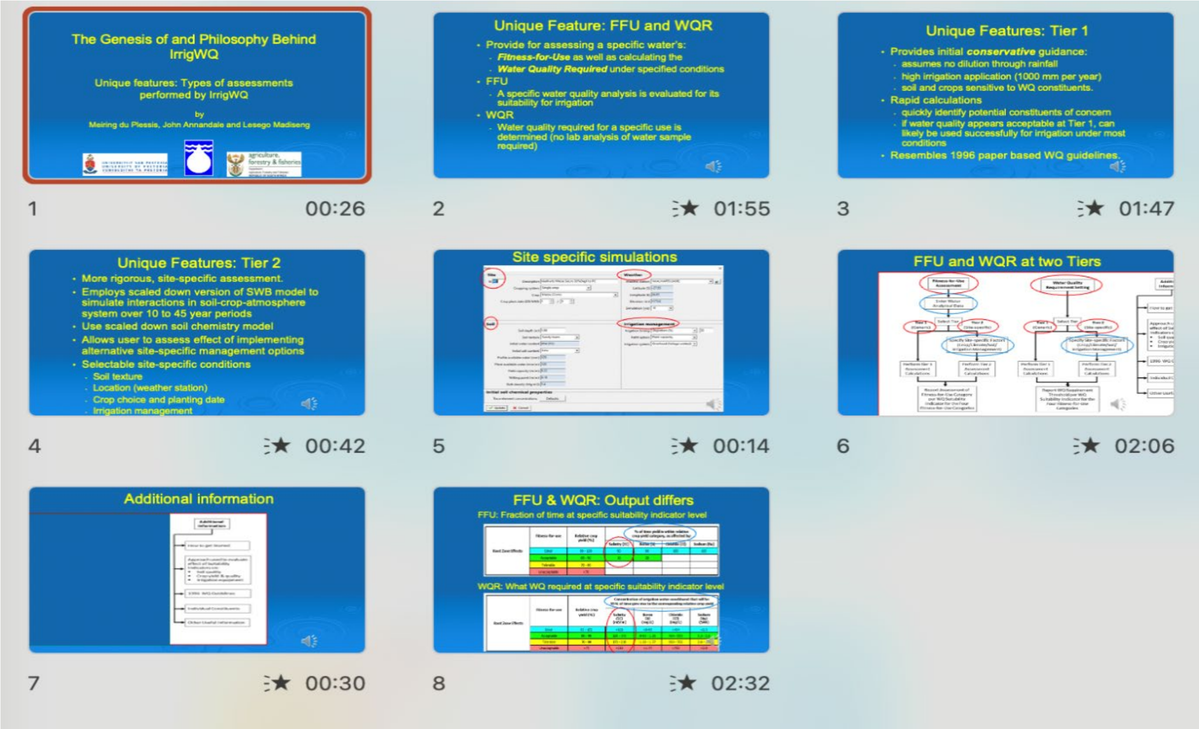
APPENDIX D: SAMPLES OF THE NARRATED PRESENTATIONS AND DEMONSTRATION VIDEOS

SAMPLE OF THE "GENESIS OF AND PHILOSOPHY BEHIND" THEME

The Genesis of and Philosophy Behind IrrigWQ

Unique features: Types of assessments performed by IrrigWQ

by
Meiring du Plessis, John Annandale and Lesego Madiseng



The Genesis of and Philosophy Behind IrrigWQ

Unique features: Types of assessments performed by IrrigWQ

by
Meiring du Plessis, John Annandale and Lesego Madiseng

1 00:26

Unique Feature: FFU and WQR

- Provide for assessing a specific water's:
  - ***Fitness-for-Use*** as well as calculating the
  - ***Water Quality Required*** under specified conditions
- FFU
  - A specific water quality analysis is evaluated for its suitability for irrigation
- WQR
  - Water quality required for a specific use is determined (no lab analysis of water sample required)

2 ★ 01:55

Unique Features: Tier 1

- Provides initial ***conservative*** guidance:
  - assumes no dilution through rainfall
  - high irrigation application (1000 mm per year)
  - soil and crops sensitive to WQ constituents.
- Rapid calculations
  - quickly identify potential constituents of concern
  - if water quality appears acceptable at Tier 1, can likely be used successfully for irrigation under most conditions
- Resembles 1996 paper based WQ guidelines.

3 ★ 01:47

Unique Features: Tier 2

- More rigorous, site-specific assessment.
- Employs scaled down version of SWB model to simulate interactions in soil-crop-atmosphere system over 10 to 45 year periods
- Use scaled down soil chemistry model
- Allows user to assess effect of implementing alternative site-specific management options
- Selectable site-specific conditions
  - Soil texture
  - Location (weather station)
  - Crop choice and planting date
  - Irrigation management

4 ★ 00:42

Site specific simulations

5 ★ 00:14

FFU and WQR at two Tiers

6 ★ 02:06

Additional information

7 ★ 00:30

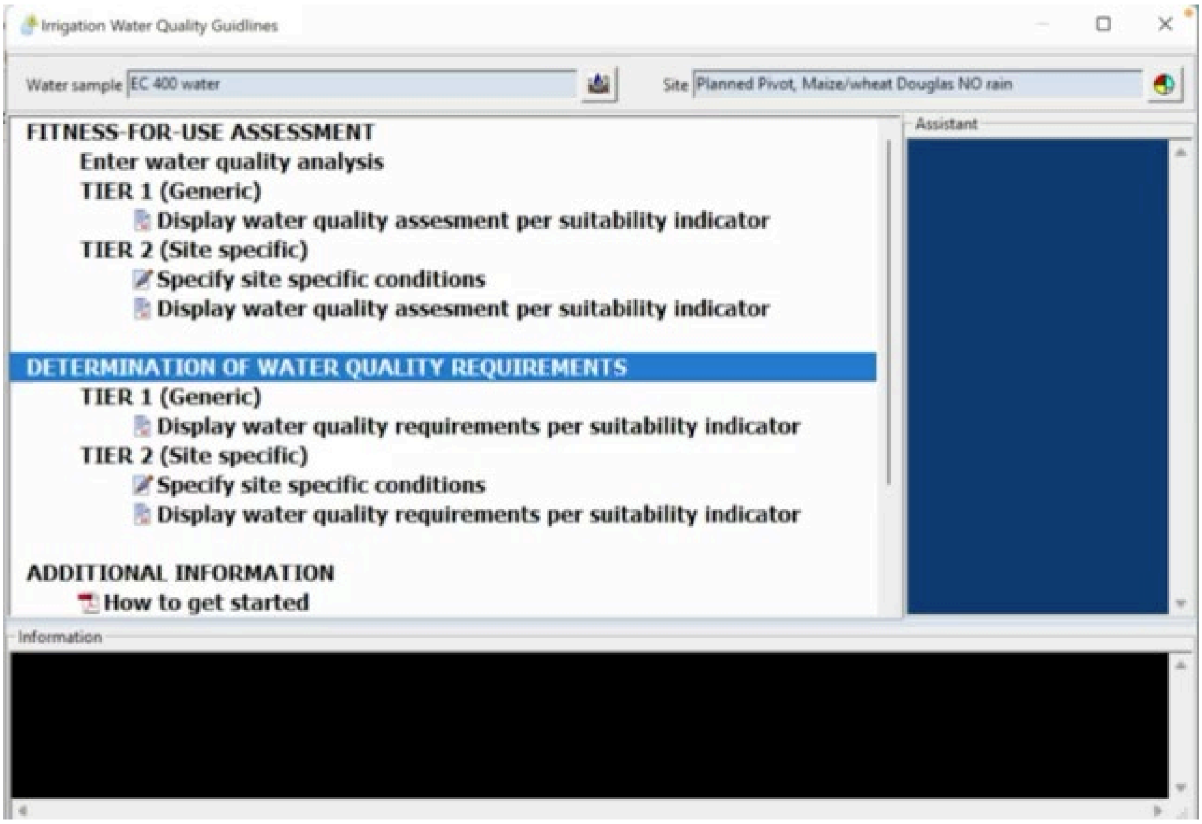
FFU & WQR: Output differs

FFU: Fraction of time at specific suitability indicator level

WQR: What WQ required at specific suitability indicator level

8 ★ 02:32

SAMPLE OF THE “SOFTWARE DEMONSTRATION” THEME



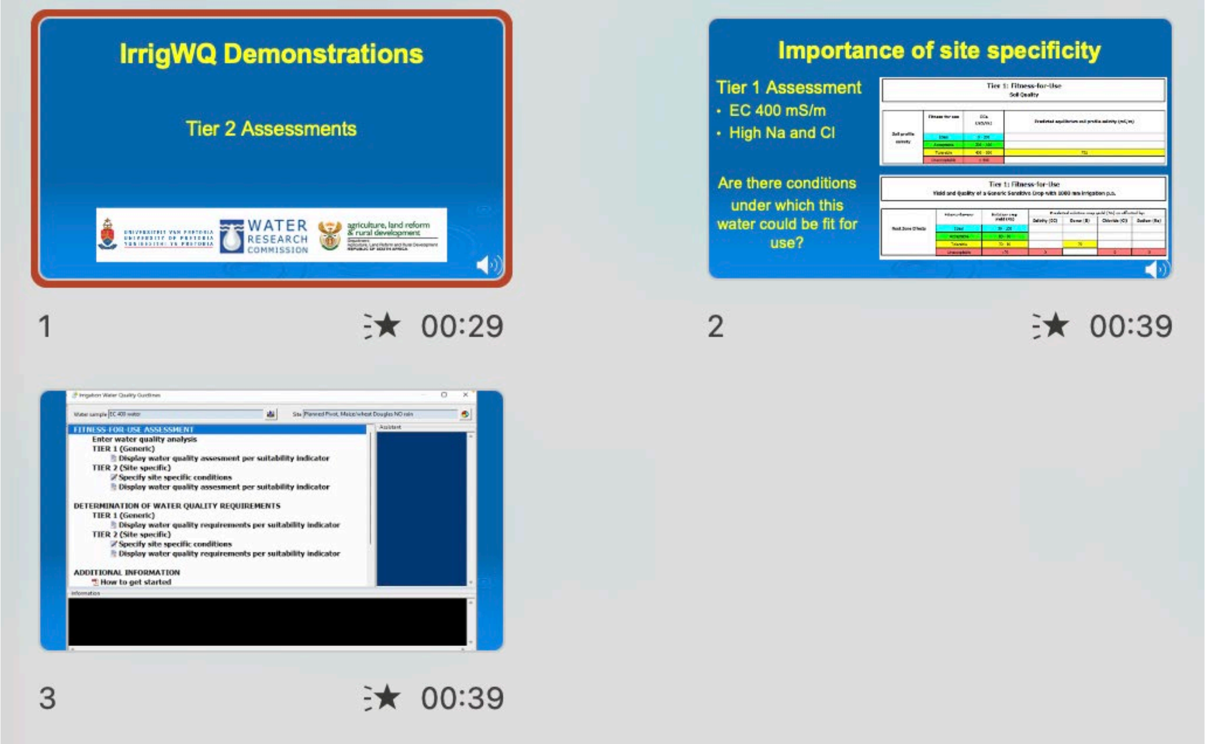
Water sample: EC 400 water

Site: Planned Pivot, Maize/wheat Douglas NO rain

FITNESS-FOR-USE ASSESSMENT
- Enter water quality analysis
- TIER 1 (Generic)
  - Display water quality assesment per suitability indicator
- TIER 2 (Site specific)
  - Specify site specific conditions
  - Display water quality assesment per suitability indicator

DETERMINATION OF WATER QUALITY REQUIREMENTS
- TIER 1 (Generic)
  - Display water quality requirements per suitability indicator
- TIER 2 (Site specific)
  - Specify site specific conditions
  - Display water quality requirements per suitability indicator

ADDITIONAL INFORMATION
- How to get started



IrrigWQ Demonstrations

Tier 2 Assessments

1 ★ 00:29

Importance of site specificity

Tier 1 Assessment
- EC 400 mS/m
- High Na and Cl

Are there conditions under which this water could be fit for use?

2 ★ 00:39

3 ★ 00:39

SAMPLE OF THE “TECHNICAL TALKS” THEME

IrrigWQ Technical Talks

Soil Profile Salinity
(as indicator of soil quality)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

WATER
RESEARCH
COMMISSION

agriculture, land reform
& rural development
Department:
Agriculture, Land Reform and Rural Development
REPUBLIC OF SOUTH AFRICA

IrrigWQ

Soil Profile Salinity
(as indicator of soil quality)

1

IrrigWQ

Assess the effect of irrigation water on

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

2

IrrigWQ

Assess the effect of irrigation water on

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

3

IrrigWQ

Assess the effect of irrigation water on

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

4

IrrigWQ

Assess the effect of irrigation water on

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

5

EC of soil saturation extract (mS/m)	Fitness for (effect) on crop production
<200	Salinity effects mostly negligible
200 - 400	Yields of very sensitive crops may be restricted
400 - 800	Yields of many crops restricted
800 - 1600	Only tolerant crops yield satisfactory
>1600	Only very tolerant crops yield satisfactory

6

Measurement of Soil Profile Salinity

1. Saturate a soil sample with distilled water.
2. Extract a watery sample from the soil-water mixture
3. Determine the electrical conductivity of the watery extract and report as ECe (in mS/m)

Soil Profile Salinity

determines which crops can be successfully produced on a specific piece of land

Criteria used to determine FFU categories for soil profile salinity

Fitness-for-Use	EC of soil saturation extract (mS/m)
Ideal	<200
Acceptable	200 – 400
Tolerable	400 – 800
Unacceptable	>800