

# Groundwater quality assessment in the Ngaka Modiri Molema District using the Water Quality Index

**CM van der Merwe**



**[orcid.org/0000-0002-0244-038X](https://orcid.org/0000-0002-0244-038X)**

Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering Chemical Engineering* at the North-West University

Supervisor: Mr. C.J. Schabort  
Co-supervisor: Prof Q.P. Campbell

Graduation: May 2021  
Student number: 26989972

## **ACKNOWLEDGEMENTS**

I would like to express my great appreciation to the following people, who assisted and contributed towards this study. Your guidance and support have been of great value, more than words can explain, and none of this would have been possible if it has not been for all of you.

Research related acknowledgements:

- Mr. Corneels Schabort for your guidance, encouragement, and support before and during this study. It has been a great honour to be under your leadership and supervision. Your input during this thesis was invaluable and I am truly grateful for it.
- Prof. Quentin Campbell for your role as co-supervisor for this study. I greatly appreciate your time and assistance in the development of this dissertation. Your guidance has truly been of great value.
- Dr. Stephan Pretorius for giving me the opportunity to conduct the study with the use of Africa Geo-Environmental Services (Pty) Ltd resources. Without your generous support, this research would not have been possible.
- Nkateko Ndobe for your kind help and assistance during this study. You have played a great role throughout this time and I am truly grateful for your support.
- Shaunelle Pretorius for your assistance with the maps.

Personal acknowledgements:

- Our Heavenly Father for His kindness, grace, and peace that surpasses all understanding. He has strengthened and led me throughout this study and I can confidently say that without Him, I would neither have had this opportunity, nor the strength an ability to complete it. All the glory, praise and honour to Him.
- My father, Jean, and mother, Liane, for your support, encouragement and endless love. I have learned a great deal about perseverance and believing in myself from you. And I am so grateful to have you as my parents and would not be the woman I am today if it was not for both of you.

- My brother (Carl), sisters (Kirstin and Anl  h) and sweet grannies (Anne and Evie) for all your words of encouragement, prayers and support during this study.
- My church community and all my beloved friends. Thank you for all your prayers and words of encouragement.

## ABSTRACT

In the conducted research, the groundwater quality of different boreholes located in the Ngaka Modiri Molema District (NMMD), more specifically Ratlou, Ditsobotla, and Tswaing local municipalities (LM), for drinking, livestock, and irrigation purposes were assessed. The obtained water quality results were also presented in straightforward and understandable form, along with a developed water purification technology decision tree in order to assist policymakers and/or concerned citizens with the evaluation and improvement of the water sources. It was found that the NMMD not only lacks a water management plan but also that irregular and ineffective groundwater monitoring is taking place. Furthermore, concerns were raised that the obtained results from the analysis would be rich in data, but poor in information for the necessary personnel. The objectives were therefore to not only effectively assess the groundwater quality of the specific area, but to also present the data in an easily understandable form for the necessary personnel by using the Water Quality Index (WQI) model.

The WQI model used in the research was constructed by integrating the variable weights of several WQI studies. A final water quality class classification, ranging between Class I and V, was allocated to the individual water sources. 90 boreholes were evaluated, where the assessed parameters for drinking purposes include, *Escherichia coli* (*E. coli*), *Faecal coliform*, total dissolved solids (TDS), electrical conductivity (EC), pH, nitrate, sulfate, fluoride, chloride, manganese, iron, zinc, and copper. For livestock purposes TDS, EC, pH, nitrate, sulfate, chloride, calcium, magnesium, sodium, and copper were evaluated and for irrigation purposes, TDS, EC, pH, chloride, permeability index (PI), Kelly ratio (KR), sodium percentage (%Na), sodium adsorption rate (SAR), magnesium adsorption rate (MAR), and potential salinity (PS) were evaluated.

For drinking purposes, the majority of the boreholes shifted from Class I to the unacceptable Class V when microbial contaminants were included in the evaluation, placing 51.1% of the boreholes in Class V. For livestock purposes, the majority of the boreholes (90%) had a WQI rating of Class I. The majority of the boreholes (66.7%) were classified as acceptable for irrigation purposes, with 27.8% and 38.9 of them classified as Class I and Class II, respectively. Further investigation was conducted on the investigated parameters that were proven to have elevated levels. It was found that nitrate, manganese, fluoride, EC, *Faecal coliform*, and *E. coli* had levels too high for drinking purposes. Only EC has proven to be a problem for livestock purposes and the levels of EC, calcium, magnesium, nitrate, sulfate, and chloride were too high for irrigation purposes. Water purification technologies were

recommended for each of the investigated boreholes in order to bring the water quality to the recommended standard.

It was therefore concluded that the majority of the boreholes in the NMMD area had a water quality that is unsuitable for drinking purposes, however suitable for both livestock and irrigation purposes. Water management strategies, as well as effective and regular groundwater monitoring, are of utmost importance, especially for drinking purposes in the NMMD area.

**Keywords:** *Groundwater quality; Water Quality Index (WQI); Ngaka Modiri Molema District (NMMD); Water treatment; Water purification technology decision tree; Drinking; Irrigation; Livestock.*

# TABLE OF CONTENTS

|                                                     |      |
|-----------------------------------------------------|------|
| Declaration.....                                    | ii   |
| Acknowledgements.....                               | iii  |
| Abstract.....                                       | v    |
| Table of contents .....                             | vii  |
| List of figures .....                               | x    |
| List of tables.....                                 | xiv  |
| List of symbols .....                               | xvii |
| Chapter 1: Introduction.....                        | 1    |
| 1.1    Project background and motivation .....      | 1    |
| 1.2    Problem statement.....                       | 3    |
| 1.3    Project Aim and Objectives .....             | 4    |
| 1.3.1    Aim .....                                  | 4    |
| 1.3.2    Objectives .....                           | 4    |
| 1.4    Project scope and Research Methodology ..... | 5    |
| 1.5    Report outline .....                         | 7    |
| Chapter 2: Literature study.....                    | 9    |
| 2.1    Water availability as a human right .....    | 9    |
| 2.2    Water resources .....                        | 9    |
| 2.2.1    Management of water resources.....         | 10   |
| 2.2.2    Groundwater .....                          | 11   |
| 2.3    Water pollution.....                         | 13   |
| 2.3.1    Causes of water pollution.....             | 13   |
| 2.3.2    Effect of polluted water .....             | 14   |
| 2.4    Water quality.....                           | 15   |
| 2.4.1    Water quality index (WQI) .....            | 15   |
| 2.4.2    Water quality parameters .....             | 15   |
| 2.5    Water purification methods .....             | 36   |

|                                         |                                                                                                 |     |
|-----------------------------------------|-------------------------------------------------------------------------------------------------|-----|
| 2.5.1                                   | Chemical oxidation and disinfection .....                                                       | 36  |
| 2.5.2                                   | UV technology .....                                                                             | 39  |
| 2.5.3                                   | Coagulation/Flocculation and Sedimentation .....                                                | 40  |
| 2.5.4                                   | Filtration.....                                                                                 | 41  |
| 2.5.5                                   | Ion exchange .....                                                                              | 50  |
| 2.5.6                                   | pH adjustment.....                                                                              | 52  |
| 2.5.7                                   | A brief overview of the cost and effectiveness of the treatment technologies .                  | 53  |
| 2.5.8                                   | Multistage water treatment systems.....                                                         | 57  |
| Chapter 3: Methodology .....            |                                                                                                 | 59  |
| 3.1                                     | Study Area.....                                                                                 | 59  |
| 3.1.1                                   | Environmental overview.....                                                                     | 60  |
| 3.1.2                                   | Social factors .....                                                                            | 62  |
| 3.2                                     | Data collection .....                                                                           | 65  |
| 3.2.1                                   | Sampling.....                                                                                   | 65  |
| 3.2.2                                   | Laboratory analysis.....                                                                        | 68  |
| 3.3                                     | Data analysis .....                                                                             | 69  |
| 3.3.1                                   | Database .....                                                                                  | 69  |
| 3.3.2                                   | Data manipulation.....                                                                          | 70  |
| Chapter 4: Results and discussion ..... |                                                                                                 | 81  |
| 4.1                                     | Groundwater quality analysis with use of the WQI along with the borehole distribution map ..... | 81  |
| 4.1.1                                   | Drinking purposes.....                                                                          | 81  |
| 4.1.2                                   | Water quality for livestock purposes.....                                                       | 89  |
| 4.1.3                                   | Irrigation purposes .....                                                                       | 94  |
| 4.2                                     | Groundwater quality parameters.....                                                             | 99  |
| 4.2.1                                   | <i>Faecal coliform</i> and <i>E. coli</i> .....                                                 | 103 |
| 4.2.2                                   | Electrical conductivity.....                                                                    | 107 |
| 4.2.3                                   | pH.....                                                                                         | 110 |
| 4.2.4                                   | Nitrate concentration.....                                                                      | 111 |

|        |                                                                  |     |
|--------|------------------------------------------------------------------|-----|
| 4.2.5  | Fluoride concentration .....                                     | 114 |
| 4.2.6  | Iron concentration .....                                         | 115 |
| 4.2.7  | Manganese concentration.....                                     | 116 |
| 4.2.8  | Permeability Index .....                                         | 118 |
| 4.2.9  | Kelly ratio, percentage sodium, and sodium adsorption rate ..... | 120 |
| 4.2.10 | Potential Salinity .....                                         | 124 |
| 4.2.11 | Overall .....                                                    | 127 |
| 4.3    | Water purification technology decision tree .....                | 129 |
| 5      | Chapter 5: Conclusion and recommendations.....                   | 132 |
| 5.1    | Conclusion .....                                                 | 132 |
| 5.2    | Recommendations .....                                            | 133 |
| 5.2.1  | Future studies for the specific area .....                       | 133 |
| 5.2.2  | Future studies in general .....                                  | 135 |
|        | Reference list.....                                              | 136 |
|        | Appendix A: Raw data.....                                        | 152 |
|        | Appendix B: WQI scores and recommendations .....                 | 160 |

## LIST OF FIGURES

|                                                                                                                                                   |    |
|---------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Figure 1:</b> Project scope. ....                                                                                                              | 5  |
| <b>Figure 2:</b> Overview of the WQI method. ....                                                                                                 | 6  |
| <b>Figure 3:</b> Renewable and non-renewable groundwater sources, with the effect of groundwater depletion (Bierkens & Wada, 2019). ....          | 12 |
| <b>Figure 4:</b> Various parameters' percentage contribution to the electrical conductivity (Shrestha & Basnet, 2018). ....                       | 19 |
| <b>Figure 5:</b> The ozonation process for water treatment (Ahmad & Azam, 2019). ....                                                             | 37 |
| <b>Figure 6:</b> UV light disinfection (Ahmad & Azam, 2019). ....                                                                                 | 40 |
| <b>Figure 7:</b> Schematic representation of the coagulation, flocculation and sedimentation process (Safe Drinking Water Foundation, 2021). .... | 41 |
| <b>Figure 8:</b> Porous carbon particle (Mazille & Spuhler, 2020b). ....                                                                          | 42 |
| <b>Figure 9:</b> Activated carbon filters (Mazille & Spuhler, 2020b). ....                                                                        | 43 |
| <b>Figure 10:</b> Schematic representation of a slow sand filtration process (Bruni & Spuhler, 2020). ....                                        | 44 |
| <b>Figure 11:</b> Large-scale slow sand filtration operation (Bruni & Spuhler, 2020). ....                                                        | 44 |
| <b>Figure 12:</b> Schematic representation of a household slow sand filter system (Medeiros et al., 2020). ....                                   | 45 |
| <b>Figure 13:</b> Schematic representation of a coarse gravel media filtration system (Medeiros et al., 2020). ....                               | 45 |
| <b>Figure 14:</b> Schematic representation of a household multistage filtration system (Medeiros et al., 2020). ....                              | 46 |
| <b>Figure 15:</b> Schematic representation of the reverse osmosis process (Ahmad & Azam, 2019). ....                                              | 48 |
| <b>Figure 16:</b> The pores within an ion exchange resin (Mazille & Spuhler, 2020d). ....                                                         | 50 |
| <b>Figure 17:</b> Schematic representation of the ion exchange reaction (Mazille & Spuhler, 2020d). ....                                          | 51 |
| <b>Figure 18:</b> Ion exchange process for water softening and recharge (Mazille & Spuhler, 2020d). ....                                          | 51 |
| <b>Figure 19:</b> Total production cost as a function of the plant flow rate (Campinas et al., 2021). ....                                        | 54 |
| <b>Figure 20:</b> Ngaka Modiri Molema District Municipality (Ngaka Modiri Molema District Municipality, 2020b). ....                              | 60 |
| <b>Figure 21:</b> Household sanitation of the NMMD and local municipalities within the district municipality in 2016 (Stats SA, 2018). ....       | 64 |

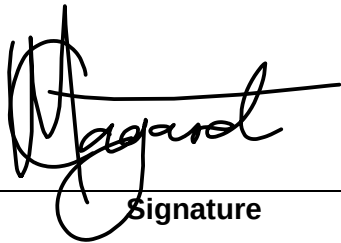
|                                                                                                                                                                                     |     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Figure 22:</b> The percentage of households that have access to a safe drinking water supply in the NMMD area (Stats SA, 2018).....                                              | 64  |
| <b>Figure 23:</b> Boreholes investigated in the NMMD area. ....                                                                                                                     | 67  |
| <b>Figure 24:</b> The drinking water quality statuses of boreholes according to physical and chemical parameters.....                                                               | 82  |
| <b>Figure 25:</b> The water quality statuses of boreholes for drinking purposes according to physical, chemical and microbiological parameters.....                                 | 84  |
| <b>Figure 26:</b> Drinking water quality classification of each borehole located in the Ditsobotla LM. ....                                                                         | 86  |
| <b>Figure 27:</b> Drinking water quality classification of each borehole located in the Ratlou LM.                                                                                  | 87  |
| <b>Figure 28:</b> Drinking water quality classification of each borehole located in the Tswaing LM. ....                                                                            | 88  |
| <b>Figure 29:</b> Livestock water quality statuses of boreholes according to the WQI.....                                                                                           | 89  |
| <b>Figure 30:</b> Livestock water quality classification of each borehole located in the Ditsobotla LM. ....                                                                        | 91  |
| <b>Figure 31:</b> Livestock water quality classification of each borehole located in the Ratlou LM. ....                                                                            | 92  |
| <b>Figure 32:</b> Livestock water quality classification of each borehole located in the Tswaing LM. ....                                                                           | 93  |
| <b>Figure 33:</b> The irrigation water quality statuses of boreholes according to the WQI model.                                                                                    | 94  |
| <b>Figure 34:</b> Irrigation water quality classification of each borehole located in the Ditsobotla LM. ....                                                                       | 96  |
| <b>Figure 35:</b> Irrigation water quality classification of each borehole located in the Ratlou LM.                                                                                | 97  |
| <b>Figure 36:</b> Irrigation water quality classification of each borehole located in the Tswaing LM. ....                                                                          | 98  |
| <b>Figure 37:</b> The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific <i>Faecal coliform</i> count range for drinking purposes. .... | 103 |
| <b>Figure 38:</b> The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific <i>E. coli</i> count range for drinking purposes.....          | 104 |
| <b>Figure 39:</b> The number of investigated boreholes located in the Ratlou LM area that fell within a specific <i>Faecal coliform</i> count range for drinking purposes. ....     | 104 |
| <b>Figure 40:</b> The number of investigated boreholes located in the Ratlou LM area that fell within a specific <i>E. coli</i> count range for drinking purposes.....              | 105 |
| <b>Figure 41:</b> The number of investigated boreholes located in the Tswaing LM area that fell within a specific <i>Faecal coliform</i> count range for drinking purposes. ....    | 105 |

|                                                                                                                                                                                     |     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Figure 42:</b> The number of investigated boreholes located in the Tswaing LM area that fell within a specific <i>E. coli</i> count range for drinking purposes.....             | 106 |
| <b>Figure 43:</b> The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific EC range for drinking, livestock and irrigation purposes. .... | 108 |
| <b>Figure 44:</b> The number of investigated boreholes located in the Tswaing LM area that fell within a specific EC range for drinking, livestock and irrigation purposes. ....    | 109 |
| <b>Figure 45:</b> The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific nitrate concentration range for drinking purposes. ....        | 112 |
| <b>Figure 46:</b> The number of investigated boreholes located in the Ratlou LM area that fell within a specific nitrate concentration range for drinking purposes. ....            | 112 |
| <b>Figure 47:</b> The number of investigated boreholes located in the Tswaing LM area that fell within a specific nitrate concentration range for drinking purposes. ....           | 113 |
| <b>Figure 48:</b> The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific fluoride concentration range for drinking purposes. ....       | 114 |
| <b>Figure 49:</b> The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific manganese concentration range for drinking purposes. ....      | 117 |
| <b>Figure 50:</b> The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific manganese concentration range for drinking purposes. ....      | 117 |
| <b>Figure 51:</b> The number of investigated boreholes located in the Tswaing LM area that fell within a specific manganese concentration range for drinking purposes. ....         | 118 |
| <b>Figure 52:</b> The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific PI range for irrigation purposes. ....                         | 119 |
| <b>Figure 53:</b> The number of investigated boreholes located in the Ratlou LM area that fell within a specific KR range for irrigation purposes. ....                             | 121 |
| <b>Figure 54:</b> The number of investigated boreholes located in the Ratlou LM area that fell within a specific %Na range for irrigation purposes. ....                            | 122 |
| <b>Figure 55:</b> The number of investigated boreholes located in the Ratlou LM area that fell within a specific SAR range for irrigation purposes. ....                            | 123 |
| <b>Figure 56:</b> The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific PS range for irrigation purposes. ....                         | 125 |
| <b>Figure 57:</b> The number of investigated boreholes located in the Ratlou LM area that fell within a specific PS range for irrigation purposes. ....                             | 125 |
| <b>Figure 58:</b> The number of investigated boreholes located in the Tswaing LM area that fell within a specific PS range for irrigation purposes. ....                            | 126 |
| <b>Figure 59:</b> Overall status of the water quality parameters for the NMMD area for drinking purposes. ....                                                                      | 127 |

|                                                                                                                 |     |
|-----------------------------------------------------------------------------------------------------------------|-----|
| <b>Figure 60:</b> Overall status of the water quality parameters for the NMMD area for livestock purposes.....  | 128 |
| <b>Figure 61:</b> Overall status of the water quality parameters for the NMMD area for irrigation purposes..... | 129 |
| <b>Figure 62:</b> Water purification technology decision tree.....                                              | 130 |

## DECLARATION

I, Caitlin M. van der Merwe, hereby declare that the thesis entitled: **“Groundwater quality assessment in the Ngaka Modiri Molema District using the Water Quality Index”** is my own work and that it has not previously been submitted for any degree at the NWU or any other university. Furthermore, all external sources (e.g. journal articles, books, and reports) were referenced accordingly.



---

Signature

24/11/2021

---

Date

## LIST OF TABLES

|                                                                                                                                  |    |
|----------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Table 1:</b> Summary of the microbial contaminant limits for drinking purposes (SANS, 2015).<br>.....                         | 18 |
| <b>Table 2:</b> Summary of the EC limits for drinking, livestock and irrigation use. ....                                        | 20 |
| <b>Table 3:</b> Summary of the TDS limits for drinking, livestock and irrigation use. ....                                       | 21 |
| <b>Table 4:</b> Summary of the pH limits at 25 °C for drinking, livestock and irrigation use. ....                               | 22 |
| <b>Table 5:</b> Summary of the nitrate concentration limits for drinking, livestock and irrigation use.<br>.....                 | 23 |
| <b>Table 6:</b> Summary of the sulfate concentration limits for drinking, livestock and irrigation use.<br>.....                 | 24 |
| <b>Table 7:</b> Summary of the fluoride concentration limits for drinking, livestock and irrigation use.<br>.....                | 25 |
| <b>Table 8:</b> Summary of the chloride concentration limits for drinking, livestock and irrigation use.<br>.....                | 26 |
| <b>Table 9:</b> Summary of the zinc concentration limits for drinking, livestock and irrigation use.                             | 27 |
| <b>Table 10:</b> Summary of the copper concentration limits for drinking, livestock and irrigation use.<br>.....                 | 27 |
| <b>Table 11:</b> Summary of the iron concentration limits for drinking, livestock and irrigation use.<br>.....                   | 28 |
| <b>Table 12:</b> Summary of the manganese concentration limits for drinking, livestock and irrigation<br>use.....                | 29 |
| <b>Table 13:</b> Summary of the calcium concentration limits for drinking, livestock and irrigation<br>use.....                  | 30 |
| <b>Table 14:</b> Summary of the magnesium concentration limits for drinking, livestock and irrigation<br>use.....                | 31 |
| <b>Table 15:</b> Summary of the sodium concentration limits for drinking, livestock and irrigation<br>use.....                   | 32 |
| <b>Table 16:</b> Summary of the irrigation index limits for irrigation purposes. ....                                            | 35 |
| <b>Table 17:</b> Criteria weight and ranking number of the investigated disinfection technologies<br>(Gelete et al., 2020). .... | 53 |
| <b>Table 18:</b> Total cost of filtration technologies for water purification. ....                                              | 55 |
| <b>Table 19:</b> Water treatment efficiency and CC ranking (Yuan et al., 2019).....                                              | 56 |
| <b>Table 20:</b> Possible water purification treatment trains .....                                                              | 57 |
| <b>Table 21:</b> Water production costs of possible water treatment trains (Jung et al., 2021).....                              | 57 |
| <b>Table 22:</b> Equipment and/or methods for water quality parameter analysis. ....                                             | 68 |

|                                                                                                                                                  |     |
|--------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Table 23:</b> Chromogenic E. coli or coliform and m-FC agar incubation information. ....                                                      | 69  |
| <b>Table 24:</b> The assigned parameter weights from recent studies for drinking purposes. ....                                                  | 72  |
| <b>Table 25:</b> The assigned parameter weights from recent studies for livestock purposes. ....                                                 | 73  |
| <b>Table 26:</b> The assigned parameter weights from recent studies for irrigation purposes. ....                                                | 74  |
| <b>Table 27:</b> The ten studies used to assign parameter weights. ....                                                                          | 75  |
| <b>Table 28:</b> Assigned relative weights and SANS 241-1(2015) drinking water quality standards for the specified parameters.....               | 76  |
| <b>Table 29:</b> Assigned relative weights and water quality standards for the specified parameters for water used for livestock purposes. ....  | 77  |
| <b>Table 30:</b> Assigned relative weights and water quality standards for the specified parameters for water used for irrigation purposes. .... | 78  |
| <b>Table 31:</b> Water quality classification based on the water quality index (WQI).....                                                        | 79  |
| <b>Table 32:</b> Water quality classification.....                                                                                               | 79  |
| <b>Table 33:</b> Water quality status of each parameter for drinking purposes in Ditsobotla, Ratlou and Tswaing LM areas.....                    | 100 |
| <b>Table 34:</b> Water quality status of each parameter for livestock purposes in the Ditsobotla, Ratlou and Tswaing LM areas.....               | 101 |
| <b>Table 35:</b> Water quality status of each parameter for irrigation purposes for Ditsobotla, Ratlou and Tswaing LM areas.....                 | 102 |
| <b>Table 36:</b> Summary of the EC limits for drinking, livestock and irrigation use. ....                                                       | 107 |
| <b>Table 37:</b> The borehole numbers with elevated EC and E. coli levels.....                                                                   | 109 |
| <b>Table 38:</b> Water treatment technology code .....                                                                                           | 131 |
| <b>Table 39:</b> Borehole coordinates of Ditsobotla LM area. ....                                                                                | 152 |
| <b>Table 40:</b> Borehole coordinates of Ratlou LM area.....                                                                                     | 154 |
| <b>Table 41:</b> Borehole coordinates of Tswaing LM area .....                                                                                   | 154 |
| <b>Table 42:</b> Raw data of the measured water quality parameters for the Ditsobotla LM area. ....                                              | 156 |
| <b>Table 43:</b> Raw data of the measured water quality parameters for the Ratlou LM area. ...                                                   | 158 |
| <b>Table 44:</b> Raw data of the measured water quality parameters for the Tswaing LM area.                                                      | 159 |
| <b>Table 45:</b> WQI scores of the investigated boreholes for drinking, livestock, and irrigation purposes for the Ditsobotla LM area. ....      | 160 |
| <b>Table 46:</b> WQI scores of the investigated boreholes for drinking, livestock, and irrigation purposes for the Ratlou LM area.....           | 161 |
| <b>Table 47:</b> WQI scores of the investigated boreholes for drinking, livestock, and irrigation purposes for the Tswaing LM area.....          | 161 |

|                                                                                                                                               |     |
|-----------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Table 48:</b> WQI ratings and water treatment recommendation for drinking, livestock, and irrigation purposes for the Ditsobotla area..... | 162 |
| <b>Table 49:</b> WQI ratings and water treatment recommendations for drinking, livestock, and irrigation purposes for the Ratlou area. ....   | 178 |
| <b>Table 50:</b> WQI ratings and water treatment recommendations for drinking, livestock, and irrigation purposes for the Tswaing area. ....  | 184 |

# LIST OF SYMBOLS

| NOMENCLATURE      |                                  |                      |                                    |
|-------------------|----------------------------------|----------------------|------------------------------------|
| $C_i$             | Measured water quality parameter | $NO_3$               | Nitrate                            |
| $C_{pH}$          | Measured pH value                | RM/m <sup>3</sup>    | Malaysian Ringgit per cubic meter  |
| $Ca$              | Calcium                          | $q$                  | Water quality rating               |
| $Ca^{2+}$         | Calcium ions                     | $S_i$                | Water quality standard             |
| $CaCO_3$          | Calcium carbonate                | $S_{Lower}$          | Lower limit of the pH standard     |
| $Cl$              | Chloride                         | $S_{Upper}$          | Upper limit of the pH standard     |
| $Cl^-$            | Chloride ions                    | $SI_i$               | Sub-index                          |
| $CO_2$            | Carbon dioxide                   | $SO_4$               | Sulfate                            |
| $CO_3^{2-}$       | Carbonate ion                    | $SO_4^{2-}$          | Sulfate ions                       |
| $H^+$             | Hydrogen ions                    | $w_i$                | Variable weight                    |
| $HCO_3^-$         | Bicarbonate ion                  | $W_i$                | Relative weight                    |
| $H_2O$            | Water                            | ZAR/m <sup>3</sup>   | South African rand per cubic meter |
| $K$               | Potassium                        | \$/m <sup>3</sup>    | US dollar per cubic meter          |
| $K^+$             | Potassium ions                   | €/m <sup>3</sup>     | Euro per cubic meter               |
| m <sup>3</sup>    | Cubic meters                     | >                    | Greater than                       |
| $Mg$              | Magnesium                        | <                    | Less than                          |
| $Mg^{2+}$         | Magnesium ions                   | ≥                    | Greater than or equal to           |
| $MgO$             | Magnesium oxide                  | ≤                    | Less than or equal to              |
| m <sup>3</sup> /d | Cubic meter per day              | <b>Greek symbols</b> |                                    |
| mg/L              | Milligrams per litre             | μm                   | Micrometre                         |
| mL                | Millilitres                      | μg/L                 | Micrograms per litre               |
| mm                | Millimetre                       | Σ                    | Sum                                |
| mS/m              | Millisiemens per meter           | Δπ                   | Osmotic pressure                   |
| mS/cm             | Millisiemens per centimeter      | Δp                   | External pressure                  |
| $Na$              | Sodium                           | <b>Subscripts</b>    |                                    |
| $Na^+$            | Sodium ions                      | $i$                  | i-th parameter                     |
| Nm                | Nanometre                        | $n$                  | n-th parameter                     |

---

## ABBREVIATIONS

---

|                |                                                  |
|----------------|--------------------------------------------------|
| ACF            | Activated carbon filters                         |
| AMD            | Acid mine drainage                               |
| AGES           | Africa Geo-Environmental Engineering and Science |
| BOD            | Biological oxygen demand                         |
| CC             | Capital cost                                     |
| CCR            | Complexity and cost ranking                      |
| CD             | Corona discharge                                 |
| CF             | Coagulation and flocculation                     |
| COD            | Chemical oxygen demand                           |
| D1             | UV                                               |
| D2             | Ozone                                            |
| D3             | Chlorine                                         |
| D4             | Chloramine                                       |
| D5             | Chlorine dioxide                                 |
| DBP            | Disinfection by-products                         |
| DWS            | Department of Water and Sanitation               |
| EC             | Electrical conductivity                          |
| <i>E. coli</i> | Escherichia coli                                 |
| F1             | ACF                                              |
| F2             | HSSF                                             |
| F3             | SSF                                              |
| F4             | MF                                               |
| F5             | UF                                               |
| F6             | NF                                               |
| F7             | RO                                               |
| F8             | Electrodialysis                                  |
| GLCZ           | Grootpan/ Lichtenburg/ Grootfontein/ Zeerust     |
| HSSF           | Household slow sand filter                       |
| IX             | Ion exchange                                     |
| KR             | Kelly ratio                                      |
| LM             | Local municipality                               |
| MAR            | Magnesium adsorption rate                        |
| MF             | Microfiltration                                  |
| MOC            | Maintenance and operational cost                 |
| N/A            | Not applicable or not available                  |
| NF             | Nanofiltration                                   |
| NMMD           | Ngaka Modiri Molema District                     |

---

---

## ABBREVIATIONS

---

|      |                                  |
|------|----------------------------------|
| NWSA | National Water Service Act       |
| NWA  | National Water Act               |
| OS   | Operational simplicity           |
| PI   | Permeability index               |
| PRE  | Pathogen removal efficiency      |
| PS   | Potential salinity               |
| R    | Reliability                      |
| RF   | Formation of undesired products  |
| RO   | Reverse osmosis                  |
| SANS | South African National Standards |
| SAR  | Sodium adsorption rate           |
| SF   | Safety risk                      |
| SSF  | Slow sand filtration             |
| TA   | Total alkalinity                 |
| TDS  | Total dissolved solids           |
| TH   | Total hardness                   |
| UF   | Ultrafiltration                  |
| UV   | Ultraviolet                      |
| WSMP | Water Service Master Plan        |
| WQI  | Water Quality Index              |
| %Na  | Sodium percentage                |

---

# CHAPTER 1: INTRODUCTION

Chapter 1 serves as the introductory chapter, wherein the research work for the dissertation is presented. An overview of the research background is given in **Section 1.1**, where the most important facts on this research are mentioned. In **Section 1.2**, the problem statement and research motivation are given, followed by the research aim and objectives in **Section 1.3**. The research scope and methodology are presented in **Section 1.4**, which contains a brief overview of the steps that were followed. **Section 1.5** outlines the dissertation content.

## 1.1 Research background

Water is one of the essential elements to maintain life (Edokpayi *et al.*, 2015; World Health Organization, 2011). Access to safe, sufficient, affordable and physically reachable water, for both domestic and personal use, has been recognised by the UN General Assembly as a human right in 2010 (World Health Organization & United Nations-Water, 2019). Water is not only essential for domestic purposes, but also for agricultural needs, which include irrigation and livestock (Al-Saffawi, Ibn Abubakar, Al-Asaat, *et al.*, 2020). However, due to the increase in the population growth rate in South Africa, which led to the increase in water usage and water pollution, great stress is being exerted on the environment (Banda & Kumarasamy, 2020a; Maphela & Cloete, 2020).

It has been reported that over 2 billion people worldwide did not have access to safely managed services for drinking water in 2017 (World Health Organization & United Nations-Water, 2019). Furthermore, 435 million people used water from unprotected wells and springs, and 144 million people used untreated surface water (World Health Organization, 2019). Concerning South Africa's population, it was recorded in 2018 that 2.7 % relied on local water sources due to the lack of piped water. Of the nine provinces in South Africa, the North West Province is rated 7<sup>th</sup> concerning access to piped water, where a staggering 14.8 % of the people in the North West Province do not have access to it (Stats SA, 2019).

Due to the lack of piped potable water, rural communities are forced to turn to local water sources, which are prone to point and non-point sources of water pollution. These water sources include rainfall harvesting, rivers, springs, ponds and wells. The water obtained from these local water sources are usually used untreated (Edokpayi *et al.*, 2018). Untreated water poses a considerable risk to the health of the consumers (Colvin *et al.*, 2016; Edokpayi *et al.*, 2018; Garg *et al.*, 2018), livestock (Crooks, 2020) and lead to a decrease in crop production (Al-Saffawi, Ibn Abubakar, Abbass, *et al.*, 2020).

Water pollution can be caused by chemical, radiological and microbial contamination, which causes the drinking water supply to be extremely harmful to human health (Colvin *et al.*, 2016). The primary sources of water pollution in South Africa are agriculture, mining, industry and human settlements (Colvin *et al.*, 2016; Evans *et al.*, 2019). It is due to ineffective sewage treatment and poor sanitation services that the water contains microbial pollutants (Colvin *et al.*, 2016; Verlicchi & Grillini, 2020). Furthermore, harmful agricultural runoff, industrial effluents, as well as mining activity lead to chemical contamination (Colvin *et al.*, 2016; Verlicchi & Grillini, 2020).

Groundwater is used as the sole water supply in most rural communities (Colvin *et al.*, 2016) and is regarded as the largest freshwater source in the world (Gao *et al.*, 2020; De Graaf *et al.*, 2019). For the North West Province, more specifically the NMMD area, groundwater is considered an extremely important water resource (Department of Rural Development and Land Reform, 2016), as it is extensively used for domestic purposes in rural communities (Ngaka Modiri Molema District Municipality, 2019). Furthermore, over 64% of the national groundwater is used for irrigation, and livestock farming also rely greatly on it (Du Preez & Van Huyssteen, 2020).

Subsurface and underground water, which is stored in rock pores, soil, aquifers or crevices, are regarded as groundwater. Groundwater can emerge as springs and can also be obtained using either boreholes or wells (Colvin *et al.*, 2016). In South Africa, and particularly in the North West Province, dolomite aquifers are one of the highest yielding aquifers. Dolomite aquifers can be divided into compartments, leading to them being semi-independent aquifers rather than one single unit (Cobbing, 2018).

In the North West Province, anthropogenic, farming, industrial, and mining activities exerts great pressure on groundwater resources, which can lead to the depletion thereof (Ibrahim, 2019; Park & Allaby, 2017). Not only does over-abstraction cause a fall in water tables (Bierkens & Wada, 2019; De Graaf *et al.*, 2019; Park & Allaby, 2017) but it also leads to the deterioration of groundwater quality (Abbasnia *et al.*, 2018; Ibrahim, 2019). The quality of groundwater is the main indication of whether the source is suitable for various uses (Ibrahim, 2019).

Water management strategies are, therefore, of utmost importance for the protection and conservation of the country's water resources (Colvin *et al.*, 2016; Maphela & Cloete, 2020). To ensure good quality water, the local resources need to be managed more effectively (Colvin *et al.*, 2016). Therefore, the assessment and monitoring of groundwater quality play a key role in the safeguarding thereof (Ibrahim, 2019).

Proper water resource management, leading to improved water supplies, not only benefits human health but also contributes to economic growth. It also helps with poverty reduction (World Health Organization, 2011; World Health Organization, 2019). It is, however, important to remember that South Africa has an incredibly diverse natural and socio-economic environment (Colvin *et al.*, 2016). Therefore, there needs to be awareness that more than one model is required to meet the needs of all the users of the country (Colvin *et al.*, 2016).

## **1.2 Problem statement and research motivation**

It has been reported in the 2019/20 Integrated Development Plan that the NMMD area lacks a water management plan. It is further reported that groundwater monitoring is irregular and ineffective, particularly in rural communities. Irregular groundwater monitoring is a significant challenge for the NMMD, as it was reported as a risk in the 2017/2018 annual report for the NMMD (Ngaka Modiri Molema District Municipality, 2018). The North West Provincial Government stated that water quality monitoring should be included in groundwater management plans, as there are various activities that can affect the quality of groundwater (Government, 2017). Irregular and ineffective groundwater monitoring poses a significant risk, as groundwater is a resource that is extensively used. Concerning the Water Service Master Plan (WSMP) for the NMMD, it was reported that some information is outdated, as it is over three years old (Ngaka Modiri Molema District Municipality, 2019).

Due to poor water management and the absence of adequate water treatment technologies for rural communities, the water quality is not up to acceptable standards (Edokpayi *et al.*, 2018). The poor groundwater quality in the NMMD area poses a significant risk to the health of consumers and livestock, as well as a risk to crop production. Citizens and policymakers need to be aware of the groundwater quality status so that they can make the necessary decisions and implement intervention strategies (Olasoji *et al.*, 2019).

Another problem that needs to be addressed is the form in which data is presented. Water quality analysis and monitoring are conducted for the main purpose of presenting necessary data for decision making. Concerns are that some analyses are rich in data, but poor in information (Wanda *et al.*, 2016). Therefore, information needs to be provided in a straightforward and understandable form for the use of policymakers and citizens (Olasoji *et al.*, 2019).

Due to the irregular and ineffective groundwater monitoring taking place in the NMMD area and the available data being outdated, there is a gap in information regarding the suitability of the groundwater quality in the region. Without the needed information on the groundwater

quality in the area, a water management plan along with intervention strategies cannot be developed and implemented. The current research will therefore fill the gap by providing comprehensive information on the current water quality state of the NMMD area, as well as recommended intervention strategies. Furthermore, the obtained information will be provided in such a manner, that it can be used by policy makers and/or concerned citizens and not only water experts.

## **1.3 Research aim and objectives**

### **1.3.1 Aim**

The study aims to assess the groundwater quality of different boreholes located in the NMMD, more specifically the Ratlou, Ditsobotla, and Tswaing LM area, for drinking, livestock, and irrigation purposes. The study further aims to present the groundwater quality data in a straightforward and understandable form, along with the intervention strategies needed for the improvement the water quality. In effect, policymakers will be able to use the data for the development of a water management plan as well as the implementation of needed intervention strategies to improve the groundwater quality. Concerned citizens will also be made aware of the water quality state as well as way to improve it.

### **1.3.2 Objectives**

The objectives of the study include:

1. The evaluation of the groundwater quality of different boreholes located in the NMMD, more specifically the Ratlou, Ditsobotla, and Tswaing LM areas, for drinking, livestock and irrigation purposes. The WQI will be used for the evaluation and classification of the groundwater quality.
2. The in-depth evaluation on the parameters which exceeds the recommended limit for drinking, livestock and irrigation purposes, where the degree of contamination, possible causes and intervention strategies will be discussed.
3. An investigation into possible purification methods/technologies that can be used to improve the groundwater quality of the boreholes.
4. The design of a water treatment technology decision tree, in order for relevant stakeholders, who aren't water experts, to know what intervention strategies is needed for the improvement of a specific water quality parameter that exceeds the limit.

5. Presenting a spatial distribution map, indication the water quality status for drinking, livestock, and irrigation purposes, for the Ditsobotla, Ratlou, and Tswaing LMs.

## 1.4 Research scope and methodology

The scope for the research is presented in Figure 1, where a full explanation follows.

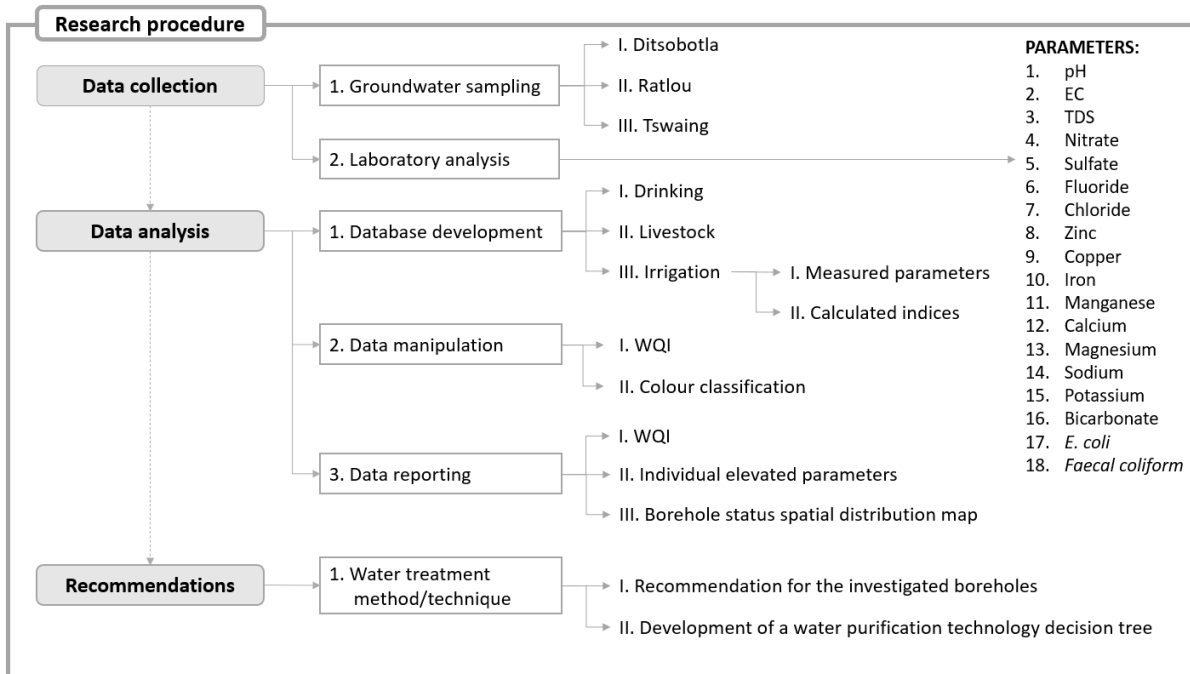


**Figure 1:** Research scope.

The existing raw data was obtained from Africa Geo-Environmental Engineering and Science (AGES) group. Sample collection and laboratory analyses had therefore already been conducted in 2019, before this research. The groundwater quality of 90 boreholes in the NMMD were analysed in this research, where 13, 10, and 10 water quality parameters were considered for drinking, livestock, and irrigation purposes, respectively. The parameters for drinking purposes included *E. coli*, *Faecal coliform*, TDS, EC, pH, nitrate, sulfate, fluoride, chloride, manganese, iron, zinc and copper. For livestock purposes, the 10 parameters included TDS, EC, pH, nitrate, sulfate, chloride, calcium, magnesium, sodium and copper. Lastly, for irrigation purposes, the parameters included TDS, EC, pH, chloride, PI, KR, %Na, SAR, MAR, and PS.

Excel spreadsheet was used for the database development, as well as for data analysis. Data manipulation was done with the use of the WQI to classify the groundwater quality into different water quality classes. This was done to ensure that the data is presented in a simple and understandable form, which can be used by policymakers and/or concerned citizens. An

overview of the WQI method is presented in Figure 2. A further colour classification was conducted, where the water quality was categorised into three groups, namely “Acceptable”, “Marginal” and “Unacceptable”. The three classes were used for borehole classification during mapping.

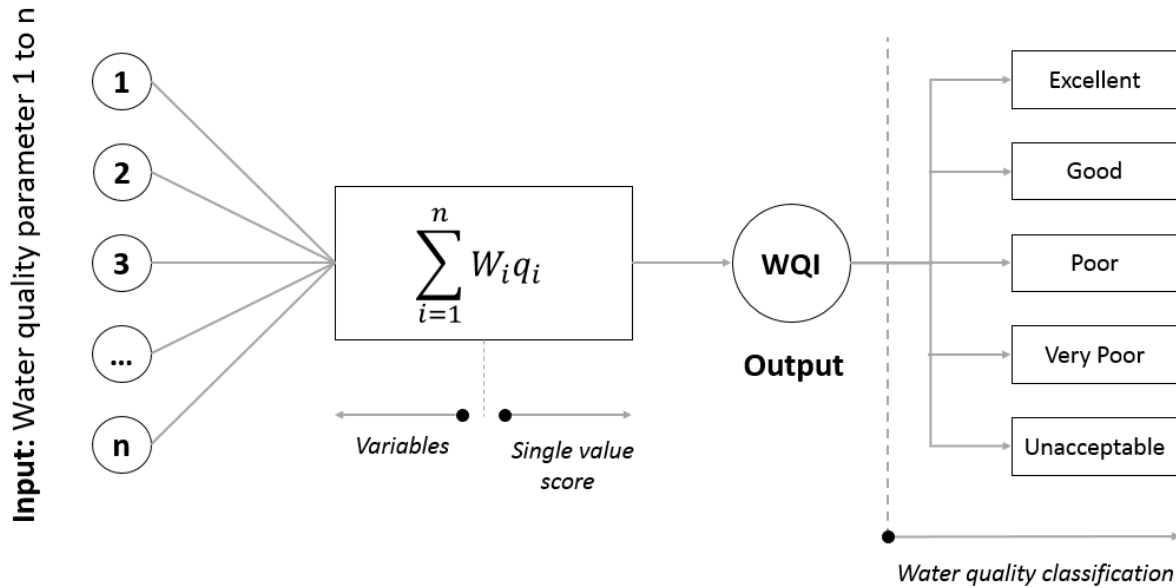


**Figure 2:** Overview of the WQI method.

Data reporting was conducted on the following aspects:

1. Groundwater quality assessment of the investigated boreholes, with the use of the WQI, for drinking, livestock, and irrigation purposes. The assessment included:
  - I. Individual groundwater quality assessments for the Ditsobotla, Ratlou, and Tswaing LMs. The percentage boreholes which fall within a specific WQI group is indicated, along with a spatial distribution map of the boreholes' statuses for the different LM areas and different water uses.
  - II. An overall water quality status for the NMMD area. The percentage of boreholes that fall within a specific WQI group is indicated.
2. An individual assessment of the elevated parameters. The assessment included:
  - I. The degree of contamination for the specific parameters.
  - II. Possible causes for the contamination, as well as recommended water purification technologies which can be followed to improve the water quality for the specific parameter.

3. The recommended water purification technology that is needed to improve the water quality for drinking, livestock, and/or irrigation purposes for each of the investigated boreholes. A water purification technology decision tree is included.

## **1.5 Dissertation outline**

- **Chapter 1: Introduction**

In the first chapter, the research background and motivation are presented, along with the problem statement for the study. The overall aim and objectives, which are presented in two sections; primary and secondary objectives, are given. The research scope, as well as a description for the methodology, is presented.

- **Chapter 2: Literature Review**

In Chapter 2, a literature review was done on groundwater as a water source, the management of water resources as well as factors causing stress on water sources. Furthermore, the causes and effects of water pollution, along with a description of the WQI and important water quality parameters are presented. Different water treatment methods and technologies that can be used to improve the water quality of groundwater were also investigated and are presented in this chapter. An overview on the cost and effectiveness of the different treatment technologies is presented, as well as different multistage water treatment systems which can be considered.

- **Chapter 3: Methodology**

In Chapter 3, an environmental and social overview of the study area is reported. The data collection that was conducted by AGES is presented, along with information on sampling and laboratory analysis. Furthermore, the conducted data analyses are reported in this chapter, where the database development and data manipulation are listed for drinking, livestock, and irrigation purposes. The WQI method is presented in detail, along with all the obtained parameter weights and the water quality classification ranges. Lastly, the water quality classification method is presented in full.

- **Chapter 4: Results and Discussion**

In Chapter 4, the results for the WQI are reported and spatial distribution maps of the investigated boreholes for drinking, livestock, and irrigation purposes are presented. The map

includes the current water quality status (acceptable/marginal/unacceptable) of the boreholes. The investigation on the elevated parameters is also presented, where the degree of contamination as well as possible causes and recommended water treatment technologies for the specific parameter, are given. Lastly, the recommended water treatment technology for each borehole, which is required to improve the water quality for drinking, livestock, and irrigation purposes, is presented along with a water purification technology decision tree.

- **Chapter 5: Conclusion and Recommendations**

In Chapter 5, a summary of the obtained results is presented. Conclusions were drawn concerning the specific objectives. Lastly, suggestions for future studies and analysis are also included in the chapter.

- **References**

All the references that were cited in all five chapters are listed here.

- **Appendices**

The following section includes three appendices. In Appendix A the raw data is presented. The WQI scores and recommendations to improve that water quality is presents in Appendix B. The ethics approval letter for the study is presented in Appendix C.

## CHAPTER 2: LITERATURE STUDY

The following chapter encloses a literature review. In **Section 2.1** and **Section 2.2**, water availability as a human right and a study on water resources are presented, respectively. The causes, as well as the effect of water pollution, are presented in **Section 2.3**. **Section 2.4** focuses on water quality classification, as well as important water quality parameters for drinking, livestock and irrigation purposes. Water treatment technologies are considered in **Section 2.5**, along with an overview of the cost and effectiveness of the treatment technologies. Possible combinations for multistage water treatment system are also investigated in the section. Lastly, in **Section 2.6** a critical summary is provided on the conducted literature study.

### 2.1 Water availability as a human right

Access to water, both for domestic and personal use, has been recognised by the UN General Assembly as a human right in 2010 (World Health Organization & United Nations-Water, 2019). Human rights state that this water should be safe, acceptable, sufficient, affordable and physically reachable for the users (United Nations General Assembly, 2016).

The South African Water Services Act 108 of 1997 has been enacted by Parliament to put this right into action. This Act provides the right to the basic supply of water and sanitation services to all people and recognises the necessity to ensure a safe environment and a sufficient supply of water (SAHRC, 2018).

It is therefore clear that every person is a right-holder and that the Government is the duty-bearer, who needs to provide these services (United Nations General Assembly, 2016). South Africa is however known as a water-scarce, semi-arid country, where the limited water resources have proven to be a challenge (Colvin *et al.*, 2016; Edokpayi *et al.*, 2018; Maphela & Cloete, 2020; Du Preez & Van Huyssteen, 2020).

### 2.2 Water resources

Water resources in South Africa include surface and groundwater sources (Colvin *et al.*, 2016). Rivers, lakes and ponds are classified as surface water and are mostly used as water supply for urban areas (Colvin *et al.*, 2016; Van der Meulen *et al.*, 2020). Subsurface water and underground water are classified as groundwater (Colvin *et al.*, 2016), which is used as the sole water supply in most rural communities (Colvin *et al.*, 2016; Mathivha *et al.*, 2021).

However, due to the absence of adequate water systems, people in rural communities are forced to turn to any available local water sources, which may also include untreated surface water (Edokpayi *et al.*, 2018).

The water security of South Africa is dependent on the sustainability of the water resources (Colvin *et al.*, 2016; World Bank, 2017). It is therefore of utmost importance that the natural water capital is protected, maintained, restored and well managed (Colvin *et al.*, 2016; Maphela & Cloete, 2020).

### **2.2.1 Management of water resources**

Not only has the water demand been difficult to meet due to the high population growth rate, but the water quality has been negatively affected by it (Banda & Kumarasamy, 2020a; Ibrahim, 2019; Maphela & Cloete, 2020). The increase in population has led to the increase in industrialisation (Al-Assaf *et al.*, 2020; Banda & Kumarasamy, 2020a; Ibrahim, 2019), urbanisation as well as an increase in agricultural production (Al-Assaf *et al.*, 2020; Banda & Kumarasamy, 2020a). Water management strategies are, therefore, of utmost importance, for the protection and conservation of the country's water resources (Colvin *et al.*, 2016; Maphela & Cloete, 2020).

South Africa's water is governed by means of the National Water Act (NWA) of 1998, as well as the National Water Service Act (NWSA) of 1997. The NWA originated from the principle that the country's water should be managed under consistent rules, as it forms part of an interdependent water cycle (Colvin *et al.*, 2016). Therefore, management strategies need to be put into place to protect the water resources for long-term security (Colvin *et al.*, 2016; Maphela & Cloete, 2020). Protection is needed against pollution as well as against stress on water resources, such as the over-abstraction of groundwater. The NWA, contains extensive strategies for the use, conservation, development, control and management of the country's water resources (Colvin *et al.*, 2016). The task of managing and planning the water infrastructure system has been allocated to the Department of Water and Sanitation (DWS). Due to the partnership with private water companies, the number of institutional contributors responsible for water provision, management, treatment, and distribution has increased. In effect, great confusion has arisen regarding accountability, jurisdiction, and responsibility for water management (Du Preez & Van Huyssteen, 2020).

Furthermore, even though South Africa's legislation identifies the importance of the country's water cycle and the basic human right to safe and sufficient water (Colvin *et al.*, 2016), the implementation thereof is still not done adequately (Maphela & Cloete, 2020). There have

been cases reported where the municipalities either ineffectively implemented the NWA (Maphela & Cloete, 2020) or where some municipalities lack water managements plans (Ngaka Modiri Molema District Municipality, 2019). However, even though municipalities are responsible for the effective implementation of the NWA, citizens need to realise that they too play a key role in the conservation of water resources. It has been reported that some citizens did not follow sustainable water consumption procedures, but were set in old patterns that did not adhere to the guidelines set by the municipality (Maphela & Cloete, 2020).

Groundwater has become a key water resource in many countries (Ibrahim, 2019) and is regarded as the largest freshwater source in the world (Gao *et al.*, 2020; De Graaf *et al.*, 2019). Groundwater management (Alaviani *et al.*, 2018; Ibrahim, 2019), along with the assessment and monitoring of groundwater quality, plays a key role in the safeguarding of this water resource (Ibrahim, 2019).

### 2.2.2 Groundwater

Groundwater can be stored in either rock pores, soil, aquifers or crevices and can emerge as springs (Bierkens & Wada, 2019; Colvin *et al.*, 2016), lakes, and swamps (Bierkens & Wada, 2019). To obtain the groundwater, boreholes and wells are used (Colvin *et al.*, 2016). In South Africa, and particularly in the North West Province, dolomite aquifers are one of the highest yielding aquifers. Dolomite aquifers can be divided into compartments, leading to it being semi-independent aquifers, rather than single units (Cobbing, 2018).

Groundwater can be classified as either renewable or non-renewable, which is defined by the mean renewal time. The mean renewal time is determined by the use of Equation 1 (Bierkens & Wada, 2019).

$$\text{Mean renewal time} = \frac{\text{Groundwater stock volume}}{\text{Mean recharge rate}} \quad (1)$$

If the groundwater stock is large and/or the recharge rate is low, the groundwater source will have a large mean renewal time. Non-renewable groundwater is classified as having a high mean renewable time that surpasses a human time-scale of 100 years (Bierkens & Wada, 2019). Non-renewable groundwater is most likely to be found in deep, confined aquifers, as well as in aquifers located in arid climates (Elshall *et al.*, 2020). Renewable groundwater will have a small stock volume and/or a high recharge rate (Bierkens & Wada, 2019; Elshall *et al.*, 2020), where the replenishment rate is used to determine the withdrawal rate (Bierkens & Wada, 2019).

Over-abstraction can lead to groundwater depletion, which is caused when the abstraction rate exceeds the groundwater recharge rate of an aquifer (Bierkens & Wada, 2019; Elshall *et al.*, 2020; Ibrahim, 2019; Park & Allaby, 2017). This can cause the water table to fall across a widespread area and also lead to the reduction of water in rivers and lakes (Bierkens & Wada, 2019; De Graaf *et al.*, 2019; Park & Allaby, 2017). In Figure 3, the difference between renewable and non-renewable groundwater sources is presented, along with the effect of groundwater depletion.

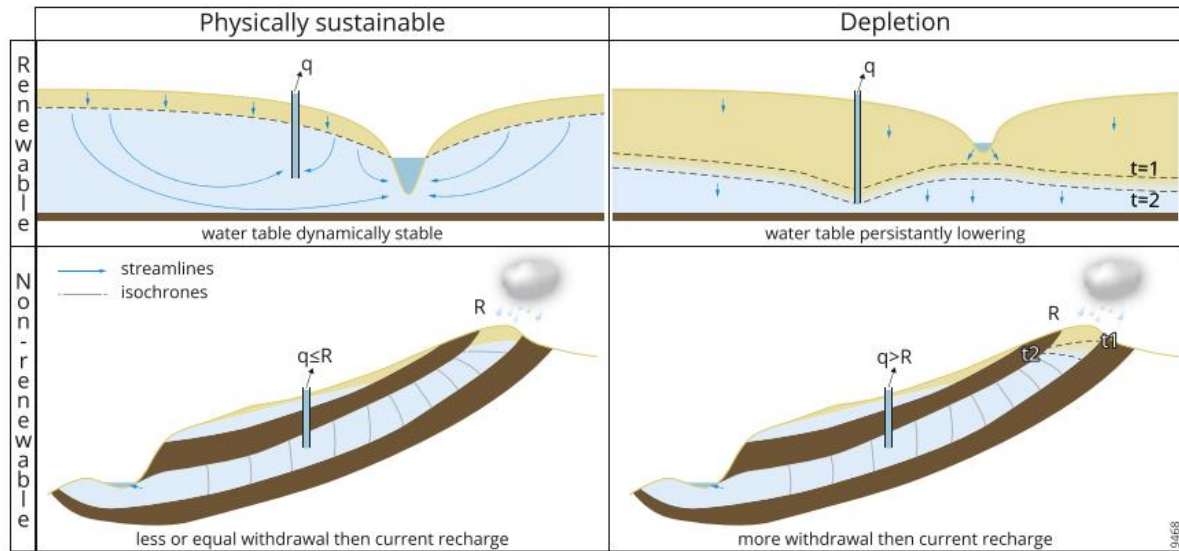


**Figure 3:** Renewable and non-renewable groundwater sources, with the effect of groundwater depletion (Bierkens & Wada, 2019).

The water supply for domestic, agricultural, and environmental use is being threatened by the over-abstraction from dolomite compartments (Cobbing, 2018). Water depletion, which is caused by over-abstraction, along with water quality deterioration, is one of the main causes of stress on water sources, specifically in arid areas (Gao *et al.*, 2020).

#### 2.2.2.1 Stress on groundwater sources

The rapid increase in population and industrialization has exerted great stress on freshwater resources (Ibrahim, 2019). In the North West Province, anthropogenic, farming, industrial, and mining activities are the main sources of pressure on groundwater resources (Ibrahim, 2019; Park & Allaby, 2017). The increase in population has led to an increase in agricultural production (Al-Assaf *et al.*, 2020; Banda & Kumarasamy, 2020a; Bierkens & Wada, 2019; World Bank, 2017). Due to the high irrigation usage in South Africa, the use of groundwater has increased drastically (Bierkens & Wada, 2019; Du Preez & Van Huyssteen, 2020). Over

64% of the national groundwater is used for irrigation. Livestock farming also relies greatly on it (Du Preez & Van Huyssteen, 2020). The groundwater resource depletion rate has therefore increased over the last decade (Bierkens & Wada, 2019) due to the increase in water abstraction for human needs (Bierkens & Wada, 2019; Hanasaki *et al.*, 2018). Not only does over-abstraction cause a fall in water tables (Bierkens & Wada, 2019; De Graaf *et al.*, 2019; Park & Allaby, 2017), but it also causes groundwater quality to deteriorate (Abbasnia *et al.*, 2018; Ibrahim, 2019).

Rainwater is the primary input of South Africa's water sources. In South Africa, the rainfall is, however, highly variable, especially in dry regions, and the amount of rain is only around half as much as the world's average rainfall. The projected national water demand in 2030 is 17 700 million m<sup>3</sup>, due to the increase in industrial development and population growth (Colvin *et al.*, 2016).

Due to groundwater depletion and the deterioration of the water quality, water stress is experienced worldwide (Gao *et al.*, 2020). More so, over-abstraction, along with groundwater pollution, are seen as major problems for certain areas in South Africa (WRC, 2018). Concerns have increased regarding the sustainability of groundwater sources due to the decline in groundwater quality caused by water pollution (Qian *et al.*, 2020).

## **2.3 Water pollution**

Water pollution is a general problem found across the world (Sharma & Bhattacharya, 2017). It has a lethal effect on the environment, aquatic life and on humans, where people living in rural communities are most affected (Colvin *et al.*, 2016; WRC, 2018). Aspects causing water pollution, along with the effect of polluted water on the human health and environment are further investigated.

### **2.3.1 Causes of water pollution**

Water contaminants can be divided into four groups, namely organic, inorganic, radiological, and biological (Sharma & Bhattacharya, 2017). In South Africa, agricultural, mining, industrial and anthropogenic activities are the primary causes of water pollution (Colvin *et al.*, 2016; Evans *et al.*, 2019). According to Colvin *et al.* (2016) and Verlicchi and Grillini (2020), these causes can more specifically be classified as (Colvin *et al.*, 2016; Verlicchi & Grillini, 2020):

1. the leakage of fertilisers, pesticides and sediment in agricultural runoff,
2. acid mine drainage (AMD) caused by mining activities,

3. the release of harmful chemicals due to industrial effluents, and
4. ineffective sewage treatment and poor sanitation services in rural settlements.

Water pollution can also be due to natural contaminants such as magnesium, calcium, chloride, fluoride, nitrate, and iron, which are found in geological materials. The natural contaminants can dissolve into the water as the groundwater moves through the soil and sedimentary rocks. The acceptability of the groundwater quality depends on the concentration of these natural contaminants (Sharma & Bhattacharya, 2017). Natural causes, such as heavy rain and floods, can also lead to an increase in water pollution (Sharma & Bhattacharya, 2017; Verlicchi & Grillini, 2020). With the current city design, where hard surfaces and the channelling of stormwater dominate, rainwater, along with pollutants, flows out of the city into nearby bays or rivers. Through increasing the use of natural surfaces and slowing down the water flow to allow infiltration, local groundwater resources can be recharged and river pollution can be reduced (Colvin *et al.*, 2016).

Furthermore, water pollution sources can be classified into two groups, namely point and non-point sources of pollution. Point pollution refers to water pollution that originates from a single source, for example, oil and chemical spills and wastewater disposal. Non-point source pollution refers to water pollution that is caused by diffuse sources, for example, agricultural and storm water runoff (Denchak, 2018; Falconer *et al.*, 2018).

Sources of water pollution need to be addressed, as water pollution effects not only the health of consumers (Garg *et al.*, 2018), but also the environment (Al-Saffawi, Ibn Abubakar, Abbass, *et al.*, 2020).

### **2.3.2 Effects of polluted water**

Water pollution has a significant effect on the health of humans (Garg *et al.*, 2018) and livestock (Crooks, 2020), and also leads to the decrease in crop production (Al-Saffawi, Ibn Abubakar, Abbass, *et al.*, 2020).

Waterborne diseases, which arise from freshwater pollution, are of the main causes of illness and death in rural communities (Garg *et al.*, 2018), who are most affected due to the lack of adequate water treatment systems and limited health care (Edokpayi *et al.*, 2018). Children and immunocompromised people are the most vulnerable to these diseases (Colvin *et al.*, 2016; Garg *et al.*, 2018). These waterborne diseases include cholera, gastroenteritis, hepatitis, salmonellosis and more (Colvin *et al.*, 2016).

Due to the rise in groundwater pollution, the characterisation and assessment of groundwater quality parameters are essential (Gao *et al.*, 2020). A clean, safe water supply is not only regarded as a basic human right (World Health Organization & United Nations-Water, 2019) but is also essential for sustainable social and human development (Gao *et al.*, 2020).

## **2.4 Water quality**

### **2.4.1 Water quality index**

The main reason for water quality analysis and monitoring is to present necessary data for decision making. There are, however, concerns that these analyses are rich in data, but poor in information (Wanda *et al.*, 2016). It is therefore important to provide the information in a simple, understandable form to be used by people who are not water specialists, like policymakers and citizens (Olasoji *et al.*, 2019).

The WQI is a scientifically-based communication model (Banda & Kumarasamy, 2020b), used to convert complex, multi-variable data into a single score (Banda & Kumarasamy, 2020b; Khanoranga, 2019; Masoud & Ali, 2020; Olasoji *et al.*, 2019). This score is used to give an overall description of the particular water source's water quality (Al-Assaf *et al.*, 2020; Banda & Kumarasamy, 2020b; Khanoranga, 2019; Saikrishna *et al.*, 2020). The level of contamination is measured to determine whether water resource restoration is required and to which degree (Banda & Kumarasamy, 2020a). The WQI is therefore an effective tool which is used as a rating scale assessment for the evaluation of water quality (Khanoranga, 2019; Saikrishna *et al.*, 2020).

The aim of the WQI is not to replace detailed water quality analyses (Banda & Kumarasamy, 2020b), but rather to obtain an overall understanding of the water quality of water resources (Banda & Kumarasamy, 2020b; Khanoranga, 2019; Olasoji *et al.*, 2019).

The WQI was initially proposed by Horton in 1965 and has since been applied worldwide by numerous researchers for water quality analysis (Gaikwad *et al.*, 2020). It is a weighted sum method, which consists of water quality parameters, weight coefficients, a water quality rating and a sub-index score. These assigned weights are traditionally chosen by a large number of experts in the field and/or from literature extracts (Banda & Kumarasamy, 2020a).

## **2.4.2 Water quality parameters**

For the evaluation of water quality, different aspects need to be considered regarding the suitability of the water for livestock, irrigation, and drinking purposes.

For livestock watering, the evaluation of physical and chemical parameters remains of importance, although the considered parameters do vary from those for human consumption. For livestock use, the physical and chemical parameters include TDS, EC, pH, and the concentration of nitrate, sulfate, chloride, calcium, magnesium, sodium and copper (Al-Saffawi, Al-Assaf, *et al.*, 2020; Al-Saffawi, Ibn Abubakar, Al-Asaat, *et al.*, 2020; Hussain *et al.*, 2018; Saucedo-Terán *et al.*, 2017).

For the evaluation of water quality for irrigation purposes, the following parameters are of importance, namely TDS (Elangovan & Rani, 2017), EC, pH, chloride (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021), permeability index (PI), Kelly ratio (KR), sodium percentage (%Na), sodium absorption rate (SAR), magnesium adsorption rate (MAR) and potential salinity (PS) (Al-Saffawi *et al.*, 2021; Elangovan & Rani, 2017; Ememu & Nwankwoala, 2018).

Lastly, for the classification of drinking water quality, physical, chemical and microbiological parameters should be measured. The investigated physical and chemical parameters include total dissolved solids (TDS), electrical conductivity (EC), pH, and the concentration of nitrate, sulfate, fluoride, chloride, manganese, iron, zinc and copper. The microbiological contaminants include *E. coli* and *Faecal coliform* (Enitan-Folami *et al.*, 2019; SANS, 2015; World Health Organization, 2019). The SANS 241-1(2015) drinking water standards were used for the classification.

### **2.4.2.1 Definitions for drinking water**

For the measured water quality parameters used to classify water for drinking purposes, the following definitions are of importance for the different risks involved, according to the SANS 241-1(2015) drinking water standards:

#### **Aesthetic**

Water quality properties that will negatively affect the colour, taste and odour of the water, but will not cause any unacceptable health risks when the concentration exceeds the specified SANS 241 limits (SANS, 2015).

### **Acute health**

Water quality properties that will cause immediate unacceptable health risks when the concentration exceeds the specified SANS 241 limits (SANS, 2015).

### **Chronic health**

Water quality properties that will cause unacceptable health risks when ingested over an extended period if the concentration exceeds the specified SANS 241 limits (SANS, 2015).

### **Operational**

Water quality properties that are critical for the assessment of the efficiency of the water treatment systems and any risks to infrastructure when the concentration exceeds the specified SANS 241 limits (SANS, 2015).

An investigation was conducted on the evaluated parameters for drinking, livestock, and irrigation purposes, where the recommended limit as well as possible causes for the presence thereof in water are presented.

#### **2.4.2.2 Microbial contaminants**

Microbial contamination is reported to be the most common health risk with regard to drinking water (World Health Organization, 2017). *Faecal coliform* is a specific subgroup of total coliforms, of which *E. coli* is the most common member. Organisms that form part of the *Faecal coliform* group are associated with warm-blooded species' faecal matter. It is therefore an indication of faecal matter contamination (Oram, 2020). Faecal contamination can be caused by domestic sewage, direct waste discharge of animals and agricultural runoff from livestock farms (Dangi *et al.*, 2017; Oram, 2020).

*Faecal coliform* contamination can lead to waterborne diseases such as typhoid fever, hepatitis A, dysentery, bacterial and viral gastroenteritis, as well as ear infection (Dangi *et al.*, 2017; Mahmud *et al.*, 2019; Oram, 2020).

##### **2.4.2.2.1 *Faecal coliform***

*Faecal coliform* are indicator organisms, which indicate whether other pathogens are present. It is impractical to monitor pathogens directly, as the amount thereof is usually very small (Oram, 2020). Bacterial pathogens which fall under *Faecal coliform* include; *Salmonella*, *Shigella*, *Yersinia*, *Vibrio cholera*, *Campylobacter* and *E. coli* (Dangi *et al.*, 2017; Mahmud *et al.*, 2019).

*Faecal coliform* bacteria are (World Health Organization, 2017):

- rod-shaped,
- non-spore forming,
- Gram-negative, and
- can grow with or without oxygen.

*Faecal coliform* are regarded to be a suitable substitute for *E. coli* when tests are conducted to determine whether microbial contaminants are present, as *E. coli* has some limitations (World Health Organization, 2017). To avoid acute health risks, the drinking water should have no traces of *Faecal coliform* per 100 mL (SANS, 2015).

#### 2.4.2.2.2 *Escherichia coli*

*E. coli* is regarded to be an essential water quality parameter, as it is a great indicator organism for faecal contamination (World Health Organization, 2017). However, *E. coli* is only one type of organism found in faecal matter, where it is not as resistant to disinfection as enteric viruses and protozoa are. Therefore, the absence of *E. coli* will not necessarily mean the absence of faecal bacterial (World Health Organization, 2017). For drinking water, there should be no traces of *E. coli* per 100 mL to avoid acute health risks (SANS, 2015; World Health Organization, 2017).

A summary of the microbial contaminant limits is presented in Table 1. It is important that water sources are tested frequently for faecal indicator organisms, as faecal contamination is dependent on local conditions, rainfall and the change in seasons (World Health Organization, 2017).

**Table 1:** Summary of the microbial contaminant limits for drinking purposes (SANS, 2015).

| Microbial contaminant  | Risk         | Limit        |                  |
|------------------------|--------------|--------------|------------------|
|                        |              | Value        | Unit             |
| <i>E. coli</i>         | Acute health | Not detected | Count per 100 mL |
| <i>Faecal coliform</i> | Acute health | Not detected | Count per 100 mL |

#### 2.4.2.3 Electrical conductivity

The ability of water to conduct an electrical charge is measured as EC (Rusydi, 2018). Dissolved salts and inorganic matter produce conductive ions, which make it possible for water

to conduct electrical flow (Fondriest Environmental Inc., 2020a). EC is therefore directly related to the ion concentration present in the water (Rusydi, 2018). Alkalis, carbonates, sulfides as well as chloride compounds are examples of dissolved salts and inorganic compounds (Fondriest Environmental Inc., 2020a).

EC is used to measure the salt level of water. High salt levels can harm both aquatic life and human health. Freshwater usually has a low salt level, with a conductivity ranging between 0 and 150 mS/m (Mary River Catchment Coordinating Committee, 2013). The salt levels in different geographic regions can, however, vary due to the solubility of minerals in that area (Hendrawati *et al.*, 2016).

A sudden change in the EC of water can be an indication of pollution. An increase in EC can be due to sewage leakage and/or agricultural runoff, as it causes an increase in phosphate, nitrate and chloride ion concentrations. A decrease in EC can be caused by the addition of organic compounds, such as an oil spill. Organic compounds do not break down into ions and will therefore cause a decrease in conductivity. Both a sudden increase and decrease in EC can negatively affect the quality of water (Fondriest Environmental Inc., 2020a).

EC has a strong correlation with TDS (Rusydi, 2018; Shrestha & Basnet, 2018), total alkalinity (TA), total hardness (TH) chloride, calcium, sodium, and magnesium, as seen in Figure 4 (Shrestha & Basnet, 2018).

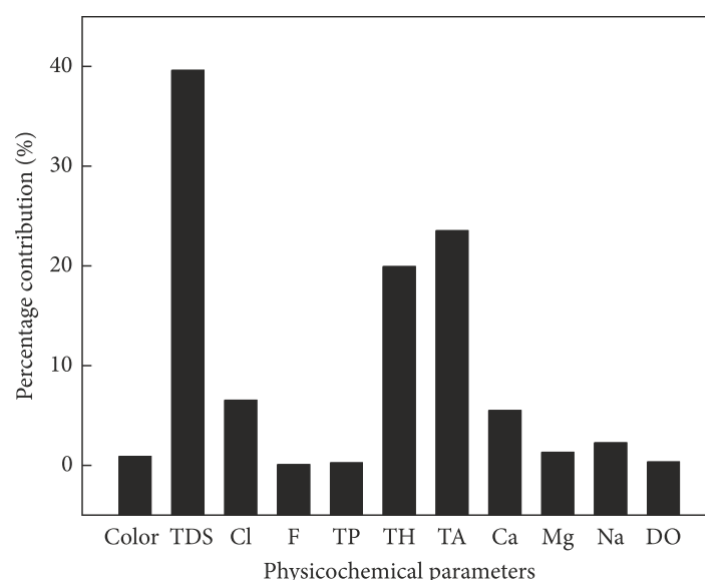


**Figure 4:** Various parameters' percentage contribution to the electrical conductivity (Shrestha & Basnet, 2018).

The EC limits for drinking, livestock and irrigation use are listed in Table 2. For drinking water, the risk involved beyond the limit is aesthetic (SANS, 2015). An EC level beyond the standard limit for livestock can result in health risks, such as weight loss and diarrhoea, as well as a reduction in productivity (Alam *et al.*, 2017; German *et al.*, 2008).

For irrigation, an EC value of 200 mS/m or higher is unsuitable (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Hussain *et al.*, 2018), as it can lead to salt accumulation (Al-Assaf *et al.*, 2020). A high EC value will negatively affect plant growth and soil properties (Al-Saffawi *et al.*, 2021).

**Table 2:** Summary of the EC limits for drinking, livestock and irrigation use.

| USE        | Limit      |      | References                                                                                                 |
|------------|------------|------|------------------------------------------------------------------------------------------------------------|
|            | Value      | Unit |                                                                                                            |
| Drinking   | $\leq 170$ | mS/m | SANS, 2015                                                                                                 |
| Livestock  | $\leq 160$ | mS/m | Al-Saffawi, Al-Assaf, <i>et al.</i> , 2020;<br>Al-Saffawi, Ibn Abubakar, Al-Asaat,<br><i>et al.</i> , 2020 |
| Irrigation | $\leq 200$ | mS/m | Al-Assaf <i>et al.</i> , 2020;<br>Al-Saffawi <i>et al.</i> , 2021;<br>Hussain <i>et al.</i> , 2018         |

#### 2.4.2.4 Total dissolved solids

TDS consist of inorganic salts as well as small amounts of dissolved organic matter (Safe Drinking Water Foundation, 2020a; World Health Organization, 2013). The inorganic salts are mainly magnesium, calcium, potassium, and sodium. However, nitrates, carbonates, bicarbonates, chlorides, and sulfates are also commonly found (Safe Drinking Water Foundation, 2020a).

TDS in water can originate from geogenic sources (Khanoranga, 2019; Safe Drinking Water Foundation, 2020a; World Health Organization, 2013), as well as human activities, such as industrial waste, urban runoff and sewage (Safe Drinking Water Foundation, 2020a). The TDS values of mineral springs and groundwater sources are especially high due to water flowing through rocks with high salt content (Safe Drinking Water Foundation, 2020a; World Health Organization, 2017).

The TDS levels of water are an indication of the hardness of water. Water with high levels of TDS is classified as “hard”, whereas water with low levels of TDS is classified as “soft” (World Health Organization, 2013). The hardness of water mostly affects the taste and can negatively affect appliances and copper plumbing (World Health Organization, 2017). Hard water can cause scaling on appliances and in pipes and very hard water can have a salty bitter taste. People do, however, prefer the taste of hard water, because of the high levels of dissolved minerals. Soft water does not cause any negative effect on appliances and is therefore preferred above hard water, but due to the flat taste thereof, it may be unacceptable (World Health Organization, 2013).

Although the risk beyond the TDS limit for drinking water is aesthetic (SANS, 2015) and can also negatively affect appliances and pipes, high levels thereof can also be an indication of the presence of iron, sulfate, manganese, arsenic, as well as bromide. These chemicals are harmful to human health and can be present in water when it is exposed to human pollution, such as the discharge of wastewater or runoff (Safe Drinking Water Foundation, 2020a).

With regard to livestock, a TDS value higher than the recommended limit can lead to poor feed conversion, as well as loose stool (Meehan *et al.*, 2020). For irrigation, a TDS value beyond the limit can cause salts to accumulate in the crop’s root zone, leading to a reduction in crop yield (Elangovan & Rani, 2017). The TDS limits for drinking, livestock and irrigation purposes are presented in Table 3.

**Table 3:** Summary of the TDS limits for drinking, livestock and irrigation use.

| USE        | Limit   |      | References                                                         |
|------------|---------|------|--------------------------------------------------------------------|
|            | Value   | Unit |                                                                    |
| Drinking   | ≤ 1 200 | mg/L | SANS, 2015                                                         |
| Livestock  | ≤ 3 000 | mg/L | Meehan <i>et al.</i> , 2020;<br>Saucedo-Terán <i>et al.</i> , 2017 |
| Irrigation | ≤ 1 400 | mg/L | Hussain <i>et al.</i> , 2018                                       |

#### 2.4.2.5 pH

The acidity or alkalinity of water is indicated by the pH value. The pH is the measurement of the hydrogen ion concentration of a sample and ranges between 0 and 14. A pH value of 7,

at 25 °C, is classified as neutral. A solution is classified as acidic if the pH value is lower than 7 and basic if the pH value is higher than 7 (Helmenstine, 2019).

The pH of natural water sources can be influenced by various aspects, such as temperature, the carbon dioxide-bicarbonate-carbonate equilibrium, acid rain, and the presence of limestone. Furthermore, a sudden change in pH can be an indication of point source pollution (Fondriest Environmental Inc., 2020b), such as accidental spills or cement mortar pipe linings that have been insufficiently cured (World Health Organization, 2017). A high or low pH value, as well as very low temperatures, can have a negative impact on chlorine disinfection, which is used for the treatment of microbial contaminants (World Health Organization, 2017).

The pH limits for drinking, livestock and irrigation purposes are listed in Table 4. A pH level beyond the reported range for drinking water can result in operational risks (SANS, 2015). Water used for livestock with high alkalinity (high pH value) can result in laxative actions, digestive upset, low feed and/or water intake, as well as low feed conversion (Meehan *et al.*, 2020).

The pH level in water is vital for irrigation, as it affects the carbonate balance, as well as the mineral elements present in water (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021). In acidic water, the absorption of magnesium and calcium ions by the plant's roots is hindered. Although alkaline water is suitable for the absorption of various nutrients, it leads to the accumulation of calcium carbonate (Al-Assaf *et al.*, 2020).

**Table 4:** Summary of the pH limits at 25 °C for drinking, livestock and irrigation use.

| USE        | Limit                         | References                                                                                      |
|------------|-------------------------------|-------------------------------------------------------------------------------------------------|
| Drinking   | $5.0 \leq \text{pH} \leq 9.5$ | SANS, 2015                                                                                      |
| Livestock  | $6.0 \leq \text{pH} \leq 9.0$ | Al-Saffawi, Ibn Abubakar, Al-Asaat, <i>et al.</i> , 2020;<br>Saucedo-Terán <i>et al.</i> , 2017 |
| Irrigation | $6.5 \leq \text{pH} \leq 8.5$ | Al-Assaf <i>et al.</i> , 2020;<br>Al-Saffawi <i>et al.</i> , 2021                               |

#### 2.4.2.6 Nitrate

Nitrate is a common chemical found in the environment. It is generally used in fertilisers for agriculture and is also found in faeces. In ground and surface water, the nitrate levels are usually low, but can be increased as a result of agricultural runoff or leaching and/or faeces contamination from humans and/or animals (Block, 2020; Meehan *et al.*, 2020; SANS, 2015; World Health Organization, 2013). High levels of nitrate in drinking water can lead to nitrate poisoning, which causes methaemoglobinaemia. Bottle-fed infants are vulnerable to nitrate poisoning (SANS, 2015; World Health Organization, 2013), which can lead to death as this causes difficulty in breathing (World Health Organization, 2013). Nitrate is one of the few chemicals which have been shown to cause various health effects due to excessive amounts present in exposed drinking water (World Health Organization, 2017). Livestock is also at risk of nitrate poisoning, as some of the plants used in livestock feed accumulate nitrate (Block, 2020). It is of importance to take into consideration the amount of nitrate present in both water and food supplies for livestock (Block, 2020; Meehan *et al.*, 2020).

The nitrate concentration limits for drinking, livestock and irrigation purposes are listed in Table 5. The risks involved beyond the standard limit for drinking and livestock use are acute health problems (SANS, 2015) and nitrate poisoning, respectively (Block, 2020; Meehan *et al.*, 2020).

**Table 5:** Summary of the nitrate concentration limits for drinking, livestock and irrigation use.

| USE        | Limit      |      | References                                                                                                 |
|------------|------------|------|------------------------------------------------------------------------------------------------------------|
|            | Value      | Unit |                                                                                                            |
| Drinking   | $\leq 11$  | mg/L | SANS, 2015                                                                                                 |
| Livestock  | $\leq 133$ | mg/L | Al-Saffawi, Al-Assaf, <i>et al.</i> , 2020;<br>Al-Saffawi, Ibn Abubakar, Al-Asaat,<br><i>et al.</i> , 2020 |
| Irrigation | N/A        |      |                                                                                                            |

N/A – Not applicable to this study

#### 2.4.2.7 Sulfate

Sulfate is naturally found in various minerals, and high levels thereof are present in groundwater due to natural sources. Other sources of sulfate in water are industrial waste and atmospheric deposits (World Health Organization, 2017).

A relatively high sulfate concentration can affect the taste of drinking water (World Health Organization, 2017). Therefore, to prevent aesthetic risk, the amount of sulfate present in water should be less than 250 mg/L. If the sulfate concentration in drinking water is extremely high, unaccustomed users may experience laxative effects. According to the SANS 241-1 drinking water standards, the sulfate concentration should be less than 500 mg/L to avoid acute health risks (SANS, 2015).

The recommended sulfate intake for livestock varies with the livestock type, as well as size. A sulfate limit of 500 mg/L is recommended for calves and sheep, whereas less than or equal to 1 000 mg/L is acceptable for adult cattle and chicks. Elevated levels of sulfate can cause loose stool, central nervous system symptoms and can lead to brain disorders (Meehan *et al.*, 2020). Sulfate is also found in livestock feed and therefore the sulfate present in both water and feed should be monitored (Meehan *et al.*, 2020). A summary of the lowest sulfate concentration limits for drinking, livestock and irrigation purposes is given listed in Table 6.

**Table 6:** Summary of the sulfate concentration limits for drinking, livestock and irrigation use.

| USE        | Limit |      | References                                                                                                                                 |
|------------|-------|------|--------------------------------------------------------------------------------------------------------------------------------------------|
|            | Value | Unit |                                                                                                                                            |
| Drinking   | ≤ 250 | mg/L | SANS, 2015                                                                                                                                 |
| Livestock  | ≤ 500 | mg/L | Al-Saffawi, Al-Assaf, <i>et al.</i> , 2020;<br>Al-Saffawi, Ibn Abubakar, Al-Asaat,<br><i>et al.</i> , 2020;<br>Meehan <i>et al.</i> , 2020 |
| Irrigation | N/A   |      |                                                                                                                                            |

N/A – Not applicable to this study

#### 2.4.2.8 Fluoride

Fluorine is a commonly found element in the earth's crust and is present in numerous elements in the form of fluoride. High concentrations of fluoride are commonly found in groundwater and is, therefore, a natural contaminant (Brindha & Elango, 2011; NRC, 2006; World Health Organization, 2017). Anthropogenic activities, such as agricultural fertilising or coal combustion can lead to high fluoride concentrations in groundwater sources (Brindha & Elango, 2011). Fluoride can also be found in drinking water as an additive to protect against dental decay (NRC, 2006).

Fluoride is one of the few chemicals that have been shown to cause various health effects due to excessive amounts present in drinking water. It is also one of the few chemicals present in natural water sources, which causes great concern for human health as long-term exposure to high fluoride levels can lead to skeletal fluorosis (World Health Organization, 2017) and/or dental fluorosis (Medical News Today, 2018; World Health Organization, 2017). Fluoride is classified as a developmental neurotoxin and can therefore be hazardous to the development of children (Grandjean & Landrigan, 2015).

The fluoride concentration in water should be less than 1.5 mg/L to avoid chronic health risks (SANS, 2015). Although the guideline value for fluoride is given as 1.5 mg/L, the value in the specific areas should be considered when setting the national standard. An area's climate should be taken into consideration, as this will affect the amount of water intake, as well as the intake from other sources which may contain fluoride (World Health Organization, 2017). A summary of the fluoride concentration limits for drinking, livestock and irrigation purposes is given in Table 7.

**Table 7:** Summary of the fluoride concentration limits for drinking, livestock and irrigation use.

| USE        | Limit |      | References |
|------------|-------|------|------------|
|            | Value | Unit |            |
| Drinking   | ≤ 1.5 | mg/L | SANS, 2015 |
| Livestock  | N/A   |      |            |
| Irrigation | N/A   |      |            |

N/A – Not applicable to this study

#### 2.4.2.9 Chloride

Chlorides are commonly present in nature in the form of salts such as potassium chloride, sodium chloride and calcium chloride (Sharma & Bhattacharya, 2017). The presence of chloride in water can be due to natural sources (Sharma & Bhattacharya, 2017; World Health Organization, 2017), urban runoff, as well as industrial or sewage effluent (World Health Organization, 2017). With regard to natural sources, various rocks are sources of chlorides from which they are leached into the soil and groundwater (Sharma & Bhattacharya, 2017).

There are no health-based guidelines, but there is a taste threshold for chloride in drinking water. A high chloride concentration in drinking water results in a salty taste (World Health Organization, 2017). To prevent this aesthetic risk, the chloride concentration should be less

than 300 mg/L. For livestock, the chloride concentration in water should not exceed 2 000 mg/L (Hussain *et al.*, 2018). Chloride levels beyond the recommended level can lead to weight loss, a decrease in water and food intake (Al-Saffawi, Al-Assaf, *et al.*, 2020; Department of Water Affairs and Forestry, 1996) and lower productivity (Department of Water Affairs and Forestry, 1996).

A high chloride concentration in irrigation water places plants at risk of ion toxicity (Al-Saffawi *et al.*, 2021; Al Sinjari *et al.*, 2019). A chloride concentration beyond the recommended limit will lead to the accumulation of chloride in the leaf tissue and as a result cause wilting (burning) of the plant's leaves (Hussain *et al.*, 2018; Jalil *et al.*, 2020). The plant's growth and production will also be negatively affected. This, however, depends on the plant type and rate of absorption (Al-Saffawi *et al.*, 2021). A summary of the chloride concentration limits for drinking, livestock and irrigation purposes is given in Table 8.

**Table 8:** Summary of the chloride concentration limits for drinking, livestock and irrigation use.

| USE        | Limit   |      | References                   |
|------------|---------|------|------------------------------|
|            | Value   | Unit |                              |
| Drinking   | ≤ 300   | mg/L | SANS, 2015                   |
| Livestock  | ≤ 2 000 | mg/L | Hussain <i>et al.</i> , 2018 |
| Irrigation | ≤ 350   | mg/L | Jalil <i>et al.</i> , 2020   |

#### 2.4.2.10 Zinc

Zinc is an essential element that is found in the form of salts in potable water and food (Hasan *et al.*, 2017; Noulas *et al.*, 2018; World Health Organization, 2017). It is also regarded as a common groundwater contaminant (Noulas *et al.*, 2018; Pullin *et al.*, 2017). The zinc concentration can be increased through acid mine drainage, urban runoff, erosion of zinc-rich soil as well as municipal and industrial waste (Noulas *et al.*, 2018).

There are no health risks related to high zinc concentrations in water, but it can affect the acceptability of drinking water (World Health Organization, 2017). Therefore, to avoid aesthetic risks, the concentration of zinc in drinking water should be less than 5 mg/L (SANS, 2015). When this limit is exceeded, it causes an undesirable taste in drinking water (Noulas *et al.*, 2018). A summary of the zinc concentration limits for drinking, livestock and irrigation purposes is given in Table 9.

**Table 9:** Summary of the zinc concentration limits for drinking, livestock and irrigation use.

| USE        | Limit |      | References |
|------------|-------|------|------------|
|            | Value | Unit |            |
| Drinking   | ≤ 5   | mg/L | SANS, 2015 |
| Livestock  | N/A   |      |            |
| Irrigation | N/A   |      |            |

N/A – Not applicable to this study

#### 2.4.2.11 Copper

Copper, along with zinc, is a common groundwater contaminant (Pullin *et al.*, 2017). Although it is regarded as a contaminant, it remains an essential nutrient to human health. The primary source of copper in drinking water is due to the corrosion of copper pipes. The concentration of copper in drinking water can therefore vary greatly (World Health Organization, 2017).

It has been reported that high levels of copper in drinking water can lead to diarrhoea, vomiting, gastric problems, and headaches. Exposure to high copper concentrations over a long period can also lead to liver damage in humans (Government of Western Australia: Department of Health, 2016). To prevent chronic health risks, the copper concentration in drinking water should be less than 2 mg/L (SANS, 2015). For livestock, an elevated level of copper concentration in water can lead to liver damage (Sheep Connect SA, 2021). The copper concentration limit for livestock is 0.5 mg/L (Meehan *et al.*, 2020; Saucedo-Terán *et al.*, 2017). A summary of the copper concentration limits for drinking, livestock and irrigation purposes is presented in Table 10.

**Table 10:** Summary of the copper concentration limits for drinking, livestock and irrigation use.

| USE        | Limit |      | References                                                          |
|------------|-------|------|---------------------------------------------------------------------|
|            | Value | Unit |                                                                     |
| Drinking   | ≤ 2   | mg/L | SANS, 2015                                                          |
| Livestock  | ≤ 0.5 | mg/L | Meehan <i>et al.</i> , 2020;<br>Saucedo-Terán <i>et al.</i> , 2017; |
| Irrigation | N/A   |      |                                                                     |

N/A – Not applicable to this study

#### 2.4.2.12 Iron

A high iron concentration is found in the earth's crust, which therefore leads to the high concentration thereof in fresh water sources. Ferrous iron can be present in anaerobic groundwater, where exposure to the atmosphere can lead to the oxidization of ferrous iron into ferric iron, which then leads to the water's colour changing to a reddish-brown (World Health Organization, 2017). The amount of iron present in groundwater is dependent on the area's geology (Sharma & Bhattacharya, 2017). Iron can also be present in water due to the corrosion of cast iron or steel pipes (World Health Organization, 2017).

Although an iron concentration of less than 0.3 mg/L does not usually affect the taste (World Health Organization, 2017), the colour and turbidity might be undesirable (Sharma & Bhattacharya, 2017; World Health Organization, 2017). Therefore, the limit for iron in drinking water is less than 0.3 mg/L to avoid aesthetic risks (SANS, 2015).

Iron is an essential nutrient for human health (World Health Organization, 2017). However, high concentrations thereof can lead to various health issues (SANS, 2015). To prevent any chronic health risks, the iron concentration in drinking water should be less than 2 mg/L (SANS, 2015). A summary of the lowest iron concentration limits for drinking, livestock and irrigation purposes are listed in Table 11.

**Table 11:** Summary of the iron concentration limits for drinking, livestock and irrigation use.

| USE        | Limit |      | References |
|------------|-------|------|------------|
|            | Value | Unit |            |
| Drinking   | ≤ 0.3 | mg/L | SANS, 2015 |
| Livestock  | N/A   |      |            |
| Irrigation | N/A   |      |            |

N/A – Not applicable to this study

#### 2.4.2.13 Manganese

Manganese is a metal of which large quantities are found in the earth's crust (World Health Organization, 2017). It naturally occurs in surface water as well as groundwater sources (World Health Organization, 2017; Zhang *et al.*, 2020) and is seen as an essential nutrient for human health (Grandjean & Landrigan, 2015; World Health Organization, 2017).

High levels of manganese in drinking water can lead to an undesired taste as well as the accumulation of deposits in pipes and appliances (World Health Organization, 2017; Zhang *et al.*, 2020). Therefore, the limit for manganese in drinking water is less than 0.1 mg/L to avoid aesthetic risks (SANS, 2015).

Although manganese is an essential nutrient, it is also classified as a neurotoxin, along with fluoride (Grandjean & Landrigan, 2015). High levels thereof can lead to various health issues (Grazuleviciene *et al.*, 2009; Zhang *et al.*, 2020) and can be hazardous for the development of children (Grandjean & Landrigan, 2015). To avoid chronic health risks, the manganese concentration should be less than 0.4 mg/L (SANS, 2015). A summary of the lowest manganese concentration limits for drinking, livestock and irrigation purposes is given in Table 12.

**Table 12:** Summary of the manganese concentration limits for drinking, livestock and irrigation use.

| USE        | Limit |      | References |
|------------|-------|------|------------|
|            | Value | Unit |            |
| Drinking   | ≤ 0.1 | mg/L | SANS, 2015 |
| Livestock  | N/A   |      |            |
| Irrigation | N/A   |      |            |

N/A – Not applicable to this study

#### 2.4.2.14 Calcium

Calcium is a mineral that is naturally found in water sources due to its occurrence in the earth's crust (Lenntech, 2021). The calcium concentration can be up to 100 mg/L in natural water sources (World Health Organization, 2017). Calcium is an essential mineral for the health of all living organisms and is an important element, along with phosphate, for bone formation (Crooks, 2020; Lenntech, 2021a).

Calcium, along with magnesium, affects the hardness of water (Meehan *et al.*, 2020; World Health Organization, 2017). A low calcium concentration will lead to soft water, while a high concentration will cause the water hardness to be high. There are no health-based guidelines for calcium concentration in drinking water, or for the hardness of water (SANS, 2015; World Health Organization, 2017). There is, however, a taste threshold ranging from 100 to 300 mg/L (World Health Organization, 2017).

For livestock, the concentration of calcium present in water should not exceed 1 000 mg/L (Al-Saffawi, Al-Assaf, *et al.*, 2020; Al-Saffawi, Ibn Abubakar, Al-Asaat, *et al.*, 2020; Crooks, 2020; Department of Water Affairs and Forestry, 1996; Meehan *et al.*, 2020; Sheep Connect SA, 2021). Exposure of calcium beyond this limit over a prolonged period can lead to osteopetrosis, degenerative osteoarthritis, and vertebral ankylosis. Excessive calcium in water for livestock is, however, rare (Crooks, 2020). A summary of the calcium concentration limits for drinking, livestock and irrigation purposes is given in Table 13.

**Table 13:** Summary of the calcium concentration limits for drinking, livestock and irrigation use.

| USE        | Limit   |      | References                                                                                                                                                                          |
|------------|---------|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|            | Value   | Unit |                                                                                                                                                                                     |
| Drinking   | N/A     |      |                                                                                                                                                                                     |
| Livestock  | ≤ 1 000 | mg/L | Al-Saffawi, Al-Assaf, <i>et al.</i> , 2020;<br>Al-Saffawi, Ibn Abubakar, Al-Asaat, <i>et al.</i> , 2020;<br>Crooks, 2020;<br>Meehan <i>et al.</i> , 2020;<br>Sheep Connect SA, 2021 |
| Irrigation | N/A     |      |                                                                                                                                                                                     |

N/A – Not applicable to this study

#### 2.4.2.15 Magnesium

Magnesium is also an essential element for the health of living organisms and is naturally present in water due to its presence in some rocks like limestone. Magnesium can also be present in the water due to chemical industries, livestock feed, and fertilisers (Lenntech, 2021b).

The hardness of water is affected by magnesium, along with calcium. With regard to drinking water, there are no health-based guidelines for magnesium or for the hardness of water (SANS, 2015; World Health Organization, 2017).

For livestock, the magnesium concentration limit in water is 500 mg/L (Al-Saffawi, Al-Assaf, *et al.*, 2020; Al-Saffawi, Ibn Abubakar, Al-Asaat, *et al.*, 2020; Department of Water Affairs and

Forestry, 1996), where exceeding this limit can lead to lethargy and laxative effects (Crooks, 2020). Magnesium is, however, a very important nutrient for livestock, as it is an enzyme activator (Al-Saffawi, Al-Assaf, *et al.*, 2020) and a component of skeletal tissue (Crooks, 2020). A summary of the magnesium concentration limits for drinking, livestock and irrigation purposes is given in Table 14.

**Table 14:** Summary of the magnesium concentration limits for drinking, livestock and irrigation use.

| USE         | Limit |      | References                                                                                                                                                           |
|-------------|-------|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|             | Value | Unit |                                                                                                                                                                      |
| Drinking    | N/A   |      |                                                                                                                                                                      |
| Livestock   | ≤ 500 | mg/L | Al-Saffawi, Al-Assaf, <i>et al.</i> , 2020;<br>Al-Saffawi, Ibn Abubakar, Al-Asaat,<br><i>et al.</i> , 2020;<br><br>Department of Water Affairs and<br>Forestry, 1996 |
| Agriculture | N/A   |      |                                                                                                                                                                      |

N/A – Not applicable to this study

#### 2.4.2.16 Sodium

Sodium is a mineral that is naturally found in rocks and soil and is therefore also naturally present in water sources. Geological conditions play an integral part in the sodium concentration present in water. The presence of sodium in water can also be due to chemical industries and fertilisers (Lenntech, 2021c).

For humans, sodium is a dietary mineral which contributes to nerve function and regulates extra-cellular fluids, membrane potential and acid-base balance. An excessive sodium intake can lead to high blood pressure, oedema, arteriosclerosis, confusion and hyperosmolarity (Lenntech, 2021c). The South African National Standards do, however, only have a limit of 200 mg/L for the prevention of aesthetic risk (SANS, 2015).

Sodium is also an important dietary mineral for livestock (Crooks, 2020; Lenntech, 2021c), as it helps regulate osmotic pressure around the cells (Crooks, 2020). Animals can tolerate high sodium concentrations, but a too high intake can lead to decreased milk production (Crooks,

2020). The recommended limit of sodium concentration for livestock water is 300 mg/L (Al-Saffawi, Al-Assaf, *et al.*, 2020; Al-Saffawi, Ibn Abubakar, Al-Asaat, *et al.*, 2020).

Sodium is an important element used to describe the suitability of water quality for irrigation (Al-Saffawi *et al.*, 2021; Elangovan & Rani, 2017), due to its impact on soil properties and plant growth (Al-Saffawi *et al.*, 2021). A high sodium concentration will lead to filtration and permeability reduction, as it reacts with the soil (Al-Saffawi *et al.*, 2021; Hussain *et al.*, 2018). The plants are also at risk of ion toxicity, which leads to the debilitation of plant production and growth. Sodium toxicity is observed by the formation of burns on the plant leaves (Al-Saffawi *et al.*, 2021). For irrigation purposes, the sodium concentration present in the groundwater is evaluated using the Kelly ratio (KR), sodium percentage (%Na), and sodium absorption rate (SAR). A summary of the sodium concentration limits for drinking, livestock and irrigation purposes is given in Table 15.

**Table 15:** Summary of the sodium concentration limits for drinking, livestock and irrigation use.

| USE         | Limit |      | References                                                                                                 |
|-------------|-------|------|------------------------------------------------------------------------------------------------------------|
|             | Value | Unit |                                                                                                            |
| Drinking    | N/A   |      |                                                                                                            |
| Livestock   | ≤ 300 | mg/L | Al-Saffawi, Al-Assaf, <i>et al.</i> , 2020;<br>Al-Saffawi, Ibn Abubakar, Al-Asaat,<br><i>et al.</i> , 2020 |
| Agriculture | N/A   |      |                                                                                                            |

N/A – Not applicable to this study

#### 2.4.2.17 Irrigation indices

For the evaluation of the groundwater quality for irrigation, the following parameters were used: the PI, KR, %Na, SAR, MAR, and PS.

##### 2.4.2.17.1. Permeability index

Sodium, calcium, magnesium and bicarbonate influence the soil's permeability. This in effect influences the irrigation quality (Ememu & Nwankwoala, 2018; Jalil *et al.*, 2020). A high sodium concentration will reduce the permeability of the soil (Ememu & Nwankwoala, 2018; Hussain *et al.*, 2018). The PI is calculated with the use of Equation 2. A PI lower than 25 % is classified

as unsuitable for irrigation purposes (Al-Saffawi *et al.*, 2021; Elangovan & Rani, 2017; Ememu & Nwankwoala, 2018). A PI value below the recommended limit can lead to permeability and filtration damage (Al-Saffawi *et al.*, 2021).

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100 \quad (2)$$

#### 2.4.2.17.2. Kelly ratio

The KR is an indication of the amount of sodium present in water and is calculated with the use of Equation 3 (Kumar & Balamurugan, 2019). A KR > 1 is an indication of an excess sodium concentration present in the water, which is unsuitable for irrigation purposes (Ememu & Nwankwoala, 2018; Kumar & Balamurugan, 2019).

$$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \quad (3)$$

#### 2.4.2.17.3. Sodium percentage

The evaluation of %Na is very useful for determining groundwater quality for irrigation, as sodium greatly affects the water quality (Ememu & Nwankwoala, 2018). The %Na is calculated with the use of Equation 4 and is expressed in percentages. A %Na higher than 60 is unsuitable for irrigation purposes (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Ememu & Nwankwoala, 2018; Hussain *et al.*, 2018).

$$\%Na = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 \quad (4)$$

#### 2.4.2.17.4. Sodium adsorption rate

The SAR is used to express the water's tendency to replace absorbed magnesium and calcium with sodium (Hussain *et al.*, 2018; Khanoranga, 2019). It therefore gives an indication of the sodium hazard for the water source (Ememu & Nwankwoala, 2018; Jalil *et al.*, 2020; Khanoranga, 2019), which will affect the permeability and infiltration of the soil (Al-Saffawi *et al.*, 2021; Jalil *et al.*, 2020). The SAR is calculated with the use of Equation 5 (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Hussain *et al.*, 2018; Khanoranga, 2019).

An SAR value of higher than 18 mg/L is unsuitable for irrigation purposes (Al-Saffawi *et al.*, 2021). Values beyond the recommended limit can cause an increase in the soil swell potential (Ememu & Nwankwoala, 2018; Jalil *et al.*, 2020), soil crushing, poor aeration and poor seedling emergence (Jalil *et al.*, 2020). In effect the soil permeability will reduce and plant growth will be hindered (Ememu & Nwankwoala, 2018; Jalil *et al.*, 2020).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (5)$$

#### 2.4.2.17.5. Magnesium adsorption rate

A high concentration of magnesium present in irrigation water will reduce the overbearing effect that sodium has on water quality (Ememu & Nwankwoala, 2018). The MAR is calculated by taking not only magnesium into consideration, but also calcium, as seen in Equation 6 (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Hussain *et al.*, 2018; Khanoranga, 2019). An excess of magnesium will also have a negative effect on the soil, as it increases the alkalinity, thus causing a decrease in crop yield (Ememu & Nwankwoala, 2018; Khanoranga, 2019). An MAR value of higher than 50 mg/L is unsuitable for irrigation purposes (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Elangovan & Rani, 2017; Ememu & Nwankwoala, 2018).

$$MAR = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \quad (6)$$

#### 2.4.2.17.6. Potential salinity

The salinity of soil is dependent on the concentration of highly soluble salts, namely sulfate and chloride. The higher the soluble salt concentration, the higher the soil salinity will be (Ememu & Nwankwoala, 2018). A high soil salinity will lead to the accumulation of salts in the plant's root zone, which will decrease the plant growth (Al-Saffawi, Ibn Abubakar, Abbass, *et al.*, 2020). The PS is calculated with the use of Equation 7. The recommended PS limit for irrigation water is < 10 mg/L (Al-Assaf *et al.*, 2020; Ememu & Nwankwoala, 2018). A PS value higher than the recommended limit will negatively affect the soil texture, as well as the crop yield (Kumar & Balamurugan, 2019). In Table 16, a summary of the limits for the different irrigation indices is presented.

$$PS = \frac{1}{2}SO_4^{2-} + Cl^- \quad (7)$$

**Table 16:** Summary of the irrigation index limits for irrigation purposes.

| Irrigation indices | Limit     |      | Reference                                                                                                                        |
|--------------------|-----------|------|----------------------------------------------------------------------------------------------------------------------------------|
|                    | Value     | Unit |                                                                                                                                  |
| PI                 | $\geq 25$ | %    | Al-Saffawi <i>et al.</i> , 2021;<br>Elangovan & Rani, 2017;<br>Ememu & Nwankwoala, 2018.                                         |
| KR                 | $\leq 1$  | -    | Ememu & Nwankwoala, 2018;<br>Kumar & Balamurugan, 2019.                                                                          |
| %Na                | $\leq 60$ | %    | Al-Assaf <i>et al.</i> , 2020;<br>Al-Saffawi <i>et al.</i> , 2021;<br>Ememu & Nwankwoala, 2018;<br>Hussain <i>et al.</i> , 2018. |
| SAR                | $\leq 18$ | mg/L | Al-Saffawi <i>et al.</i> , 2021                                                                                                  |
| MAR                | $\leq 50$ | mg/L | Al-Assaf <i>et al.</i> , 2020;<br>Al-Saffawi <i>et al.</i> , 2021                                                                |
| PS                 | $\leq 10$ | mg/L | Al-Assaf <i>et al.</i> , 2020;<br>Ememu & Nwankwoala, 2018.                                                                      |

## 2.5 Water purification methods

Due to the increase in water resource scarcity, the supply of drinking water has become a top priority for urban managers. Not only does the water quality have to be up to standard, but the treatment costs need to also be taken into consideration (Qaderi & Babanezhad, 2017). Furthermore, the access to safe and sufficient water resources in rural areas in South Africa is defined as limited (Verlicchi & Grillini, 2020). In the case of existing small water treatment plants, there are management and technical problems due to inadequate maintenance and/or the lack of it (Verlicchi & Grillini, 2020). For a safe water supply, the main goal is to develop

technologies that are both effective and inexpensive (Ahmad & Azam, 2019; Yuan *et al.*, 2019).

There are various water treatment technologies that can be used to improve the quality of a water source, namely chemical oxidation and disinfection, ultraviolet (UV) technologies, media and membrane filtration, and coagulation and flocculation, which are coupled with sedimentation, and ion exchange (Ahmad & Azam, 2019).

### **2.5.1 Chemical oxidation and disinfection**

Chemical oxidation is used to change the involved elements' oxidation state. Chemical oxidation includes chlorination, adding chlorine dioxide, chloramination, using ozone (Elder & Budd, 2011; World Health Organization, 2017), and advanced oxidation (Elder & Budd, 2011). Chemical oxidants are used in industrial countries for water disinfection (Von Gunten, 2018) and have been proven to be highly effective (World Health Organization, 2017). Disinfection is a method that is used to either kill or inactivate pathogens (Von Gunten, 2018) that cause waterborne diseases (Ahmad & Azam, 2019). Disinfection is one of the most important processes in supplying safe drinking water (World Health Organization, 2017).

A drastic decrease in waterborne diseases is achieved by chemical disinfection combined with other water purification methods such as sand filtration (Von Gunten, 2018).

#### **2.5.1.1 Ozonation**

Ozonation is a disinfection process which involves the use of ozone. Ozone is a highly unstable, colourless gas with a distinctive odour. The instability leads to the breaking down of the three oxygen atoms into oxygen and free radicals (Ahmad & Azam, 2019). Furthermore, ozone's oxidising potential leads to the decrease of organic and inorganic contaminants such as manganese, sulfur, and iron (Ahmad & Azam, 2019; Cheng *et al.*, 2020; Elder & Budd, 2011; Mao *et al.*, 2018). The reduction of organic and inorganic contaminants leads to the improvement of the water's odour and taste (Ahmad & Azam, 2019; Elder & Budd, 2011). There are no additional chemicals required for the treatment of water with the use of ozone gas and it has been proven to be more effective than chlorine (Ahmad & Azam, 2019). In Figure 5, the ozonation process for the treatment of water is presented.

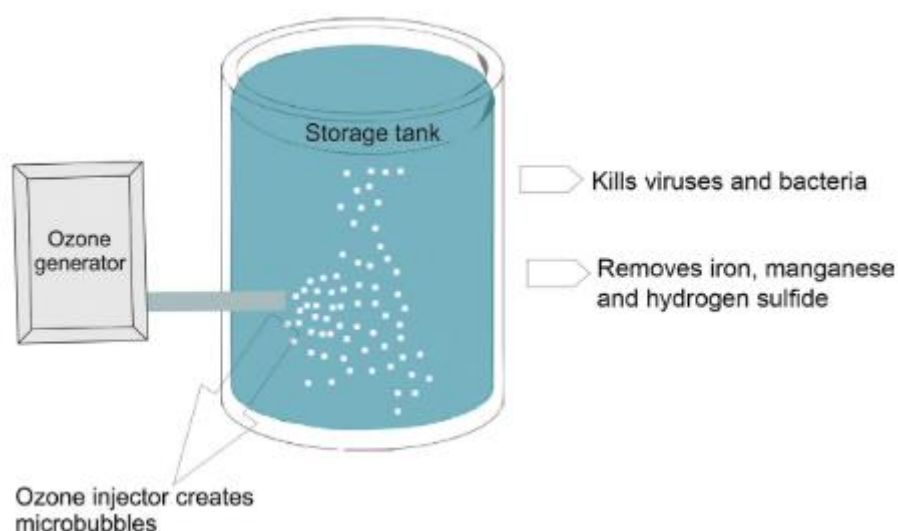


**Figure 5:** The ozonation process for water treatment (Ahmad & Azam, 2019).

A high amount of energy is required for the formation of ozone from oxygen (Ahmad & Azam, 2019; Yuan *et al.*, 2019). An instrument known as an ozone generator, such Corona discharge (CD) generators or UV-generators, is therefore used to carry out this process through electric discharge. A conventional lab process can also be followed for the formation of ozone through chemical reactions. UV ozonation, which involves UV radiation for ozone production, is recommended for smaller-scale water purification processes. For large scale production, a CD ozone generator system is recommended (Ahmad & Azam, 2019).

A disadvantage of the use of ozone is that it requires specific instruments, leading to it being more expensive compared to other disinfection processes (Ahmad & Azam, 2019; Yuan *et al.*, 2019). Furthermore, ozone cannot be used as a secondary disinfectant within distribution systems as it decays rapidly in water. Post-chlorination is therefore required for residual maintenance disinfection in distribution systems (Mao *et al.*, 2018).

#### 2.5.1.2 Chlorine

Chlorine is a common disinfectant used in water treatment (Cheng *et al.*, 2020; Elder & Budd, 2011) as it can inactivate numerous waterborne pathogens (Mao *et al.*, 2018). Manganese, iron, as well as compounds that affect the taste and odour of water, are oxidized by chlorine (Cheng *et al.*, 2020; Elder & Budd, 2011). Chlorine is available in solid (calcium hypochlorite), liquid (sodium hypochlorite), and compressed gas forms (Elder & Budd, 2011). Since chlorine is low in cost and easily accessible, it is the most commonly used disinfectant in the treatment of drinking water (Mao *et al.*, 2018; Mazhar *et al.*, 2020), especially in municipal water supply networks (Mazhar *et al.*, 2020). Chlorine does, however, have some limitations as there are

some protozoan pathogens, such as *Cryptosporidium*, that are resistant to Chlorine disinfection (Mao *et al.*, 2018; World Health Organization, 2017). Furthermore, harmful halogenated disinfection by-products (DBPs) are produced when chlorine reacts with natural organic matter (NOM) (Von Gunten, 2018; Mao *et al.*, 2018; Mazhar *et al.*, 2020).

#### **2.5.1.3 Chlorine dioxide**

Chlorine dioxide is an alternative disinfectant to chlorine and can oxidize manganese, iron, as well as compounds that cause taste and odour in water (Cheng *et al.*, 2020; Elder & Budd, 2011). The production of chlorinated organic by-products is reduced with the use of chlorine dioxide (Ben *et al.*, 2017; Elder & Budd, 2011; Han *et al.*, 2021; Padhi *et al.*, 2019). Furthermore, chlorine dioxide has proven to be more effective (Ben *et al.*, 2017; Han *et al.*, 2021; Padhi *et al.*, 2019), with a lower pH dependency than free chlorine (Ben *et al.*, 2017; Han *et al.*, 2021). There are, however, concerns for the formation of inorganic DBPs such as chlorate and chlorite, which are produced by the decomposition of chlorine dioxide (Padhi *et al.*, 2019). Chlorine dioxide is highly reactive and therefore needs to be manufactured on-site (Acumen group, 2021; Elder & Budd, 2011; Han *et al.*, 2021). According to Elder and Budd (2011), Han *et al.* (2021), and Lenntech (2021) chlorine dioxide is produced by the reactions between:

1. Hydrochloric acid, sodium chloride and sodium hypochlorite,
2. Sodium chlorite and gaseous chlorine, or
3. Sodium chloride, sodium hypochlorite, and hydrochloric acid.

The water treatment process with the use of chlorine dioxide has low energy requirements and residual generation (Yuan *et al.*, 2019). Water treatment with chlorine dioxide is used worldwide (Han *et al.*, 2021).

#### **2.5.1.4 Chloramines**

Chloramines are disinfectants consisting of ammonia and chlorine (CDC, 2020; NanoTech, 2021) and are suitable for the inactivation of microorganisms, such as *E. coli* (Yuan *et al.*, 2019). Ammonium chloride is the preferred chloramine for water purification due to its stability and biocidal properties (Heeb *et al.*, 2017). Chloramine is not usually used as the primary disinfectant in water treatment distribution systems. It is rather used as the secondary disinfectant (Heeb *et al.*, 2017; NanoTech, 2021). It has a significantly lower disinfection and oxidation efficiency, but high stability and lower potential DBP formation compared to chlorine (Heeb *et al.*, 2017). Compared to other disinfectants, such as ozone, chlorine, and chlorine

dioxide, chloramines are not as strong and are unable to oxidise manganese, iron and sulfides (NanoTech, 2021).

For water treatment, chloramine has a low energy requirement and residual generation (Yuan *et al.*, 2019). Factors to consider for water treatment with chloramine disinfectants are the treatment goal and the disinfection contact time (NanoTech, 2021)

### **2.5.2 UV technology**

UV disinfection is conducted with the use of UV lamps which produce UV irradiation (energy) (Ahmad & Azam, 2019). It is a quick and effective way to inactivate the microorganisms present in water (Ahmad & Azam, 2019; Li *et al.*, 2017). The DNA or RNA structure of the microorganism is disrupted as the UV light passes through the microorganism's cell wall and is absorbed by the nucleotides and protein (Li *et al.*, 2017). The microorganism is then inactivated, which leads to growth retardation of the microbial population (Ahmad & Azam, 2019; Li *et al.*, 2017). Germicidal wavelengths, which range from 200-300nm, are used to inactivate bacteria, protozoa and viruses. This physical procedure is chemical-free and ecologically safe for the sterilisation of water (Ahmad & Azam, 2019; Li *et al.*, 2017). There is also no carcinogenic by-product formation with UV disinfection. Another advantage of UV disinfection is that it inactivates microorganisms that are resistant to chlorine disinfection (Ahmad & Azam, 2019). The effectiveness of UV disinfection depends on the lamp power, UV dose and the fluid flow rate (Li *et al.*, 2017). In Figure 6, the process of UV disinfection is illustrated.

Pre-treatment is, however, required to produce water with high clarity, which is needed for effective UV disinfection. Microorganisms can be protected from UV disinfection by suspended solids (World Health Organization, 2017). Compared to chemical disinfection, UV radiation is a more effective and rapid physical procedure for the inactivation of microbial pollutants (Ahmad & Azam, 2019).

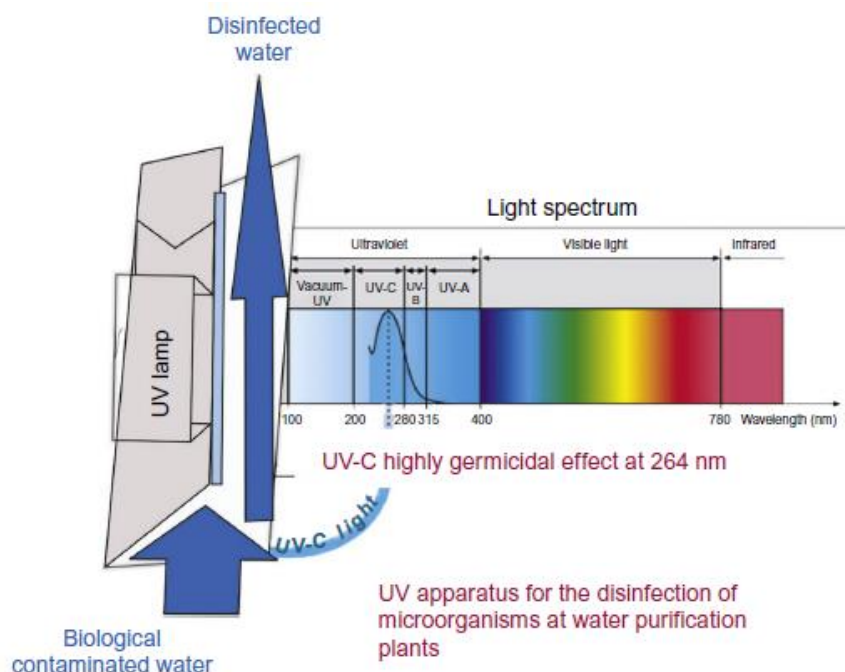


**Figure 6:** UV light disinfection (Ahmad & Azam, 2019).

### 2.5.3 Coagulation/flocculation and sedimentation

The combination of coagulation, flocculation, and sedimentation, along with filtration, is used in numerous water treatment plants (Safe Drinking Water Foundation, 2021). Coagulation and flocculation are used to enhance particle removal processes during water purification (Mazille & Spuhler, 2020a). It is also commonly used as a pre-treatment for membrane filtration technologies to reduce membrane fouling (Malkoske *et al.*, 2020).

Coagulation is the process where a chemical, known as a coagulant, is added to water for purification (Safe Drinking Water Foundation, 2021). The coagulant has a positive charge, while the suspended and dissolved particles present in the sources of water have a negative charge. Neutralisation occurs, which leads to the particles binding together (Malkoske *et al.*, 2020; Mazille & Spuhler, 2020a; Safe Drinking Water Foundation, 2021). Rapid mixing is used in the coagulation process to properly disperse the coagulant. Examples of coagulants include ferric chloride, ferric sulfate, and aluminium sulfate (Safe Drinking Water Foundation, 2021). Coagulation is followed by flocculation, which is a gentle mixing process used to increase the particle size (Mazille & Spuhler, 2020a). When the solution is slowly mixed (Mazille & Spuhler, 2020a), the micro-flocs come in contact with one another and bind to form a larger, visible floc. As the collisions continue, the floc size increases and macro-flocs are formed (Mazille & Spuhler, 2020a; Safe Drinking Water Foundation, 2021). Polymers with a high molecular

weight, known as a coagulant aid, can be added to this step to increase particle bonding, floc size and in effect the settling rate (Mazille & Spuhler, 2020a). Sedimentation is the process in which the flocs settle out (Safe Drinking Water Foundation, 2021). A schematic representation of the coagulation, flocculation and sedimentation process is presented in Figure 7.

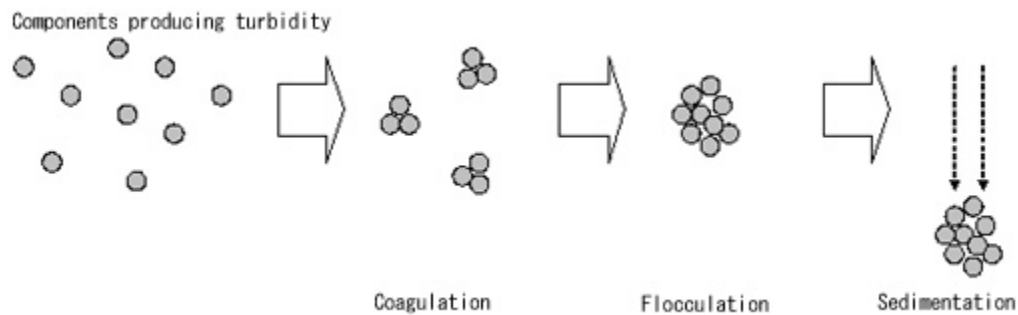


**Figure 7:** Schematic representation of the coagulation, flocculation and sedimentation process (Safe Drinking Water Foundation, 2021).

The combination of coagulation, flocculation and sedimentation is a simple, cost-effective water treatment process. Numerous kinds of particles such as iron, zinc, and copper can be separated from water (Crooks, 2020) using low-cost chemicals. However, the process is time-consuming (Mazille & Spuhler, 2020a).

## 2.5.4 Filtration

Filtration is a method that is used for the removal of particles and in effect reduces the fluid's turbidity (Ahmad & Azam, 2019). Filtration is divided into two subsections, namely media and membrane filtration. For media filtration, activated carbon and slow sand filters (SSFs) are used. The different membrane filtration methods include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and electrodialysis.

### 2.5.4.1 Media filtration

Media filtration is the process where pollutants are physically captured and adsorbed through a chemical reaction. Sand, stone, and organics such as carbon are commonly used in media filtration systems (Commercial filtration Supply, 2021).

#### 2.5.4.1.1 Activated carbon filtration

An activated carbon filter (ACF) is a commonly used water treatment technology, which is based on the principle of adsorption (Ahmad & Azam, 2019; Du *et al.*, 2020; Mazille & Spuhler, 2020b; Moona *et al.*, 2018). Contaminants are adsorbed onto the surface area of the filter. Activated carbon in the form of charcoal is produced with a high degree of porosity, leading to a larger surface area (Du *et al.*, 2020; Mazille & Spuhler, 2020b). Figure 8 represents a typical carbon particle that is used for water treatment.

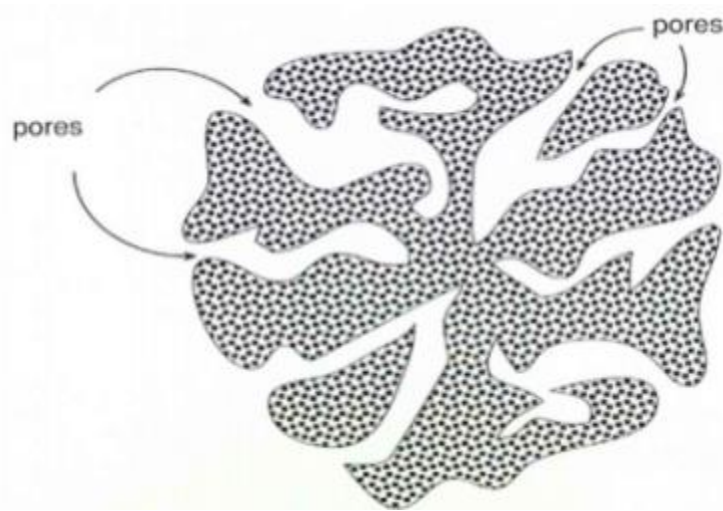


**Figure 8:** Porous carbon particle (Mazille & Spuhler, 2020b).

As the contaminants present in water become trapped within the activated carbon's pores (Antony *et al.*, 2021; Mazille & Spuhler, 2020b; Moona *et al.*, 2018), the ACF effectively removes heavy metals such as iron (Ketsela *et al.*, 2020), zinc, and copper (Alkherraz *et al.*, 2020), as well as fluoride, chloride, and organic pollution factors (Antony *et al.*, 2021; Mazille & Spuhler, 2020b; Pedroza *et al.*, 2021) such as micropollutants, unwanted odours, and taste (Mazille & Spuhler, 2020b).

ACF is used for both large-scale water treatment plants, as seen in Figure 9 (Mazille & Spuhler, 2020b), and for household water treatment (Antony *et al.*, 2021; Mazille & Spuhler, 2020b). It generally forms part of one of the last water treatment stages in large-scale water treatment plants. For a smaller-scale water treatment, it can be used for either point-of-entry or point-of-use treatment (Mazille & Spuhler, 2020b).

ACF is often combined with other water treatment processes to increase the water treatment efficiency, protect certain water treatment units, and increase the lifespan of the filters (Mazille & Spuhler, 2020b). For example, the combination of activated carbon with ozonation increases the effective elimination of organic matter (Du *et al.*, 2020; Mazille & Spuhler, 2020b).

Furthermore, the use of ACF as pre-treatment will protect treatment units such as ion exchange resins and reverse osmosis membranes from oxidation or organic fouling (Mazille & Spuhler, 2020b). ACF has moderate water treatment costs, low energy requirements and moderate residual generation (Yuan *et al.*, 2019).



**Figure 9:** Activated carbon filters (Mazille & Spuhler, 2020b).

#### **2.5.4.1.2 Slow sand filtration**

Slow sand filters are water purification systems that can effectively remove particulate matter, toxic metals (Verma *et al.*, 2017) and pathogenic organisms such as helminths through physical, chemical and biological activity (Bruni & Spuhler, 2020; Medeiros *et al.*, 2020). The particulate matter and organisms are removed from the source water by being trapped in the pores between the sand grains and attachment to the sand grain's surface area. Physicochemical and microbiological contaminants are therefore removed by filtration, microbiological activity and adsorption (Medeiros *et al.*, 2020). Studies have shown that SSFs can also be used to effectively remove bacteria, protozoa, and viruses from water (Bruni & Spuhler, 2020; Medeiros *et al.*, 2020). For biological filtration, a microbial community is established on the top layer of the sand, which is known as a 'Schmutzdecke', causing the top layer to be biologically active. The source water supplies the microbes and then the microbial community establishment is facilitated by the slow filtration rate and the fine sand. The majority of the established microbial community are predatory bacteria which consumes waterborne microbes (Bruni & Spuhler, 2020). The basic process of an SSF is presented in Figure 10.

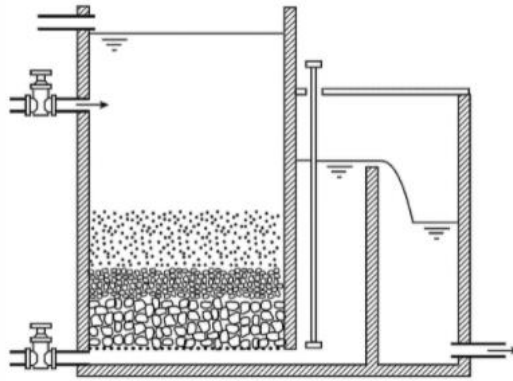


**Figure 10:** Schematic representation of a slow sand filtration process (Bruni & Spuhler, 2020).

SSFs are highly reliable (Bruni & Spuhler, 2020; Medeiros *et al.*, 2020), easy to construct, low in construction, operation, and maintenance costs, and highly effective (Bruni & Spuhler, 2020; Medeiros *et al.*, 2020; Yuan *et al.*, 2019). Gravity flow can be used, which eliminates the need for pumps, and therefore reduces operation costs, as little to no electricity is required (Bruni & Spuhler, 2020; Yuan *et al.*, 2019). Another advantage is that SSFs have a long lifespan of over 10 years (Bruni & Spuhler, 2020).

Some limitations of the SSFs are that the excess suspended materials obstruct the intergranular voids, leading to the reduction in filter flow and increases cleaning maintenance. Pre-filtration is therefore recommended (Medeiros *et al.*, 2020). A few disadvantages are that cold temperatures affect the efficiency of the process, as biological activity decreases, constant water flow, as well as regular maintenance, is required. Furthermore, DBPs that are formed by chlorine disinfection, are not removed (Bruni & Spuhler, 2020). A large-scale SSF operation is shown in Figure 11.



**Figure 11:** Large-scale slow sand filtration operation (Bruni & Spuhler, 2020).

Household slow sand filters (HSSFs), as seen in Figure 12, have proven to be an effective water treatment technology for rural communities (Bruni & Spuhler, 2020; Medeiros *et al.*, 2020). It has been reported that there was a 50% reduction in diarrhoea cases in children with the use of HSSFs (Medeiros *et al.*, 2020).

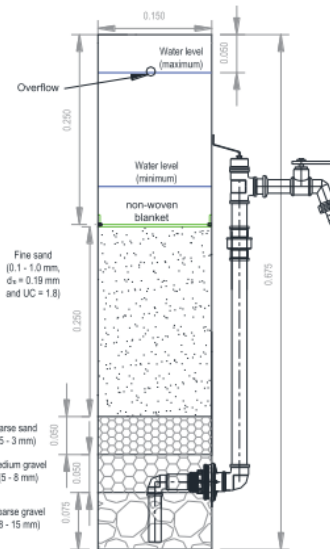


**Figure 12:** Schematic representation of a household slow sand filter system (Medeiros *et al.*, 2020).

A coarse gravel media filtration, as seen in Figure 13, can be used for pre-treatment to increase the HSSF efficiency (Medeiros *et al.*, 2020). A household multistage filtration (HMSF) system, as seen in in Figure 14, will then be created to produce safer water.

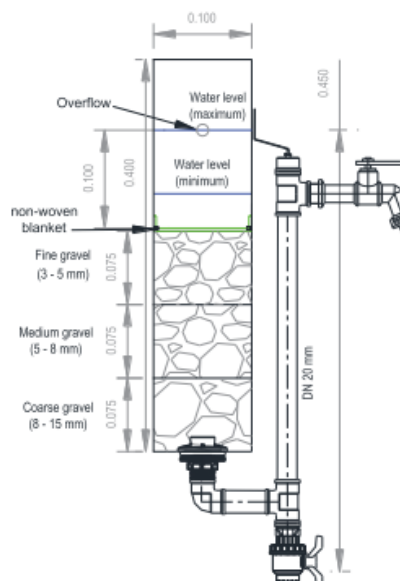


**Figure 13:** Schematic representation of a coarse gravel media filtration system (Medeiros *et al.*, 2020).

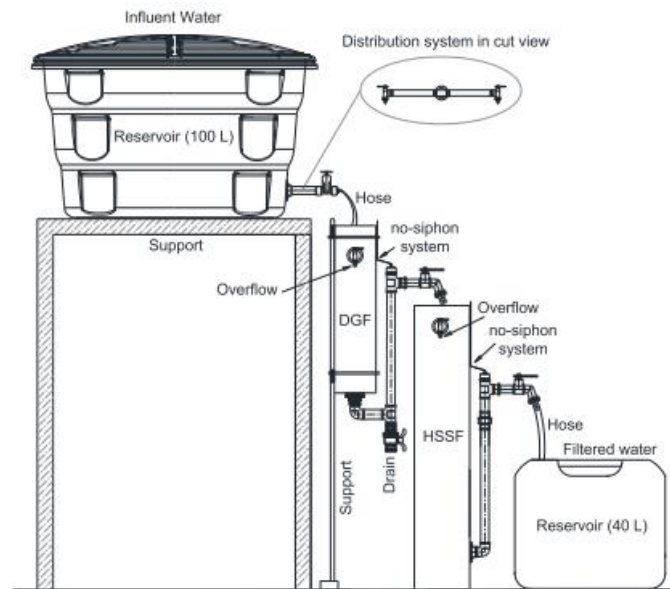


**Figure 14:** Schematic representation of a household multistage filtration system (Medeiros et al., 2020).

In a study conducted on the efficiency of an HMSF system, it was found that over 60% of the turbidity was removed, along with protozoa (>2 log) and *E. coli* (>1.5 log) removal. However, colour removal cannot effectively be done by the HMSF system, which leaves the water unsuitable for drinking purposes. Therefore an additional water treatment process will be required (Medeiros et al., 2020).

#### 2.5.4.2 Membrane filtration

Membrane filtration is a separation process for the treatment of water that requires a driving force (pressure) (Ahmad & Azam, 2019; Mazille & Spuhler, 2020c). Membranes are thin, porous material sheets that can separate contaminants from the source water under applied pressure (Mazille & Spuhler, 2020c). When the source water enters the membrane filter, the stream is divided into filtrate, which is the purified water stream, and retentate, which is the fraction that does not pass through the membrane. Membrane filtration supplies a uniform water quality and has high operational stability. Membrane filtration technologies include MF, UF, NF, RO and electrodialysis (Ahmad & Azam, 2019).

##### 2.5.4.2.1 Microfiltration

MF is an effective water treatment process that is used for the removal of microorganisms, such as bacteria and viruses, and other impurities that fall within a certain submicron particle size range (Ahmad & Azam, 2019; Ali et al., 2018). It has been recorded in a previous study

that MF had a six log efficiency for removing *Cryptosporidium* and *Giardia* (Yuan *et al.*, 2019). The pore size for MF membranes ranges from 0.1 - 1.0  $\mu\text{m}$ , where 1 mm = 1 000  $\mu\text{m}$ . A commonly used MF membrane pore size is 0.2  $\mu\text{m}$ . The operating pressure required for MF is usually five bar (Ahmad & Azam, 2019). Polymer and ceramic membranes can be used for both MF and UF, with polymer membranes most frequently selected due to the high costs for ceramic membranes (Ivanets *et al.*, 2016). Ceramic membranes are, however, more durable due to their high mechanical strength and resistance to chemically aggressive substances and high temperatures (Ali *et al.*, 2018; Ivanets *et al.*, 2016). MF has a high cost and complexity rating, with moderate energy requirements (Yuan *et al.*, 2019).

MF systems are generally combined with pre- or post-treatment steps to reduce membrane fouling, increase filtration efficiency and increase in the product quality (Ali *et al.*, 2018).

#### **2.5.4.2.2 Ultrafiltration**

UF has proven to be an effective and reliable water treatment technology (Liu *et al.*, 2020). UF membranes have a pore size ranging between 1 and 100 nm and are used to remove suspended matter, macromolecules, bacteria, protozoa and most viruses from source water (Ahmad & Azam, 2019). It has been reported that UF can achieve a 4.4 - 7 log reduction in *Cryptosporidium*, 7 log reduction in total coliform bacteria, and 4.7 – 7 log reduction in *Giardia lamblia*. UF is effective for water treatment, as no additional treatment is required to produce safe drinking water, irrespective of the water quality state before the treatment (Ahmad & Azam, 2019). Pre-treatment is, however, recommended to mitigate membrane fouling (Liu *et al.*, 2020).

#### **2.5.4.2.3 Nanofiltration**

NF is a high-pressure membrane filtration technology (Jiang *et al.*, 2019; Yuan *et al.*, 2019) and is one of the most common water purification technologies within the membrane technology group (Ahmad & Azam, 2019). NF membranes have a pore size of about 1 nm (Ahmad & Azam, 2019; Safe Drinking Water Foundation, 2020b) and an electrostatic property, which is designed to retain all the multivalent ions (Ahmad & Azam, 2019; Ang *et al.*, 2020). The surface of NF membranes is either positively or negatively charged. A positively charged membrane rejects most  $\text{Ca}^{2+}$ - and  $\text{Mg}^{2+}$  ions, but only a small amount of  $\text{SO}_4^{2-}$  ions. A negatively charged membrane rejects  $\text{SO}_4^{2-}$ , but only rejects a small amount of  $\text{Ca}^{2+}$ - and  $\text{Mg}^{2+}$  ions (Ang *et al.*, 2020). To ensure the rejection of multivalent ions, there should be a balance between the pore size and the surface charge of the NF membrane (Ang *et al.*, 2020).

Macromolecules are effectively removed due to the pore size, and the electrostatic charge is used to remove inorganic salts. It is therefore an effective technology for the removal of ions and substances with a very low molecular weight from water (Ahmad & Azam, 2019). NF can be used for the removal of microorganisms, nutrients such as nitrate and phosphorus, inorganics such as aluminium, manganese and chloride, and organics (Franke *et al.*, 2019; Yuan *et al.*, 2019).

Compared to RO, NF has a lower operational pressure (Ahmad & Azam, 2019; Jiang *et al.*, 2019; Shahriari & Hosseini, 2020), lower energy requirements and is less susceptible to membrane fouling (Shahriari & Hosseini, 2020). NF has a high complexity and cost rating, as well as high energy requirements compared to other water purification technologies (Yuan *et al.*, 2019).

#### 2.5.4.2.4 Reverse osmosis

RO is a separation water purification process (Ahmad & Azam, 2019; Albergamo *et al.*, 2019) which is extensively used for the purification of mineral-rich water (Ahmad & Azam, 2019; Qaderi & Babanezhad, 2017). RO is a high-pressure technology (Ahmad & Azam, 2019; Albergamo *et al.*, 2020; Yuan *et al.*, 2019), which uses semipermeable membranes to prevent salt content from passing through (Ahmad & Azam, 2019). Only specific water molecules can pass through the membranes. The separation of salts and water with the use of RO membranes is only possible due to the diffusion mechanism, which is dependent on the osmotic pressure ( $\Delta\pi$ ) being smaller than the external pressure ( $\Delta p$ ). The permeability of the RO membrane allows water to flow from a concentrated to a dilute solution (Ahmad & Azam, 2019; Albergamo *et al.*, 2019). The RO process is presented in Figure 15.

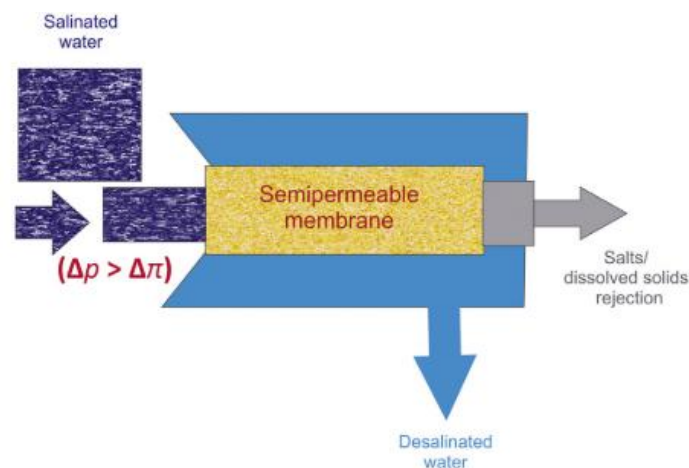


**Figure 15:** Schematic representation of the reverse osmosis process (Ahmad & Azam, 2019).

RO membranes have an average pore size of 0.1 nm (Safe Drinking Water Foundation, 2020b) and operate at a pressure of about 80 bars (Ahmad & Azam, 2019). The efficiency of an RO membrane is dependent on the salt eliminating and water fluxing properties (Ahmad & Azam, 2019). RO has been reported to effectively remove microorganisms, nutrients, and inorganic and organic elements (Albergamo *et al.*, 2020; Yuan *et al.*, 2019). As most groundwater is brackish, RO is a widely used water purification technology for agricultural applications (Ahdab *et al.*, 2021).

The membrane integrity can also be affected by disinfection agents such as chlorine, which is used in the pre-treatment process, or due to biofouling (Albergamo *et al.*, 2019). Pre-treatment is, however, extremely important for RO, as membrane blockage can lead to irreversible membrane fouling, which will influence its performance, membrane life and costs. Pre-treatment includes chlorination, multimedia filtration, followed by microfiltration and dichlorination (Ahmad & Azam, 2019).

One disadvantage of RO is brine disposal. Brine is the rejected water, which contains high amounts of minerals and salts, and other elements such as metals, metalloids, acids, and organic compounds. Brine is usually directly released into the sea, surface water, or flushed into drains, which is a great threat to the environment (Ahmad & Azam, 2019). Furthermore, RO is a highly complex and expensive water treatment process (Hansima *et al.*, 2021; Yuan *et al.*, 2019), with a high energy requirement rating (Albergamo *et al.*, 2020; Yuan *et al.*, 2019). Another disadvantage of RO is that it has an 80% lower water recovery compared to other technologies used for the improvement of brackish water (Ahdab *et al.*, 2021; Hansima *et al.*, 2021).

#### **2.5.4.2.5 Electrodialysis**

Electrodialysis is a water purification technology which uses electro-membranes (Ahmad & Azam, 2019) for the removal of nutrients and inorganics (Yuan *et al.*, 2019). These nutrients include nitrate, ammonia and phosphorus, while the inorganics include aluminium, manganese, chloride (Yuan *et al.*, 2019), and sulfate (Sharma & Kumar, 2020). Electrical potential is the driving force for electrodialysis (Kunrath *et al.*, 2020). Electrodialysis is generally used for the treatment of hard water. The water is passed through two oppositely charged electrodes. Metal ions are then attracted to the negative electrode and nonmetal ions are attracted to the positive electrode (Ahmad & Azam, 2019).

Electrodialysis is an alternative to RO, as it has a higher water recovery and a longer membrane lifetime (Ahdab *et al.*, 2021). Furthermore, it has increased efficiency and a lower water production cost (Kunrath *et al.*, 2020).

### 2.5.5 Ion exchange

Ion exchange is a water purification technology which is commonly used for water softening by removing  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions. Ion exchange is also used for the removal of nitrate (Ahmad & Azam, 2019; Crooks, 2020; Yuan *et al.*, 2019), sulfate (Sharma & Kumar, 2020), fluoride, arsenic, barium, radium, selenium, lead, and chromate (Ahmad & Azam, 2019). The process involves a fixed bed, which is packed with a synthetic microporous exchange resin. The resin consists of microporous beads with a diameter range of 0.3 – 1.3 mm, which are organic solvents and insoluble in water. The beads consist of gel-structured compartments in which water is dispersed homogeneously. Water-soluble materials can therefore freely move within the pores. Polyacrylate and polystyrene are commonly used base materials (Mazille & Spuhler, 2020d). An ion exchange resin is shown in Figure 16.

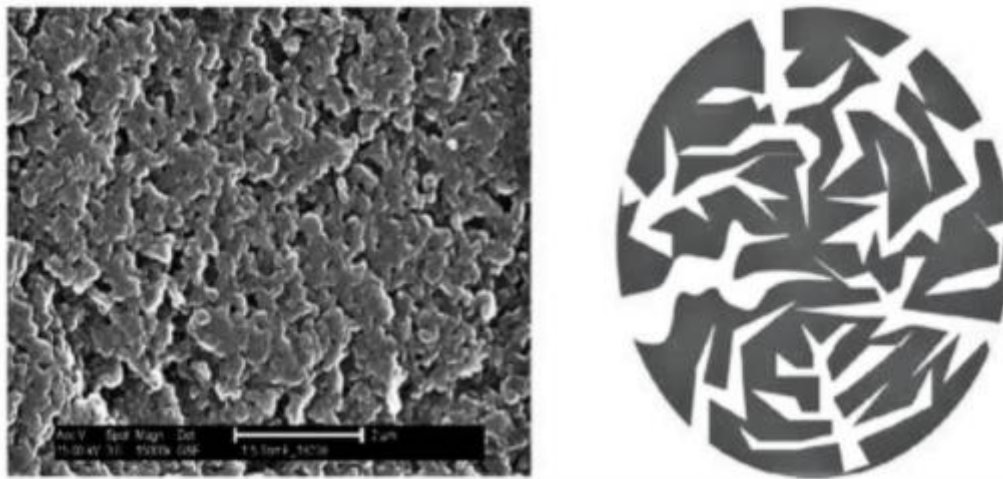


**Figure 16:** The pores within an ion exchange resin (Mazille & Spuhler, 2020d).

The resin is supersaturated with a solution that is loosely held (Mazille & Spuhler, 2020d). As the contaminated water passes through the resin bed, the contaminant ions are attached to the resin and the loosely held solution is released into the water. The functional group, which is attached to the polymer's monomer unit, interacts with water-soluble elements such as ions. Due to electrostatic forces, anions interact with functional groups that are positively charged and cations with functional groups that are negatively charged (Levchuk *et al.*, 2018; Mazille & Spuhler, 2020d). The ion exchange reaction is illustrated in Figure 17.

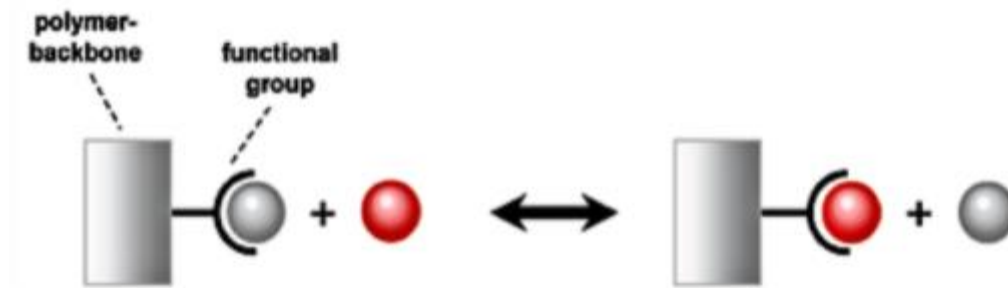


**Figure 17:** Schematic representation of the ion exchange reaction (Mazille & Spuhler, 2020d).

When the beds are saturated, the ion exchange resin is recharged or regenerated through flushing with a salt brine solution (Levchuk *et al.*, 2018; Mazille & Spuhler, 2020d). The ions are then exchanged with the sodium ions and are removed out as wastewater (Mazille & Spuhler, 2020d). The ion exchange process for both water softening and recharge is shown in Figure 18.

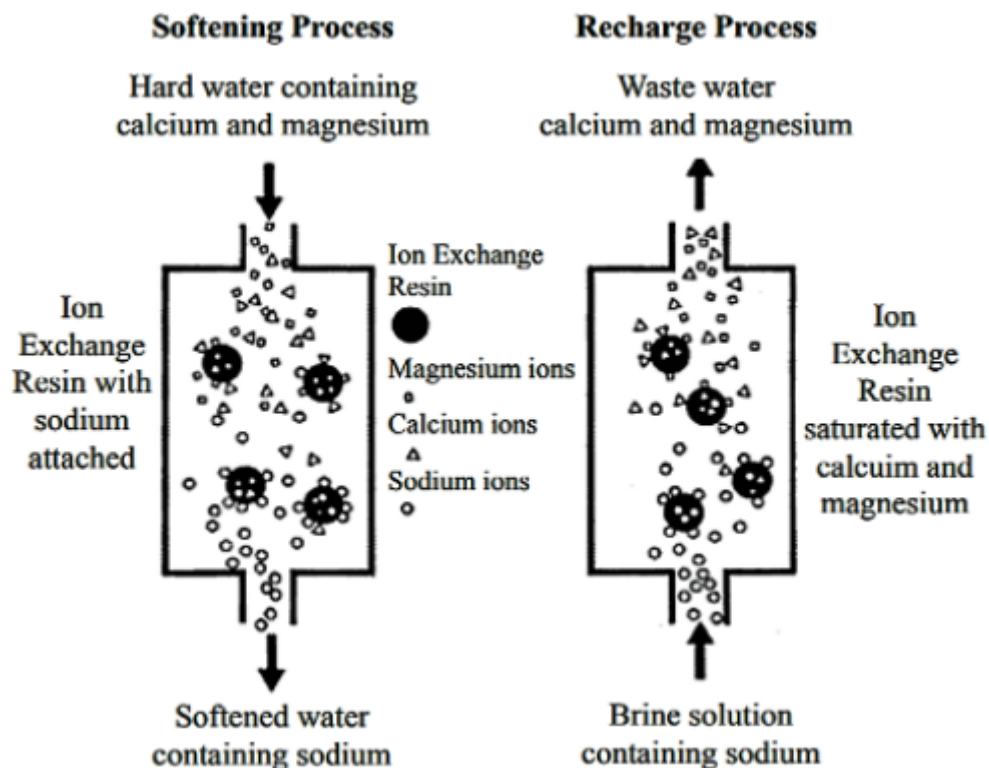


**Figure 18:** Ion exchange process for water softening and recharge (Mazille & Spuhler, 2020d).

Ion exchange has a moderate complexity and cost rating compared to other water purification technologies (Yuan *et al.*, 2019). Although it can effectively remove dissolved inorganics from

water (Lenntech, 2021e; Mazille & Spuhler, 2020d), it is unable to remove bacteria (Mazille & Spuhler, 2020d).

## **2.5.6 pH adjustment**

### **2.5.6.1 Neutralising filters**

The pH of acidic water is adjusted with the use of a neutralising filter, as the filter increases the pH to 7. Magnesium oxide (MgO) (Drinking Water, 2019) and calcium carbonate (CaCO<sub>3</sub>) (Drinking Water, 2019; Mehl & Johannsen, 2018) are used to treat water with a pH of below and above 6, respectively. The MgO and CaCO<sub>3</sub> dissolve in the water and thus raise the pH (Drinking Water, 2019).

Neutralising filtration is a time-consuming process, as adequate contact time is required for the reaction to take place. Furthermore, the filters can increase the hardness of the water, which can lead to the necessity of water softening (Drinking Water, 2019).

### **2.5.6.2 Alkalinisation**

The injection of soda ash (sodium carbonate) or sodium hydroxide is used to treat water with a low pH (Drinking Water, 2019; Khajouei *et al.*, 2021). Soda ash and sodium hydroxide do not affect the hardness of water, as it acts as a softening agent (Drinking Water, 2019; Khajouei *et al.*, 2021) and can treat water with a pH between 7 and 4. Dual treatment with the injection system and chlorine are possible. Water can therefore be treated with disinfection and pH adjustment at the same time (Drinking Water, 2019).

### **2.5.6.3 Acidification**

Acidification is a method that is used to decrease the pH level by injecting an acid into the water (Buendia *et al.*, 2018; Drinking Water, 2019). The bicarbonate and/or carbonate ion concentration will reduce as it reacts with the acid's hydrogen ions. The chemical reaction equation for the process is presented by Equations 8 and 9 (Buendia *et al.*, 2018).



Alkalinity and pH are lowered through the use of either sulfuric acid (Buendia *et al.*, 2018; Lenntech, 2021f), phosphoric acid, and nitric acid (Buendia *et al.*, 2018).

## 2.5.7 An overview of the cost and effectiveness of the treatment technologies

There are various aspects that need to be taken into consideration for the production costs of purified water. These aspects includes; the water quantity to be purified, the degree to which it should be purified, and the quality of the raw feed water affect the treatment cost (Mung, 2017; Pure-H<sub>2</sub>O, 2021). Cost comparison is conducted for disinfection technologies, as well as a cost comparison for all the treatment technologies mentioned in the research.

### 2.5.7.1 Disinfection technologies

A study conducted by Gelete *et al.* (2020) compared different water disinfection techniques, by taking capital cost (CC), safety risk (SF), maintenance and operational cost (MOC), reliability (R), pathogen removal efficiency (PRE), formation of undesired products (RF), and operational simplicity (OS) into account. The disinfection techniques that were compared are UV, chlorine, chloramine, chlorine dioxide, and ozonation (Gelete *et al.*, 2020). The obtained weight for each criterion, along with the ranking for each disinfection technique (1 – most preferable, 5 – least preferable) (Gelete *et al.*, 2020) are presented in Table 17.

**Table 17:** Criteria weight and ranking number of the investigated disinfection technologies (Gelete *et al.*, 2020).

| Disinfection technique | Criteria rating |     |     |     |     |     |     | Ranking number |
|------------------------|-----------------|-----|-----|-----|-----|-----|-----|----------------|
|                        | CC              | MOC | PRE | RF  | SF  | R   | OS  |                |
| UV                     | 0.5             | 0.4 | 0.9 | 0.3 | 0.4 | 0.9 | 0.8 | 1              |
| Ozone                  | 0.9             | 0.8 | 0.8 | 0.4 | 0.5 | 0.8 | 0.8 | 2              |
| Chlorine               | 0.6             | 0.5 | 0.7 | 0.8 | 0.8 | 0.7 | 0.6 | 3              |
| Chloramine             | 0.7             | 0.6 | 0.5 | 0.6 | 0.5 | 0.5 | 0.4 | 4              |
| Chlorine dioxide       | 0.7             | 0.7 | 0.4 | 0.6 | 0.8 | 0.4 | 0.5 | 5              |

UV disinfection has the lowest capital, as well as maintenance and operational cost, along with high removal efficiency, and is therefore ranked as the top disinfection technology. Ozone,

on the other hand, has the highest capital, as well as maintenance and operational cost, but due to the other ratings being high, is regarded as second best, above chlorine, chloramine, and chlorine dioxide (Gelete *et al.*, 2020).

### 2.5.7.2 Other treatment technologies

The evaluation of treatment costs for coagulation and SSF was conducted by Jung *et al.* (2021). The total costs for coagulation and SSF was estimated at 0.67 and 11.23 ZAR/m<sup>3</sup>\*, respectively. The flow rate for the water production was, however, not specified (Jung *et al.*, 2021).

In a study conducted by Campinas *et al.* (2021), the water treatment cost for ACF and MF at a flow rate of 100 000 m<sup>3</sup>/d were evaluated. The treatment cost for the use of ACF and MF were 0.51 and 1.18 ZAR/m<sup>3</sup>\*, respectively. It has also been indicated, as seen in Figure 19, that for a higher plant flow rate, the production cost for MF will drastically decrease (Campinas *et al.*, 2021).

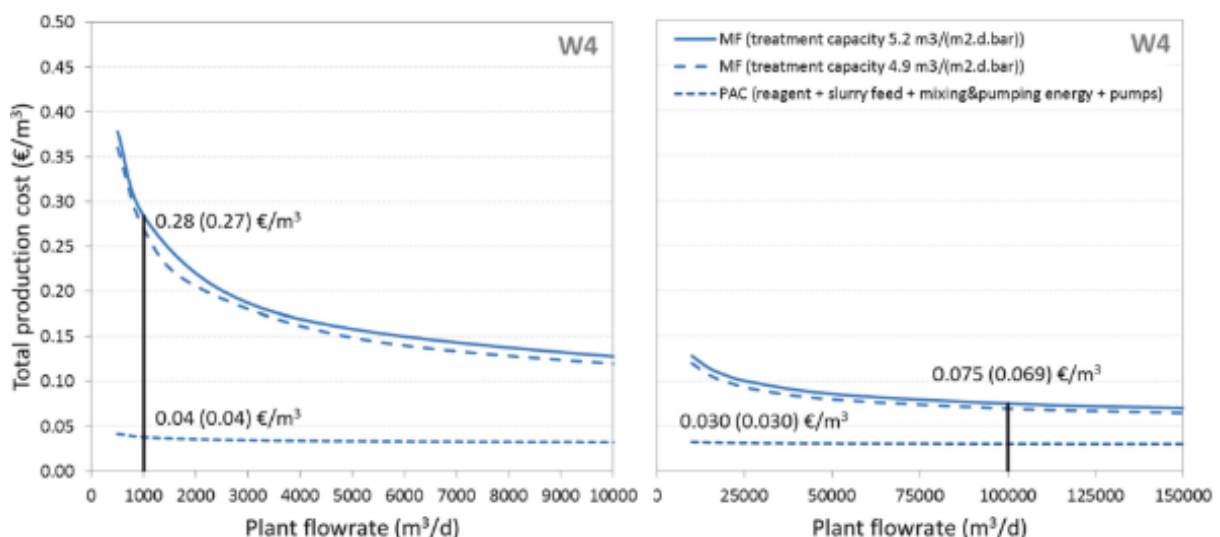


**Figure 19:** Total production cost as a function of the plant flow rate (Campinas *et al.*, 2021).

In a study conducted by Mohamad Mazuki *et al.* (2020), the costs to treat 100 m<sup>3</sup>/d and 5 000 m<sup>3</sup>/d of water with an UF system were 0.50 RM/m<sup>3</sup> and 0.10 RM/m<sup>3</sup>, respectively. It is clear that, for certain water treatment technologies, the treatment cost are lower when a higher amount of water is treated (Mohamad Mazuki *et al.*, 2020).

\* The currency conversions used were USD/ZAR 14.71 and €/ZAR 17.05 and the date of the currency conversion was 18 October 2021.

An economic analysis conducted by Tahaikt *et al.* (2021) evaluated the cost for desalination with the use of RO, NF and electrodialysis. The capital, operating, maintenance, and energy costs were taken into consideration for the production of 100 m<sup>3</sup>/d of drinking water (Tahaikt *et al.*, 2021). The total cost for the treatment technologies is presented in Table 18.

**Table 18:** Total cost for water purification technologies.

| Treatment technology | Flowrate (m <sup>3</sup> /d) | Total cost |                   |                       | Reference                             |
|----------------------|------------------------------|------------|-------------------|-----------------------|---------------------------------------|
|                      |                              | Value      | Currency          | ZAR/ m <sup>3</sup> * |                                       |
| Coagulation          | NS                           | 0.045      | \$/m <sup>3</sup> | 0.66                  | (Jung <i>et al.</i> , 2021)           |
| Ion exchange         | 11 520                       | 0.014      | €/m <sup>3</sup>  | 0.24                  | (Wang & Wu, 2015)                     |
| <b>Filtration</b>    |                              |            |                   |                       |                                       |
| ACF                  | 100 000                      | 0.030      | €/m <sup>3</sup>  | 0.51                  | (Campinas <i>et al.</i> , 2021)       |
| HSSF                 | Per unit                     | 76         | USD               | 1 118                 | (Andreoli & Sabogal-Paz, 2020)        |
| SSF                  | NS                           | 0.764      | \$/m <sup>3</sup> | 11.24                 | (Jung <i>et al.</i> , 2021)           |
| MF                   | 100 000                      | 0.069      | €/m <sup>3</sup>  | 1.18                  | (Campinas <i>et al.</i> , 2021)       |
| UF                   | 90 000                       | 0.50       | RM/m <sup>3</sup> | 1.77                  | (Mohamad Mazuki <i>et al.</i> , 2020) |
| Electrodialysis      | 100                          | 0.154      | €/m <sup>3</sup>  | 2.63                  | (Tahaikt <i>et al.</i> , 2021)        |
| NF                   | 100                          | 0.123      | €/m <sup>3</sup>  | 2.10                  | (Tahaikt <i>et al.</i> , 2021)        |
| RO                   | 100                          | 0.164      | €/m <sup>3</sup>  | 2.80                  | (Tahaikt <i>et al.</i> , 2021)        |

\* The currency conversions used were USD/ZAR 14.71, €/ZAR 17.05, and RM/ZAR 3.53 and the date of the currency conversion was 18 October 2021.

### 2.5.7.3 Overall technologies

In a study conducted by Yuan *et al.* (2019), treatment processes were given a complexity and cost ranking (CCR), along with the removal efficiency for certain contaminants. The rankings and removal efficiencies for specific contaminants are listed in Table 19.

**Table 19:** Water treatment efficiency and CC ranking (Yuan *et al.*, 2019).

| Treatment process    | CCR ranking | Removal efficiency     |         |
|----------------------|-------------|------------------------|---------|
|                      |             | Contaminant            | Removal |
| Slow sand filtration | 1           | N/A                    | N/A     |
| Coagulation          | 3           | Microbial contaminants | 3 log   |
| ACF                  |             | Manganese              | 86%     |
|                      |             | Organics               | ≥ 47%*  |
| Ion exchange         | 4           | Nitrate                | 67%     |
|                      |             | Manganese              | 99%     |
| Ozonation            | 5           | Microbial contaminants | ≥ 3 log |
|                      |             | Manganese              | 83%     |
|                      |             | Organics               | ≥ 17%*  |
| MF                   | 6           | Microbial contaminants | ≥ 6 log |
| UF                   | 6.25        | Microbial contaminants | ≥ 6 log |
| NF                   | 6.5         | Microbial contaminants | ≥ 6 log |
|                      |             | Nitrate                | 70%     |
|                      |             | Manganese              | 92%     |
|                      |             | Chloride               | 85%     |
|                      |             | Organics               | ≥ 60%*  |
| RO                   | 6.75        | Microbial contaminants | ≥ 6 log |
|                      |             | Nitrate                | 95%     |
|                      |             | Manganese              | 95%     |
|                      |             | Chloride               | 90%     |
|                      |             | Organics               | ≥ 75%*  |

N/A – not available

\* The value can vary for different organic contaminants

### 2.5.8 Multistage water treatment systems

A multistage water treatment system, also known as a treatment train, consists of a combination of water treatment units (Medeiros *et al.*, 2020; Yuan *et al.*, 2019). The combination of treatment units will lead to a higher contaminant removal efficiency compared to that of only one unit (Yuan *et al.*, 2019). Furthermore, pre-treatment and post-treatment are important for certain technologies to prevent membrane fouling (Ahmad & Azam, 2019; Ali *et al.*, 2018), increase purification efficiency (Medeiros *et al.*, 2020; World Health Organization, 2017), and product quality (Ali *et al.*, 2018).

The process for modern groundwater treatment usually consists of pre-treatment, followed by membrane filtration, and lastly, disinfection (Jung *et al.*, 2021). Suggested water treatment trains are listed in Table 20 and Table 21. For the study conducted by Jung *et al.* (2021), cost estimations were given for each possible treatment train listed in Table 21. The treatment train costs are, however, only an estimation, as the production costs of purified water is dependent on the quantity to be purified, the degree to which it should be purified, and the quality of the raw feed water (Mung, 2017; Pure-H<sub>2</sub>O, 2021).

**Table 20:** Possible water purification treatment trains.

| Treatment train                                                | Reference                   |
|----------------------------------------------------------------|-----------------------------|
| MF → RO → UV based AOP disinfection                            | (Yuan <i>et al.</i> , 2019) |
| AC → MF → RO → UV disinfection                                 | (Yuan <i>et al.</i> , 2019) |
| Coagulation and flocculation → Media filtration → Disinfection | (Mung, 2017)                |

**Table 21:** Water production costs of possible water treatment trains (Jung *et al.*, 2021).

| Treatment train                                                    | ZAR/m <sup>3</sup> * |
|--------------------------------------------------------------------|----------------------|
| Coagulation and flocculation → NF → Chlorination                   | 2.87                 |
| Coagulation and flocculation → RO → Chlorination                   | 3.12                 |
| Coagulation and flocculation → Sand filtration → NF → Chlorination | 4.84                 |
| Sand filtration → NF → Chlorination                                | 5.51                 |
| Sand filtration → RO → Chlorination                                | 5.62                 |

\* The currency conversions used were USD/ZAR 14.71 and the date of the currency conversion was 18 October 2021.

It is important to design a treatment process based on the water quality state of the specific water source by investigating the specific contaminants present in the source (Jung *et al.*, 2021). In effect, not only will the water quality be up to standard, but maximum water production at the lowest possible cost will be achieved (Jung *et al.*, 2021; Qaderi & Babanezhad, 2017). Lastly, the treatment train needs to be able to face sudden changes in feed water quality.

## **2.6 Synthesis of literature**

It is evident that water resources are not only one of the most essential elements that need to be managed but also one of the most difficult elements to protect. Groundwater specifically has been identified as one of the country's key water sources and therefore the management thereof is vital. Due to the ineffective implementation of groundwater management plans seen by local municipalities in South Africa, stress on groundwater sources are evident, which includes the decrease in groundwater quality.

Poor groundwater quality not only negatively affects the health of humans but also negatively affects crop production and the health of livestock. For people living in rural communities, it is important for the municipality to implement intervention strategies for the improvement of groundwater quality, as they are mostly affected by water pollution, for both personal as well as agricultural use.

In order for the municipalities to implement intervention strategies, or even make the citizens aware of the current water quality status of the water source in use, regular water quality analysis is important. However, only providing the raw water quality data of the different parameters to policymakers and/or concerned citizens, who are not water experts, will prove to be ineffective. The use of a rating scale model, such as the WQI, where multi-variable data is converted into a single score rating will create a clearer idea of the water quality status and whether it is suitable for use. Should the score indicate that the water source is unsuitable, it is recommended that a further evaluation is conducted on the parameter which shows to have elevated levels beyond the recommended limit. The evaluation will indicate what water treatment technology will be required for the improvement of the water source.

Taking into consideration that the evaluated groundwater source can be located in a rural community, it is important to not only take the effectiveness of the water treatment technology into consideration but also the cost thereof. When comparing the different water treatment technologies with one another, it is important to recognize that the functions of most of the treatment technologies are different and that the treatment cost can decrease with the

increase in the amount of water purified. For the removal of microbial contaminant, it is important to address the turbidity of the water beforehand. Should the water be turbid, ACF will be the best cost-effective solution. With regards to disinfection, for the presence of disinfectant residual that needs to last longer than 5 hours, chlorine will be the most cost-effective. Should no disinfectant residual be required, UV disinfection is then recommended as it is the most efficient and cost-effective solution. Ion exchange is recommended as the most cost-effective solution for the removal of TDS, EC, nitrate, manganese, and/or sulfate. For the removal of chlorine, iron, zinc, and/or copper, the most cost-effective solution is ACF.

It is clear that the combination of water treatment systems is the most effective route to follow and will probably be necessary for the government to implement it for the treatment of a large scale of groundwater. Due to the expected fluctuation in water quality over different seasons, the use of a multistage water treatment system will also be important for citizens to consider, when implementing a household water treatment system.

## CHAPTER 3: METHODOLOGY

This chapter serves as the methodology chapter, wherein the study area and the method for the experimental investigation of the groundwater quality of the NMMD are presented. The groundwater qualities of 90 boreholes located in Ditsobotla, Ratlou and Tswaing LM areas were investigated. Groundwater sampling and analyses were conducted first, followed by data analyses for drinking, livestock and irrigational purposes, with the use of the WQI.

Information on the area in which the study was conducted is presented in **Section 3.1**. An environmental overview is presented in **Section 3.1.1**, along with information on the social factors in **Section 3.1.2**. **Section 3.2** describes the data collection procedure followed for the research. The procedure included sampling, which is presented in **Section 3.2.1**, which describes the sampling method and location. The sample analysis procedures, which were conducted by two laboratories, Eco Analytica and Envirocare Laboratory, are presented in **Section 3.2.2**. The data analysis procedure is presented in **Section 3.3**, which includes database development and data manipulation. **Section 3.3.1** describes the database which was developed for the research. Data manipulation includes the use of the WQI, as well as colour classification, which is described in full in **Section 3.3.2**.

### 3.1 Study area

The study was conducted in the Ngaka Modiri Molema District (NMMD) area, which is located in the North West Province in South Africa. The NMMD forms part of the four district municipalities in the North West Province and is situated centrally within the province, bordering Botswana, as seen in Figure 20. It has a total extent of 28 206 km<sup>2</sup> and comprises of five local municipalities (LM), namely Ratlou LM, Mahikeng LM, Ditsobotla LM, Ramotshere Moiloa LM and Tswaing LM (Ngaka Modiri Molema District Municipality, 2020a).

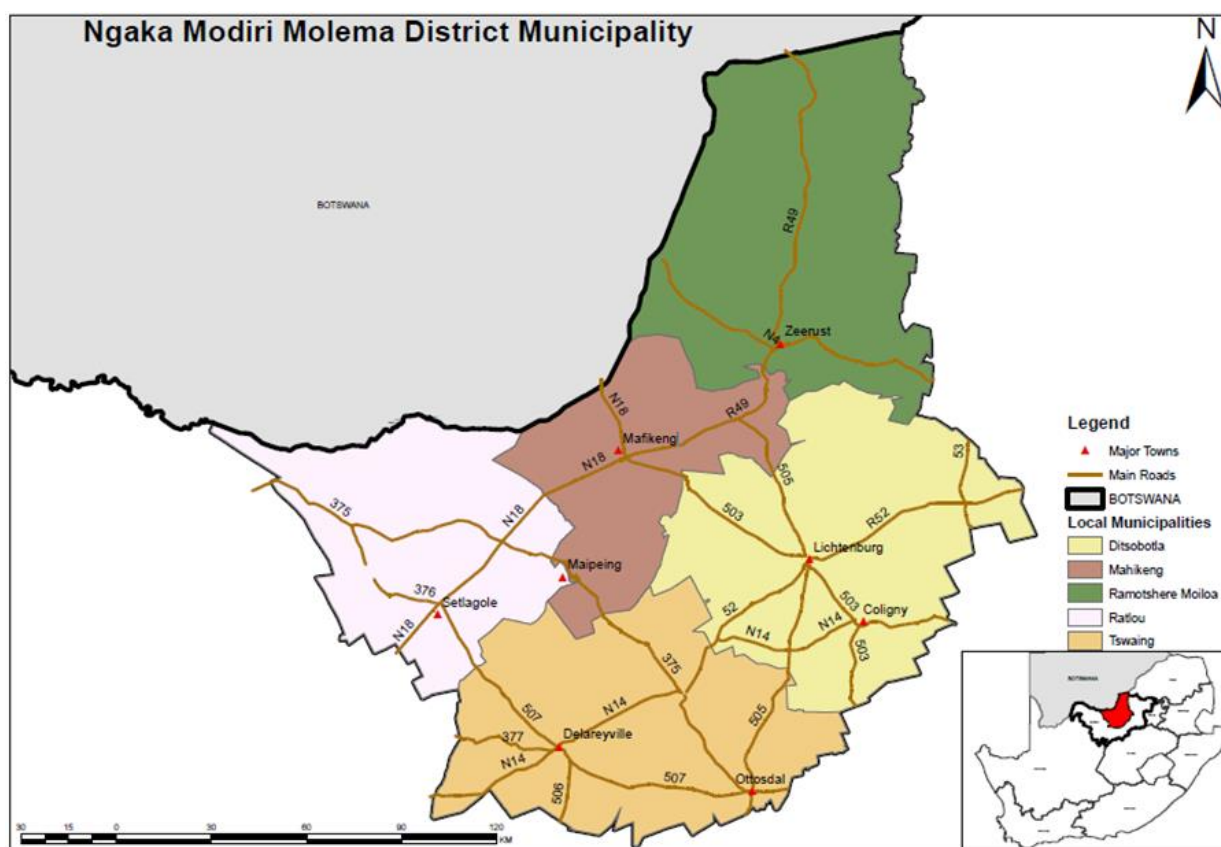


**Figure 20:** Ngaka Modiri Molema District Municipality (Ngaka Modiri Molema District Municipality, 2020b).

### 3.1.1 Environmental overview

The environmental overview covers the climate, topography, geology, as well as the vegetation of the NMMD area.

#### 3.1.1.1 Climate

The NMMD is classified as arid, with an average rainfall of 600mm per annum. Hail and thunderstorms occur in the region, but relatively seldom compared to other areas in the country, such as the Highveld (Department of Rural Development and Land Reform, 2016).

The NMMD area is being affected by climate change (Department of Rural Development and Land Reform, 2016), which is defined as the change in the average long-term weather distribution (Department of Rural Development and Land Reform, 2016; Sipple *et al.*, 2020). Climate change has been occurring over a long period and the average global temperature has been increasing (Department of Rural Development and Land Reform, 2016; Sipple *et al.*, 2020). The increase in temperature affects the rainfall and can lead to droughts, which has

been the case for the North West Province. Due to the drought experienced in the North West Province, agriculture has been threatened (Department of Rural Development and Land Reform, 2016).

For the NMMD area, climate change poses a great risk, as environmental forces are greatly relied on for agriculture and tourism. Agriculture and tourism play an integral part in the rural development of the area. It will also hurt the economy of the region, as it will affect land use and lead to a decrease in resources (Department of Rural Development and Land Reform, 2016).

#### **3.1.1.2 Topography**

The NMMD area's topography is mainly classified as flat, as 68% of the area falls within this category. Of the remaining area, 17% is classified as rolling, and 15% as mountainous (Department of Rural Development and Land Reform, 2016; Ngaka Modiri Molema District Municipality, 2019). The northern part of the NMMD area, more specifically Ramostshere LM, is mainly classified as mountainous. The areas that are prominently classified as flat are the central and south-western parts, more specifically Ditsobotla, Ratlou, Tswaing, and Mahikeng LMs (Ngaka Modiri Molema District Municipality, 2019).

The area's agricultural land use is directly linked to the topography thereof. The slope of the land influences the crop type that can be grown there. For mountainous areas, the growth of vegetation is not as successful compared to that of a flat area, due to the poor quality of the topsoil. Furthermore, the slope of the land also influences crop selection as the ability to irrigate land needs to be taken into consideration (Department of Rural Development and Land Reform, 2016).

#### **3.1.1.3 Geology and vegetation**

The geology of the NMMD area mainly consists of dystrophic to mesotrophic soils, mesotrophic to eutrophic soils, eutrophic soils, as well as non-calcareous soils (Department of Rural Development and Land Reform, 2016; Ngaka Modiri Molema District Municipality, 2019). Soil degradation is present in the region due to agricultural activities as well as overuse and neglect of communal land (Department of Rural Development and Land Reform, 2016).

With regard to the vegetation, the western parts of the NMMD area are characterised by Kalahari thornveld, as the area is relatively flat and dry. The eastern parts are mainly bushveld, as it is covered by Cymbopogon-Themedaveld and Bankenveld. Dry Cymbopogon-Themedaveld

veld and sour mixed bushveld cover the central and southern parts of the NMMD area. The extreme Northern parts comprise of mixed bushveld and turf thornveld (Department of Rural Development and Land Reform, 2016; Ngaka Modiri Molema District Municipality, 2019).

Large parts of the Tswaing and Mahikeng LM areas have endangered vegetation, while parts of the vegetation in the Ditsobotla LM area are classified as vulnerable (Department of Rural Development and Land Reform, 2016).

### **3.1.2 Social factors**

For the social factors, the demographics, general land use, as well as the quality and accessibility of water are presented.

#### **3.1.2.1 Demographic Characteristics**

In 2019 it was reported that the NMMD municipality housed 961 960 people, which is approximately 23.3% of the population in the North West Province and 1.6% of South Africa's population. It has further been recorded that the district municipality comprised of 268 099 households in 2019. The average population growth rate for the NMMD area, was recorded as 1.33% per annum between the years 2008 and 2018, which was below that of the province and the country. The population growth rate of the North West Province and South Africa was recorded as 1.97 and 1.61%, respectively during 2019 (Ngaka Modiri Molema District Municipality, 2020a).

Of the local municipalities within the NMMD area, the Ditsobotla LM was recorded to have the highest population growth rate of 1.7% per annum. The second-highest growth rate was reached by the Mahikeng LM, with an average growth rate of 1.5% per annum. Relative to the other local municipalities within the NMMD area, Ratlou LM had the lowest recorded growth rate of 0.55% per annum (Ngaka Modiri Molema District Municipality, 2020a). The projected population for the NMMD area in 2023, at an average rate of 1.6% per annum, is 1.02 million (Ngaka Modiri Molema District Municipality, 2020a).

#### **3.1.2.2 General land use**

The economic activities vary for the different areas in the NMMD area. These activities include agriculture, tourism, arts and culture, as well as mining (Ngaka Modiri Molema District Municipality, 2020a). Agriculture, which includes crops and livestock, is recognised as one of

the key sectors in South Africa, as well as in the NMMD area. It plays an integrated role in food security and job creation (Department of Rural Development and Land Reform, 2016).

### **3.1.2.3 Water quality and accessibility**

The NMMD area is generally classified as a water scarce area (Ngaka Modiri Molema District Municipality, 2020a). Unpredictable rainfall, water pollution of surface water resources, and the increasing water demand of the mining and agricultural sectors dictate the water supply. Therefore, a substantial amount of water is imported from areas outside the district municipality to meet the high demand (Department of Rural Development and Land Reform, 2016).

The area's water supply includes surface water, groundwater and externally purchased sources (Department of Rural Development and Land Reform, 2016; Ngaka Modiri Molema District Municipality, 2020a). Surface water sources such as dams, springs, rivers and rainwater harvesting, which falls within the Water Service Authority (WSA) area of jurisdiction is used for abstraction (Ngaka Modiri Molema District Municipality, 2020a). The main source of surface water is Setumo Dam (Ngaka Modiri Molema District Municipality, 2020a). It has, however, been reported that the NMMD area does not have adequate surface water sources (Ngaka Modiri Molema District Municipality, 2019). It has also been reported that mining and waste dumping in the area place pressure on the quality of surface water sources (Department of Rural Development and Land Reform, 2016).

Groundwater is regarded as an extremely important water source in the NMMD, as it is the sole water supply to most rural communities in the area (Department of Rural Development and Land Reform, 2016; Ngaka Modiri Molema District Municipality, 2019). At present, both rural and urban communities rely on it as a source of water, leading to the extensive use thereof (Ngaka Modiri Molema District Municipality, 2019, 2020a). The main groundwater source is the Grootpan/ Lichtenburg/ Grootfontein/ Zeerust (GLGZ) dolomitic formation. The GLGZ dolomitic formation is used to supply water to Mahikeng LM, as well as parts of Ditsobotla and Ramotshere LMs (Ngaka Modiri Molema District Municipality, 2020a).

Water quality deterioration in the area is caused by agricultural drainage and wash-off, mining (causing an increase in acids and salts), and industrial effluents (leading to an increase in chemical substances). Wastewater discharge, which can also be due to poor sanitation, plays a big part in the deterioration of the groundwater quality (WRC, 2018). Over 60% of the households in the NMMD area do not have access to a flushing toilet, while 5% (13 977 households) do not have access to any sanitation system (Ngaka Modiri Molema District

Municipality, 2020a; Stats SA, 2018). The sanitation distribution for the NMMD area, as well as for the different LMs, is presented in Figure 21.

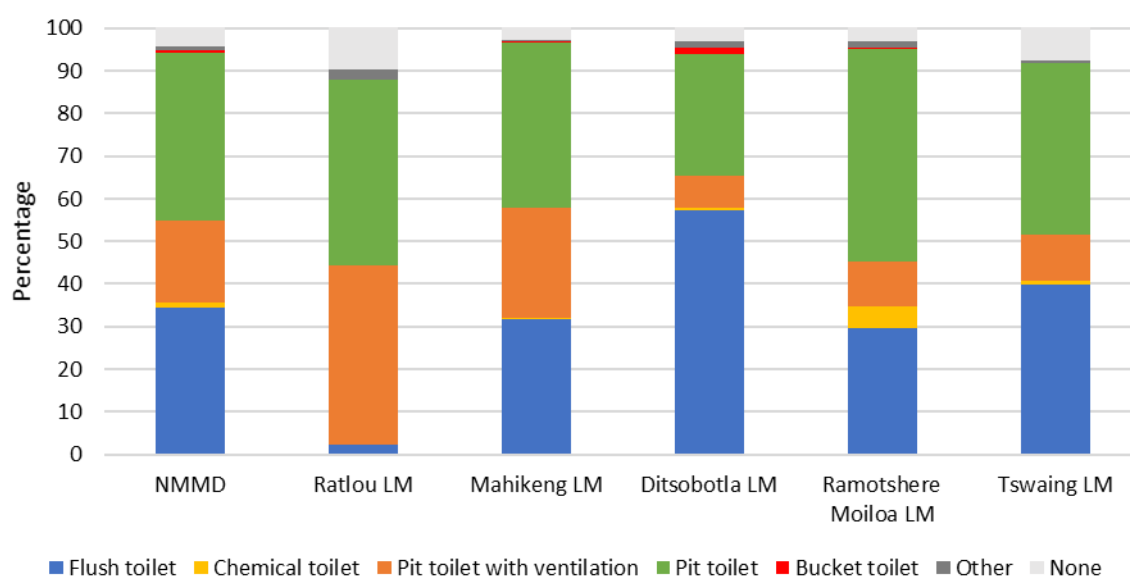


**Figure 21:** Household sanitation of the NMMD and local municipalities within the district municipality in 2016 (Stats SA, 2018).

A study conducted by Lolwana (2017) indicated that the greatest challenge experienced by people living in rural communities in the NMMD area is the lack of safe drinking water. The percentage households, located in the NMMD as well as in the different LMs, that have access to a safe drinking water supply is presented in Figure 22. Even though more than 85% of the households in the NMMD area have access to safe drinking water, 39 236 households are still lacking access (Stats SA, 2018).

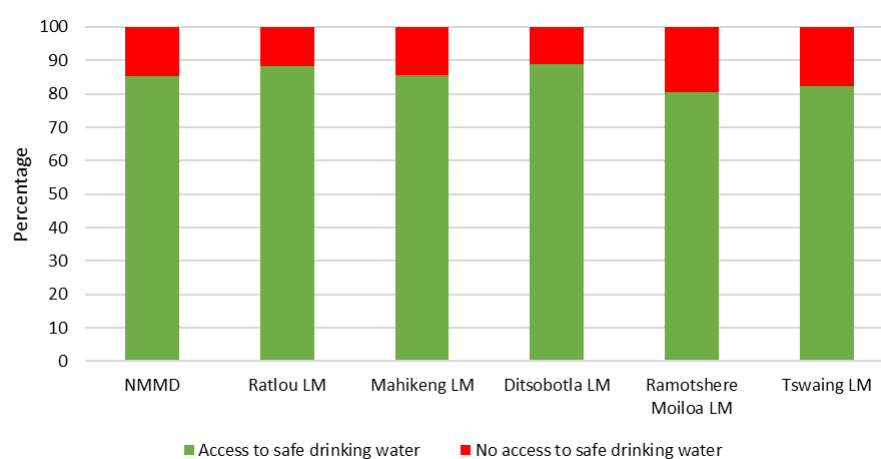


**Figure 22:** The percentage of households that have access to a safe drinking water supply in the NMMD area (Stats SA, 2018).

A survey was conducted by Stats SA (2016) in order to determine whether the households agree that the municipality is attempting to resolve the lack of safe and reliable water supplies. For the NMMD area, 48.3% and 24.8% of the households gave a rating of “strongly disagree” and “disagree”, respectively (Stats SA, 2018).

The potential exists for groundwater to be used to meet the majority water demand of the region (Ngaka Modiri Molema District Municipality, 2019), however, adequate groundwater management will be required. It was stated in the 2019/20 Integrated Development Plan of the NMMD that inconsistent and ineffective groundwater monitoring is taking place, especially in rural communities (Ngaka Modiri Molema District Municipality, 2019). Furthermore, groundwater quality testing is only done on an irregular basis (Ngaka Modiri Molema District Municipality, 2019).

## **3.2 Data collection**

In the following sections, the sampling (**Section 3.2.1**) and laboratory analysis (**Section 3.2.2**) procedures followed by Africa Geo-Environmental Engineering and Science (AGES) group, are presented. The ethical procedure which was followed for the use of the data is presented in **Section 3.2.3**

AGES is a company that specialises in the integration of natural resources, social and economic development, and building of sustainable communities. Some of the services that AGES deliver include groundwater resource development and creating solutions for the supply of water to a community (AGES, 2019).

AGES did various assessments on the status of boreholes, aquifers, and groundwater infrastructures in South Africa. The raw data used to conduct this study was therefore supplied by AGES. The assessments that were conducted in the Ngaka Modiri Molema District in 2019 were used for the research.

### **3.2.1 Sampling**

The groundwater quality of 90 boreholes located in the NMMD area, more specifically the Ditsobotla, Ratlou or Tswaing LM areas, were tested. In Figure 23, a map of the investigated boreholes is presented. The coordinates for each borehole located in Ditsobotla, Ratlou or Tswaing LM area are listed in Table 39, Table 40, and Table 41 in Appendix A, respectively.

Two samples were taken per borehole. One was sent for the chemical test and the other for the microbial test. A sampling bag was used for the chemical test sample, while a sampling

bottle was used for the microbial test sample. These sampling bags and bottles were labelled before the testing. Before the sample was taken, the sample bag and bottle were rinsed thoroughly with the groundwater to be tested. This procedure was repeated three times. Hereafter the sample was taken and the sample bag and/or bottle were sealed properly. The sample bag and bottle were then placed in a cooler box with ice and sent to the lab within 24 hours. The accepted sampling protocol according to the SANS 5667-1:2008 was followed to ensure sample integrity.

.

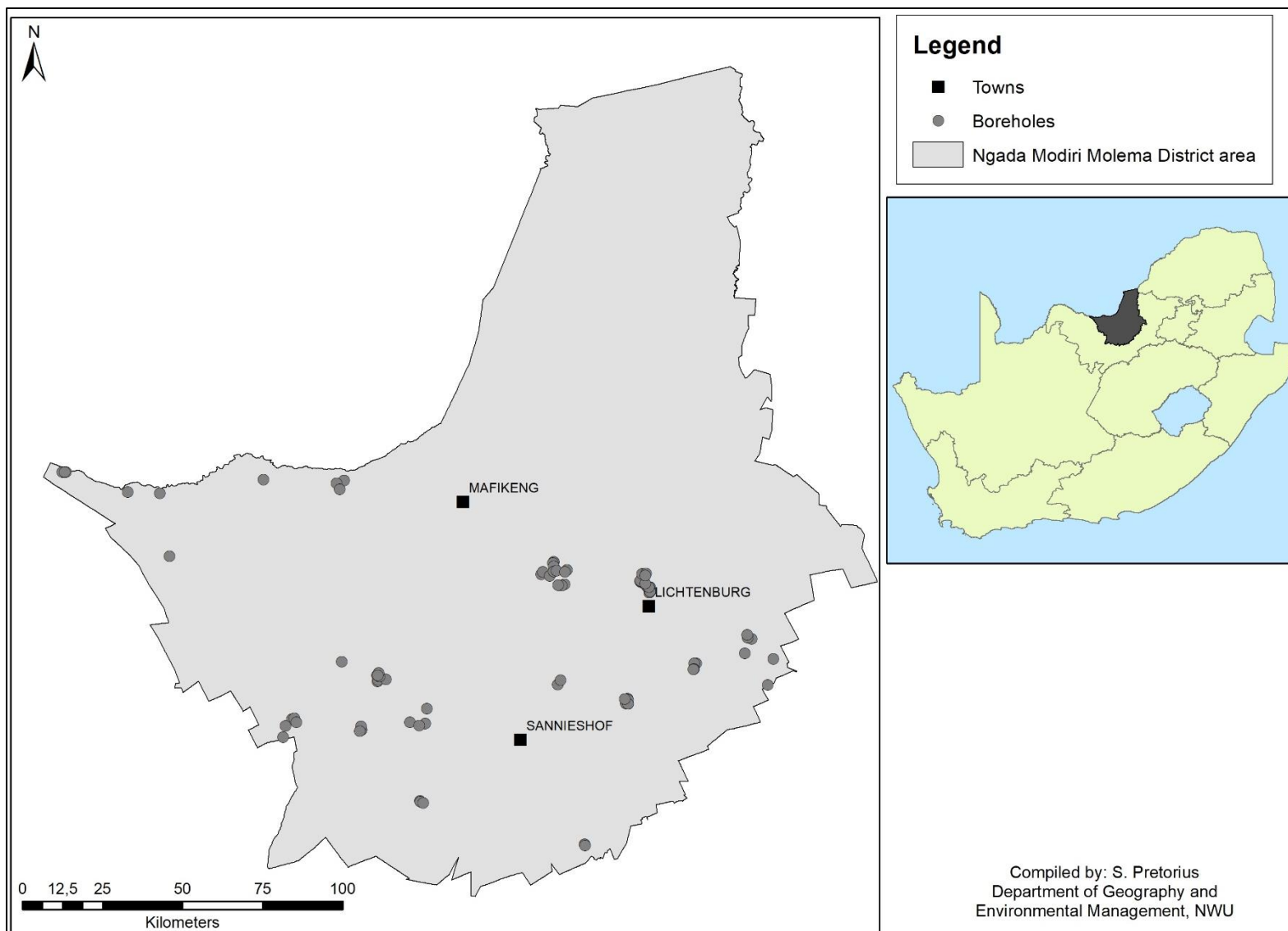


**Figure 23:** Boreholes investigated in the NMMD area.

### 3.2.2 Laboratory analysis

Eco Analytica was used as the main laboratory for the analysis of the physical and chemical parameters of the water samples. For the analysis of the microbiological parameters of the water sample, Envirocare Laboratory was used. Both laboratories are located in Potchefstroom in the North West Province (South Africa).

The physical parameters that were analysed include TDS and EC. For the chemical parameters pH, nitrate, sulfate, fluoride, chloride, zinc, copper, iron, manganese, calcium, magnesium, sodium, potassium, and bicarbonate were measured. Lastly, samples were analysed for the microbiological parameters, namely *Escherichia coli* (*E. coli*) and *Faecal coliform*.

The methods and/or equipment used for the analysis of each water quality parameter are listed in Table 22. Eco Analytica calculated the TDS value from the measured EC value.

**Table 22:** Equipment and/or methods for water quality parameter analysis.

| Water quality parameter   | Equipment                        | Method            |
|---------------------------|----------------------------------|-------------------|
| <i>E. coli</i>            |                                  | *                 |
| <i>Faecal coliform</i>    |                                  | *                 |
| Electrical conductivity   | WTW Cond 3210 Conductivity meter |                   |
| pH                        | Hanna EDGE pH meter              |                   |
| Nitrate ( $NO_3^-$ )      | Metrohm 761 Compact IC           | 1:2 Water Extract |
| Sulfate ( $SO_4^{2-}$ )   | Metrohm 761 Compact IC           | 1:2 Water Extract |
| Fluoride ( $F^-$ )        | Metrohm 761 Compact IC           | 1:2 Water Extract |
| Chloride ( $Cl^-$ )       | Metrohm 761 Compact IC           | 1:2 Water Extract |
| Bicarbonate ( $HCO_3^-$ ) | Titration                        | 1:2 Water Extract |
| Manganese ( $Mn^{2+}$ )   | Agilent ICP-MS                   | 1:2 Water Extract |
| Iron ( $Fe$ )             | Agilent ICP-MS                   | 1:2 Water Extract |
| Zink ( $Zn$ )             | Agilent ICP-MS                   | 1:2 Water Extract |
| Calcium ( $Ca^{2+}$ )     | Agilent ICP-MS                   | 1:2 Water Extract |
| Magnesium ( $Mg^{2+}$ )   | Agilent ICP-MS                   | 1:2 Water Extract |

| Water quality parameter | Equipment      | Method            |
|-------------------------|----------------|-------------------|
| Sodium ( $Na^+$ )       | Agilent ICP-MS | 1:2 Water Extract |
| Potassium ( $K^+$ )     | Agilent ICP-MS | 1:2 Water Extract |
| Copper ( $Cu$ )         | Agilent ICP-MS | 1:2 Water Extract |

\* For the analysis of *E. coli* and *Faecal coliform*, the following procedure was followed by Envirocare Laboratory:

1. The water sample was shaken thoroughly to ensure that the sample is homogeneous.
2. A sterile 0.45µm filter was placed into the filtration manifold.
3. 100ml of the sampled water was poured into the measured filtration cup.
4. The sampled water was filtered by applying a vacuum to the manifold.
5. The filter was removed aseptically and placed onto the selective growth medium.

The growth media used for *E. coli* and *Faecal coliform* were Chromogenic *E.coli* or coliform agar (Oxoid) and m-FC Agar (Difco), respectively. Information on the incubation times of the Chromogenic *E. coli*-coliform agar and m-FC agar are listed in Table 23.

**Table 23:** Chromogenic *E. coli* or coliform and m-FC agar incubation information.

|                                             | Incubation temperature | Incubation time |
|---------------------------------------------|------------------------|-----------------|
| Chromogenic <i>E. coli</i> or coliform agar | 36 ± 2°C               | 24 hours        |
| m-FC agar                                   | 43 ± 2°C               | 24 hours        |

The *E. coli* colonies showed a deep purple colour on the chromogenic agar, while the *Faecal coliform* showed a deep blue colour on the m-FC agar.

### 3.2.3 Research ethics

An ethical clearance application was conducted to the North West University ethical clearance committee in order to ensure that the research was conducted in an ethical manner. A non-disclosure agreement between AGES and the NWU was made where permission was granted to use the collected data and obtained results, however only for research purposes. The ethical clearance letter, which states the approval of the study, is presented in Figure 63 and Figure 64 Appendix C.

### **3.3 Data analysis**

#### **3.3.1 Database**

The database consists of 90 boreholes and 18 water quality parameters and therefore comprise of 1 620 data points. These data points were obtained in 2019, as all the sampling and laboratory analyses were conducted at that time. A once-off water quality measurement was taken for each borehole and therefore the database is relatively small, as it only comprises of one dataset per borehole. The database, along with information on the date of sampling and location is presented in Table 42, Table 43, and Table 44 in Appendix A.

The program which was used for the database development and data manipulation is Excel spreadsheet.

#### **3.3.2 Data manipulation**

##### **3.3.2.1 Water quality parameters**

For the analysis of water for drinking purposes, 13 water quality parameters were used, namely *E. coli*, *Faecal coliform*, TDS, EC, pH, nitrate, sulfate, fluoride, chloride, manganese, iron, zinc, and copper. For livestock purposes, 10 water quality parameters were used for the analysis of the water quality, namely TDS, EC, pH, nitrate, sulfate, chloride, calcium, magnesium, sodium, and copper. Lastly, 10 water quality parameters were used for the water quality analysis for irrigation purposes, namely TDS, EC, pH, chloride, PI, KR, %Na, SAR, MAR, and PS. The irrigation indices were calculated with the use of Equations 2 to 7, in **Section 2.4.2.17**.

##### **3.3.2.2 Water quality index**

The WQI was used to evaluate the groundwater quality for drinking, livestock and irrigation purposes.

Four steps were followed in the calculation of the WQI. In the first step, the relative weights,  $W_i$ , for each parameter were obtained with the use of Equation 10 (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Khanoranga, 2019; Masoud & Ali, 2020; Olasoji *et al.*, 2019; Saikrishna *et al.*, 2020; Zahedi, 2017).

$$W_i = \frac{w_i}{\sum_{i=1}^n w_i} \quad (10)$$

For each parameter,  $i$ , variable weights,  $w_i$ , were assigned before the relative weights could be calculated.

The variable weights indicate the importance of the specific parameter in the deterioration of the water quality. For the parameters with the highest risk, a value of 5 was assigned to it, where a value of 1 was assigned to parameters with the lowest risk (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Khanoranga, 2019; Masoud & Ali, 2020; Olasoji *et al.*, 2019; Saikrishna *et al.*, 2020; Zahedi, 2017).

These weights can be chosen with the use of a group of experts or with the use of literature (Olasoji *et al.*, 2019). For this study, various literature extracts were used for assigning the variable weights to the specific parameters. Since these weights vary in different studies and not all studies use the same parameters, a method was followed to integrate the weights of different recent WQI studies. Ten different studies that were conducted on the groundwater quality for drinking purposes were integrated in this study for the human consumption component, whereas for livestock and irrigation purposes, only four and five studies, respectively, were used due to the limitation of available information. The weights for each parameter of the different studies were added together and then divided by the number of available weights for each parameter from the studies.

The assigned parameter weights, obtained from different studies, as well as the new calculated weight for the current study, are presented in Table 24, Table 25, and Table 26 for drinking, livestock and irrigation purposes, respectively.

**Table 24:** The assigned parameter weights from recent studies for drinking purposes.

| Parameters                 | Assigned weights, $w_i$ |   |   |   |   |   |   |   |   |    |     |
|----------------------------|-------------------------|---|---|---|---|---|---|---|---|----|-----|
| Studies*:                  | 1                       | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | NEW |
| <b>Physical parameters</b> |                         |   |   |   |   |   |   |   |   |    |     |
| EC at 25 °C                | -                       | - | - | - | 4 | 4 | - | 4 | - | -  | 4.0 |
| TDS                        | 4                       | 5 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | -  | 4.4 |
| <b>Chemical parameters</b> |                         |   |   |   |   |   |   |   |   |    |     |
| pH at 25 °C                | 5                       | - | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4  | 4.0 |
| Nitrate ( $NO_3^-$ )       | 5                       | 5 | 5 | 5 | 5 | 5 | 5 | 5 | - | 5  | 5.0 |
| Sulfate ( $SO_4^{2-}$ )    | 4                       | 5 | 4 | 5 | 5 | 5 | 4 | 4 | 5 | 5  | 4.6 |
| Fluoride ( $F^-$ )         | -                       | - | 4 | 5 | 4 | 5 | 4 | - | - | -  | 4.4 |
| Chloride ( $Cl^-$ )        | 3                       | 5 | 3 | 5 | 5 | 4 | 3 | 3 | 5 | 5  | 4.1 |
| Manganese ( $Mn^{2+}$ )    | -                       | 5 | 4 | 4 | - | 4 | - | 4 | - | -  | 4.2 |
| Iron (Fe)                  | -                       | 5 | 4 | 3 | - | 4 | - | 5 | - | -  | 4.2 |
| Zink (Zn)                  | -                       | - | - | 2 | - | 3 | - | - | - | -  | 2.5 |
| Copper (Cu)                | -                       | - | - | 2 | - | 2 | - | - | - | -  | 2.0 |

\*The information of the ten studies used for the evaluation of water quality for drinking purposes, from which the assigned parameter weights were obtained, are listed in Table 27.

**Table 25:** The assigned parameter weights from recent studies for livestock purposes.

| Parameters<br>Studies*:    | Assigned weights, $w_i$                                        |                                    |                                               |                                 |     |
|----------------------------|----------------------------------------------------------------|------------------------------------|-----------------------------------------------|---------------------------------|-----|
|                            | Al-Saffawi, Ibn<br>Abubakar, Al-Asaat,<br><i>et al.</i> , 2020 | Saucedo-Terán <i>et al.</i> , 2017 | Al-Saffawi, Al-Assaf,<br><i>et al.</i> , 2020 | Hussain <i>et al.</i> ,<br>2018 | NEW |
| <b>Physical parameters</b> |                                                                |                                    |                                               |                                 |     |
| EC at 25 °C                | 4.0                                                            | 3.0                                | 4.0                                           | -                               | 3.7 |
| TDS                        | -                                                              | 3.0                                | -                                             | 1.2                             | 0.6 |
| <b>Chemical parameters</b> |                                                                |                                    |                                               |                                 |     |
| pH at 25 °C                | 4.0                                                            | 3.0                                | 4.0                                           | -                               | 3.7 |
| Nitrate ( $NO_3^-$ )       | 5.0                                                            | -                                  | 5.0                                           | -                               | 5.0 |
| Sulfate ( $SO_4^{2-}$ )    | 4.0                                                            | -                                  | 4.0                                           | 5.0                             | 4.3 |
| Chloride ( $Cl^-$ )        | 3.0                                                            | -                                  | 1.0                                           | 1.2                             | 1.7 |
| Calcium ( $Ca^{2+}$ )      | 2.0                                                            | -                                  | 2.0                                           | 2.2                             | 2.1 |
| Magnesium ( $Mg^{2+}$ )    | 2.0                                                            | 2.0                                | 2.0                                           | 2.2                             | 2.1 |
| Sodium ( $Na^+$ )          | 3.0                                                            | -                                  | 3.0                                           | 2.2                             | 2.7 |
| Copper ( $Cu$ )            | -                                                              | 2.0                                | -                                             | -                               | 2.0 |

**Table 26:** The assigned parameter weights from recent studies for irrigation purposes.

| Parameters                 | Assigned weights, $w_i$          |                                    |                                 |              |                     |     |
|----------------------------|----------------------------------|------------------------------------|---------------------------------|--------------|---------------------|-----|
|                            | Al-Assaf <i>et al.</i> ,<br>2020 | Al-Saffawi <i>et al.</i> ,<br>2021 | Hussain <i>et al.</i> ,<br>2018 | Zahedi, 2017 | Khanoranga,<br>2019 | NEW |
| <b>Physical parameters</b> |                                  |                                    |                                 |              |                     |     |
| EC at 25 °C                | 5                                | 5                                  | -                               | 5            | 4                   | 4.8 |
| TDS                        | -                                | -                                  | 2                               | -            | 4                   | 3.1 |
| <b>Chemical parameters</b> |                                  |                                    |                                 |              |                     |     |
| pH at 25 °C                | 4                                | 3                                  | 1                               | -            | 4                   | 3.1 |
| Chloride ( $Cl^-$ )        | 3                                | 1                                  | -                               | 5            | 4                   | 3.3 |
| <b>Irrigation indices</b>  |                                  |                                    |                                 |              |                     |     |
| PI                         | 5                                | 5                                  | -                               | -            | -                   | 5.0 |
| KR                         | 3                                | 4                                  | -                               | -            | -                   | 3.5 |
| %Na                        | 4                                | 4                                  | 2                               | -            | -                   | 3.4 |
| SAR                        | 5                                | 4                                  | 5                               | 3            | -                   | 4.3 |
| MAR                        | 4                                | 3                                  | -                               | -            | -                   | 3.5 |
| PS                         | 4                                | 3                                  | -                               | -            | -                   | 3.5 |

**Table 27:** The ten studies used to assign parameter weights.

| Study | References                          |
|-------|-------------------------------------|
| 1     | Al-Saffawi <i>et al.</i> , 2018     |
| 2     | Chourasia, 2018                     |
| 3     | Ramakrishnaiah <i>et al.</i> , 2009 |
| 4     | Ibrahim, 2019                       |
| 5     | Saikrishna <i>et al.</i> , 2020     |
| 6     | Khanoranga, 2019                    |
| 7     | Badeenezhad <i>et al.</i> , 2020    |
| 8     | Masoud & Ali, 2020                  |
| 9     | Soleimani <i>et al.</i> , 2018      |
| 10    | Gaikwad <i>et al.</i> , 2020        |

In the second step, the water quality rating,  $q_i$ , for each parameter,  $i$ , was calculated with the use of Equation 11 (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Khanoranga, 2019; Masoud & Ali, 2020; Olasoji *et al.*, 2019; Saikrishna *et al.*, 2020; Zahedi, 2017).

$$q_i = 100 \left( \frac{C_i}{S_i} \right) \quad (11)$$

Where  $C_i$  is the measured water quality value of the  $i$ -th parameter, which was obtained at the sampling site, and  $S_i$  is the water quality standard for each parameter

In order to determine the water quality rating for pH, Equation 12 was used, where  $C_{pH}$  is the measured pH value (Wanda *et al.*, 2016; Zahedi, 2017). The recommended pH standards for drinking, livestock, and irrigation purposes fall within different upper and lower limits, therefore,  $S_{Upper}$ , and  $S_{Lower}$  was used to describe the upper and lower pH limit, respectively.

$$q_{pH} = 100 \left( \frac{C_{pH} - S_{Lower}}{S_{Upper} - S_{Lower}} \right) \quad (12)$$

Thirdly, the sub-index,  $SI_i$ , for each parameter,  $i$ , was obtained through Equation 13 (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Khanoranga, 2019; Masoud & Ali, 2020; Olasoji *et al.*, 2019; Saikrishna *et al.*, 2020; Zahedi, 2017).

$$SI_i = W_i q_i \quad (13)$$

The relative weights,  $W_i$ , along with the SANS water quality standards,  $S_i$ , for drinking purposes are listed in Table 28. For livestock and irrigation purposes, the relative weights,  $W_i$ , along with the water quality standards,  $S_i$ , are listed in Table 29 and Table 30, respectively.

**Table 28:** Assigned relative weights and SANS 241-1(2015) drinking water quality standards for the specified parameters.

| Parameters              | $S_i$        |      | $w_i$                | $W_i$            |
|-------------------------|--------------|------|----------------------|------------------|
|                         | Value        | Unit |                      |                  |
| Physical parameters     |              |      |                      |                  |
| EC at 25 °C             | ≤ 170        | mS/m | 4.0                  | 0.0923           |
| TDS                     | ≤ 1 200      | mg/L | 4.4                  | 0.1015           |
| Chemical parameters     |              |      |                      |                  |
| pH at 25 °C             | ≥ 5 to ≤ 9.7 | -    | 4.0                  | 0.0923           |
| Nitrate ( $NO_3^-$ )    | ≤ 5          | mg/L | 5.0                  | 0.1153           |
| Sulfate ( $SO_4^{2-}$ ) | ≤ 250        | mg/L | 4.6                  | 0.1051           |
| Fluoride ( $F^-$ )      | ≤ 1.5        | mg/L | 4.4                  | 0.1015           |
| Chloride ( $Cl^-$ )     | ≤ 300        | mg/L | 4.1                  | 0.0946           |
| Manganese ( $Mn^{2+}$ ) | ≤ 100        | µg/L | 4.2                  | 0.0969           |
| Iron ( $Fe$ )           | ≤ 300        | µg/L | 4.2                  | 0.0969           |
| Zink ( $Zn$ )           | ≤ 5          | mg/L | 2.5                  | 0.0577           |
| Copper ( $Cu$ )         | ≤ 2 000      | µg/L | 2.0                  | 0.0461           |
|                         |              |      | $\Sigma w_i = 43.36$ | $\Sigma W_i = 1$ |

**Table 29:** Assigned relative weights and water quality standards for the specified parameters for water used for livestock purposes.

| Parameters              | $S_i$                |                 | $w_i$ | $W_i$          |
|-------------------------|----------------------|-----------------|-------|----------------|
|                         | Value                | Unit            |       |                |
| Physical parameters     |                      |                 |       |                |
| EC at 25 °C             | $\leq 160$           | mS/m            | 3.7   | 0.1288         |
| TDS                     | $\leq 3\ 000$        | mg/L            | 1.2   | 0.0425         |
| Chemical parameters     |                      |                 |       |                |
| pH at 25 °C             | $\geq 6$ to $\leq 9$ | -               | 3.7   | 0.1288         |
| Nitrate ( $NO_3^-$ )    | $\leq 133$           | mg/L            | 5.0   | 0.1756         |
| Sulfate ( $SO_4^{2-}$ ) | $\leq 500$           | mg/L            | 4.3   | 0.1522         |
| Chloride ( $Cl^-$ )     | $\leq 2\ 000$        | mg/L            | 1.7   | 0.0610         |
| Calcium ( $Ca^{2+}$ )   | $\leq 1\ 000$        | mg/L            | 2.1   | 0.0727         |
| Magnesium ( $Mg^{2+}$ ) | $\leq 500$           | mg/L            | 2.1   | 0.0721         |
| Sodium ( $Na^+$ )       | $\leq 300$           | mg/L            | 2.7   | 0.0961         |
| Copper ( $Cu$ )         | $\leq 0.5$           | $\mu\text{g/L}$ | 2.0   | 0.0702         |
|                         |                      |                 |       | $\sum W_i = 1$ |

**Table 30:** Assigned relative weights and water quality standards for the specified parameters for water used for irrigation purposes.

| Parameters          | $S_i$                    |      | $w_i$ | $W_i$          |
|---------------------|--------------------------|------|-------|----------------|
|                     | Value                    | Unit |       |                |
| Physical parameters |                          |      |       |                |
| EC at 25 °C         | $\leq 200$               | mS/m | 1     | 0.1273         |
| TDS                 | $\leq 1\ 400$            | mg/L | 2     | 0.0832         |
| Chemical parameters |                          |      |       |                |
| pH at 25 °C         | $\geq 6.5$ to $\leq 8.5$ | -    | 3     | 0.0818         |
| Chloride ( $Cl^-$ ) | $\leq 350$               | mg/L | 4     | 0.0871         |
| Irrigation indices  |                          |      |       |                |
| PI                  | $\leq 75$                | mg/L | 5     | 0.1340         |
| KR                  | $\leq 1$                 |      | 6     | 0.0938         |
| %Na                 | $\leq 60$                | mg/L | 7     | 0.0912         |
| SAR                 | $\leq 26$                | mg/L | 8     | 0.1139         |
| MAR                 | $\leq 50$                | mg/L | 9     | 0.0938         |
| PS                  | $\leq 10$                | mg/L | 10    | 0.0938         |
|                     |                          |      |       | $\sum W_i = 1$ |

In the final step, the WQI was calculated, as indicated by Equation 14 (Al-Assaf *et al.*, 2020; Al-Saffawi *et al.*, 2021; Khanoranga, 2019; Masoud & Ali, 2020; Olasoji *et al.*, 2019; Saikrishna *et al.*, 2020; Zahedi, 2017).

$$WQI = \sum SI_i \quad (14)$$

The WQI ranges for the classification of drinking water are listed in Table 31 (Al-Omran *et al.*, 2015; Khanoranga, 2019; Olasoji *et al.*, 2019; Saikrishna *et al.*, 2020).

**Table 31:** Water quality classification based on the WQI

| WQI Range | Class | Water quality classification |
|-----------|-------|------------------------------|
| < 50      | I     | Excellent                    |
| 50 – 100  | II    | Good                         |
| 100 – 200 | III   | Poor                         |
| 200 – 300 | IV    | Very poor                    |
| > 300     | V     | Unsuitable                   |

### 3.3.2.3 Water quality colour classification

The colour classification was developed for borehole status plotting on the NMMD area map, where each borehole was allocated a colour according to its water quality status. This was done to present the borehole status distribution in a simple manner.

The standards used for drinking, livestock and irrigation purposes do not categorise the water quality into different classes, but merely state the limit for each parameter. Therefore, the WQI classes were used and then further categorised into three groups, namely acceptable, marginal, and unacceptable. A specific colour was allocated to each classification, namely green for “acceptable”, yellow for “marginal” and red for “unacceptable”. The WQI classes I and II were classified collectively as acceptable, with the colour green allocated to them. Class III and Class IV of the WQI were classified as poor, but not unacceptable. Yellow was assigned for these two classes and were classified as “marginal”. The WQI classifies Class V as unacceptable, and therefore the colour red was allocated to it. The assigned colour classes as used for this study are presented in Table 32.

**Table 32:** Water quality classification

| WQI Class | Water quality classification | Assigned colour class for this study |
|-----------|------------------------------|--------------------------------------|
| I         | Excellent                    | Acceptable                           |
| II        | Good                         |                                      |
| III       | Poor                         | Marginal                             |
| IV        | Very poor                    |                                      |
| V         | Unsuitable                   | Unacceptable                         |

The borehole status plotting was conducted with the use of ArcMap 10.7 GIS software. The borehole coordinates were processed and the specific colour was allocated to each borehole to indicate the water quality status thereof.

### **3.4 Research limitations**

The following limitations of previous studies, as well as limitations on the current research were recognized and ways in which the limitations were addresses or minimized are presented.

#### **3.4.1 Limitations of previous studies**

1. There are some limitations to the WQI, as microbial parameters such as *E. coli*, *Faecal coliform*, total coliforms and heterotrophic plate counts are not included in the water quality analysis method for drinking water (Olasoji *et al.*, 2019). Few studies can be found where microbial parameters have been included (Olasoji *et al.*, 2019). Al-Omran *et al.* (2015) deemed the water quality unacceptable for drinking purposes (class V) in the case of the presence of *E. coli* or *Faecal coliform*. For the following study, this approach will be followed with regard to drinking water.
2. The literature extracts used for assigning the variable weights in the WQI calculation were either inconsistent in the weight allocation for the various parameters, or did not evaluate the same parameters. In order to minimize the effect of the inconsistency, several different literature extracts were intergraded, where from that the variable weights were calculated. More information on the method has been mentioned in **Section 3.3.2.2**.
3. Limited literature is available on the detailed costs of water purification technologies, which therefore limited the current research to give a clear indication on the cost ranking of the different water treatments. The amount of water purified plays a role in the treatment cost (Campinas *et al.*, 2021), and therefore a cost comparison study where different purification technologies are compared for the same amount of water purified, is important. The limit was minimized by giving the best possible estimations obtained from literature.

### **3.4.2 Limitations of the current research**

1. As mentioned in **Section 3.1**, the NMMD area comprises out of five LMs, where only three of the five are evaluated in the dissertation. The research is therefore limited, where the definite overall water quality status of the NMMD area is not evaluated. The inclusion of the outstanding LM areas' water quality data were not possible, as water quality data on the boreholes in those areas were not available. The limitation is recognized and included in the recommendations for future studies.

## CHAPTER 4: RESULTS AND DISCUSSION

In Chapter 4, the results and discussion of the water quality analyses for drinking, livestock and irrigation purposes, with the use of the WQI model, are presented. For the Ditsobotla, Ratlou, and Tswaing LM areas, located in the NMMD area, 50, 17 and 23 boreholes were investigated, respectively. The WQI class, as well as the status of the individual water quality parameters of the 90 investigated boreholes, are presented in full.

The results of the WQI classification for drinking, livestock, and irrigation purposes for each of the investigated LM areas are presented in **Section 4.1**, along with the spatial distribution of the groundwater quality status for the investigated LM areas for drinking, livestock, and irrigation use. The water quality parameters for drinking, livestock and irrigation purposes were evaluated individually for each of the investigated LMs, as discussed in **Section 4.2**. The parameters not adhering to the required standards were evaluated individually to provide an understanding as to what the cause might be for some boreholes to have a low WQI rating.

### 4.1 Groundwater quality analysis according to the WQI

The WQI classes were used to describe the overall water quality status of the investigated boreholes. Furthermore, a spatial distribution map of the water quality status of each investigated borehole for drinking, livestock and irrigation purposes were constructed for the Ditsobotla, Ratlou, and Tswaing LM areas. The colour classification was used to indicate the borehole quality status on the map. The results of the WQI status for the investigated boreholes, along with a special distribution map are presented. The WQI rating for drinking, livestock, and irrigation purposes of the investigated boreholes for the Ditsobotla, Ratlou, and Tswaing LMs are presented in Table 45, Table 46, and Table 47 in Appendix B, respectively.

#### 4.1.1 Drinking purposes

Since there are some limitations to the WQI, namely the exclusion of microbial parameters, the water quality analysis using the WQI was conducted in two phases. The physical and chemical parameters, which include EC, TDS, pH and the concentrations of nitrate, sulfate, fluoride, chloride, zinc, copper, iron, and manganese, were first analysed for each borehole. In the second phase, the microbial contaminants, including *Faecal coliform* and *E. coli*, were included.

#### 4.1.1.1 Physical and chemical parameters

In Figure 24, an overview of the WQI status, for the investigated boreholes is presented. The percentage boreholes which have a water quality status of either “excellent” (Class I), “good” (Class II), “poor” (Class III), “very poor” (Class IV), or “unacceptable” (Class V), are shown. The overall water quality status of these three municipality areas combined is also presented in Figure 24.

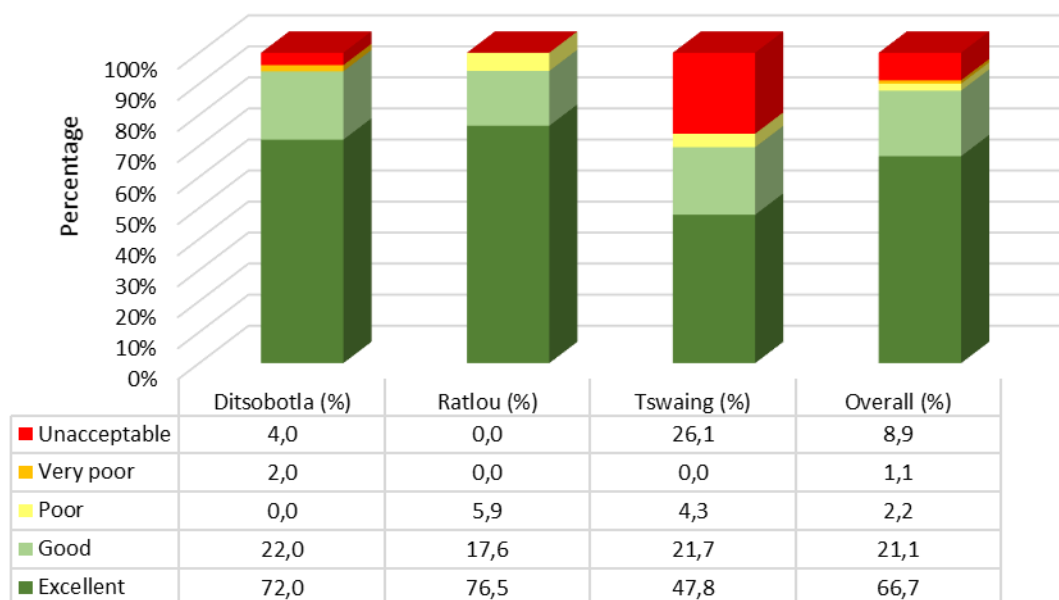


**Figure 24:** The drinking water quality statuses of boreholes according to physical and chemical parameters.

##### 4.1.1.1.1 Ditsobotla

For the Ditsobotla LM area, 72% and 22% of the boreholes were classified as Class I and Class II, respectively. 2% of the boreholes were classified as Class IV, which, even though they indicated very poor water quality, were still suitable for use. Therefore, 96% of the boreholes located in the Ditsobotla LM area were acceptable for consumption and posed little to no health risk to consumers. The water from the remaining 4% of the boreholes was unsuitable for drinking purposes.

##### 4.1.1.1.2 Ratlou

In the Ratlou LM area, 76.5% of the boreholes had Class I water and 17.6% were classified as Class II. The remaining 5.9% of the investigated boreholes fell within the Class III

classification, leaving all the boreholes as acceptable for drinking purposes when only physical and chemical parameters were considered. Of the three considered LM areas, Ratlou had the best groundwater quality.

#### **4.1.1.1.3 Tswaing**

With regard to the physical and chemical parameters, the Tswaing LM area had the worst groundwater quality of the three investigated LM areas in the NMMD. 26.1% of the investigated boreholes were classified as Class V, which is unsuitable for drinking purposes. The percentage boreholes that were classified as Class I and Class II were 47.8% and 21.7%, respectively. The remaining 4.3% were recorded as Class III.

#### **4.1.1.1.4 Overall water quality**

The overall water quality status with regard to the physical and chemical pollutants was classified as good for the three investigated municipality areas. It was recorded that 66.7% and 21.1% of the boreholes were classified as Class I and Class II, respectively. Only 2.2% and 1.1% were reported as Class III and Class IV, respectively. Overall, 8.9% of the investigated boreholes were recorded as “unacceptable”. Therefore, the overall water quality for the three investigated LM areas in the NMMD area was classified as acceptable for drinking purposes.

For the boreholes classified as Class III or Class IV, it is recommended that the physical, chemical and microbiological parameters be investigated to determine whether the water is acceptable for drinking, as it was classified as “marginal”. For the boreholes classified as Class V, the parameters need to be considered individually to determine what the cause might be for the poor WQI rating, as well as to know which water purification technologies would be required for the improvement of the water quality.

#### **4.1.1.2 Physical, chemical, and microbiological parameters**

Figure 25 presents an overview of the drinking water quality statuses of the investigated boreholes where physical, chemical, as well as microbiological contaminants were also taken into consideration.

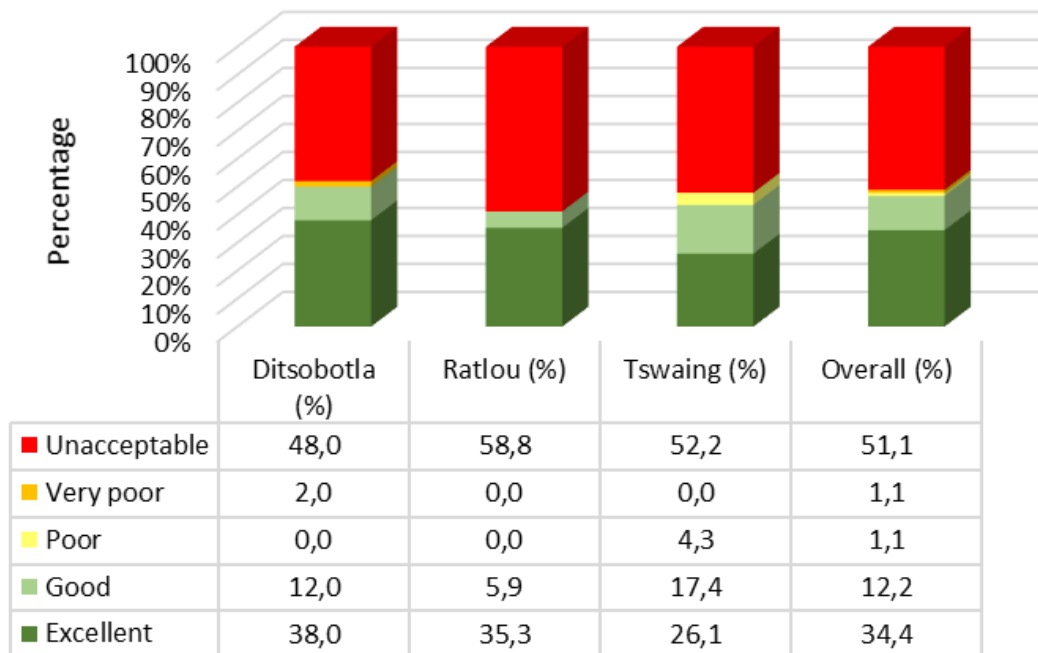


**Figure 25:** The water quality statuses of boreholes for drinking purposes according to physical, chemical and microbiological parameters.

#### 4.1.1.2.1 Ditsobotla

The percentage of boreholes in the Ditsobotla municipality area that were recorded as unacceptable increased from 4% to 48% due to the presence of microbial contaminants. This indicated severe microbial contamination, which poses a great health risk to the consumers. Just over half the boreholes (52%) were still deemed acceptable for drinking purposes, while 2% were classified as Class IV.

#### 4.1.1.2.2 Ratlou

With regard to the Ratlou LM area, the number of boreholes that were recorded as unacceptable increased from 0% to 58.8% due to microbial contaminants. Ratlou, which had been labelled as having the best water quality in **Section 5.1.1.1**, was now regarded as having the worst. The biggest problem with regard to water quality in the Ratlou LM area was microbial contamination.

#### 4.1.1.2.3 Tswaing

The percentage of boreholes that are recorded as “unacceptable” in the Tswaing municipality area increased from 26.1% to 52.2%, due to the presence of microbial contaminants. More

than half of the reported boreholes in the area posed a health risk to consumers. Of the investigated boreholes 26.1%, 17.4%, and 4.3% were classified as Class I, Class II, and Class III, respectively.

#### **4.1.1.2.4 Overall water quality**

Overall, the water quality statuses of the boreholes in the reported area worsened when microbial contaminants were taken into consideration. The percentage of boreholes regarded as “unacceptable”, increased from 8.9% to 51.1% due to microbial contamination. The majority of the boreholes posed a health risk to consumers.

The high levels of microbial contamination in the three investigated municipal areas could be due to pollution caused by poor sanitation, direct waste, as well as agricultural runoff from livestock farms (Dangi *et al.*, 2017; Oram, 2020). The high levels of microbial contaminants greatly affected the state of the drinking water quality in the NMMD area.

For the North West Province, faecal indicator bacteria have been reported to be present in groundwater sources (Nkwe *et al.*, 2015). Microbial contamination poses a great risk to the health of consumers and, therefore, intervention strategies, as well as an in-depth investigation into the source of the problem, are important. The water of the boreholes that were classified as Class V, should be purified before use.

#### **4.1.1.3 Water Quality Index quality distribution of groundwater for drinking purposes**

Physical, chemical, and microbial contaminants were taken into consideration for the construction of the groundwater for drinking purposes quality distribution map. The distribution maps for the Ditsobotla, Ratlou, and Tswaing LM areas are presented in Figure 26, Figure 27, and Figure 28, respectively.

.

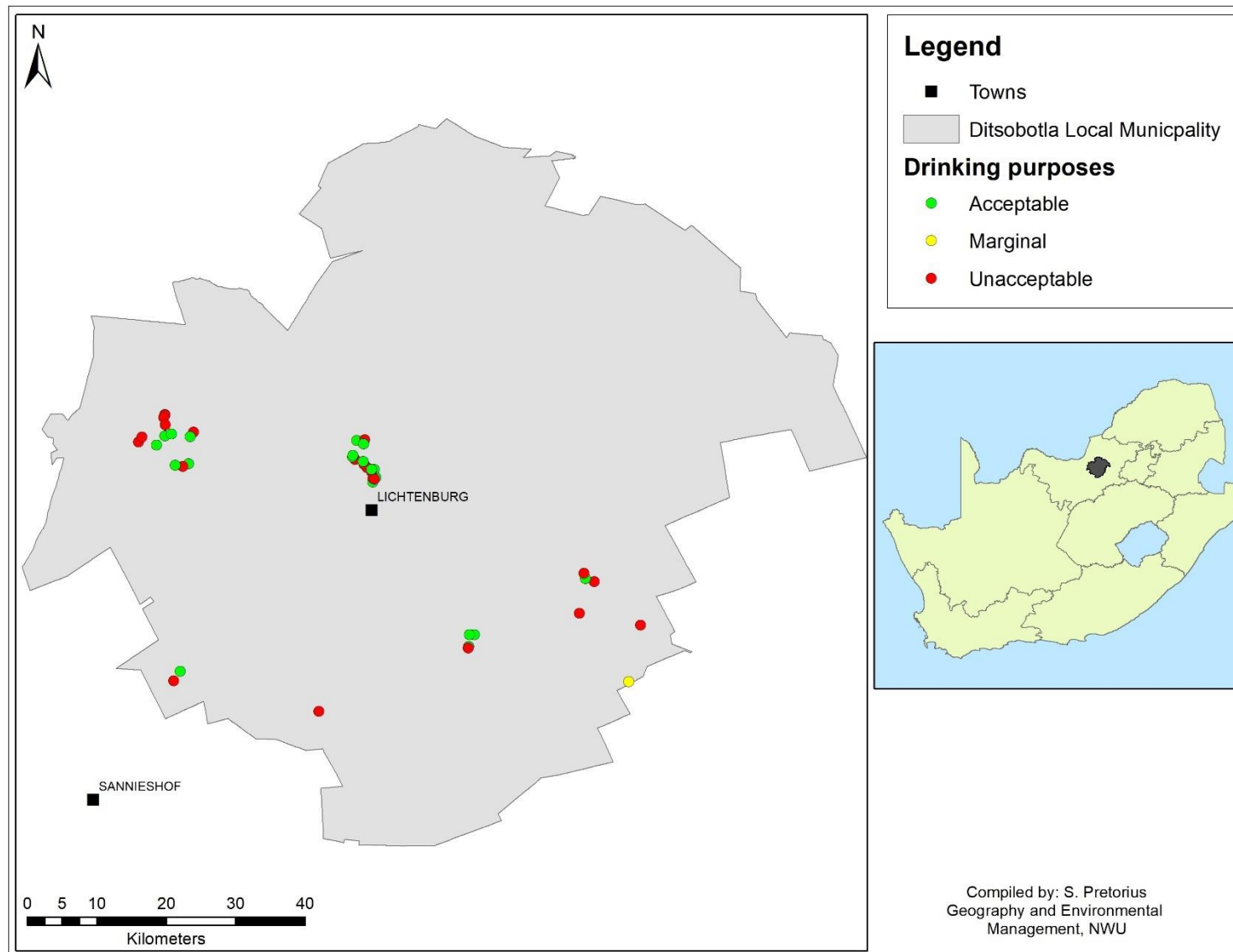


**Figure 26:** Drinking water quality classification of each borehole located in the Ditsobotla LM.

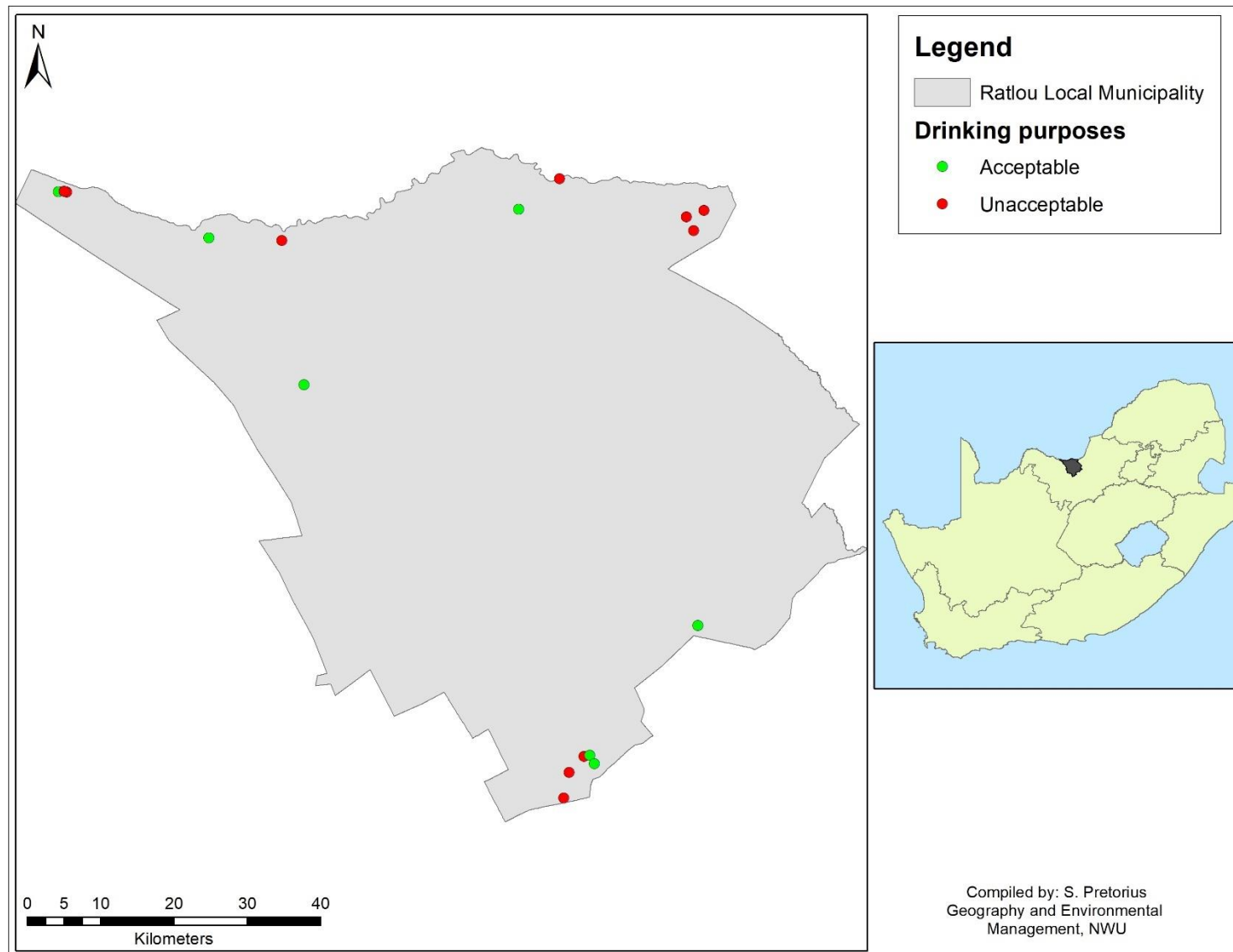


**Figure 27:** Drinking water quality classification of each borehole located in the Ratlou LM.

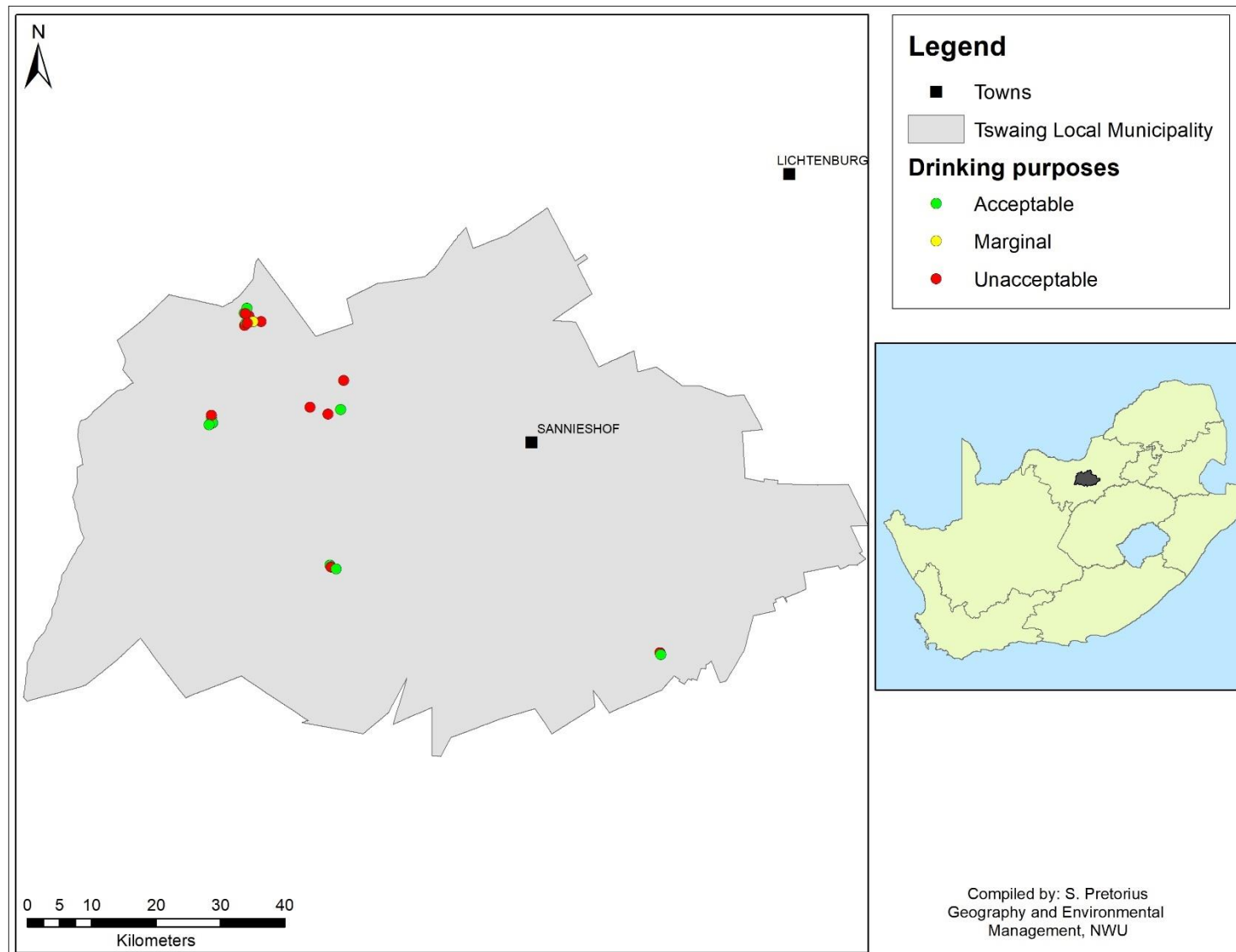


**Figure 28:** Drinking water quality classification of each borehole located in the Tswaing LM.

### 4.1.2 Water quality for livestock purposes

An overview of the water quality status for livestock use, as classified according to the WQI, for the three evaluated LM areas are presented in Figure 29.

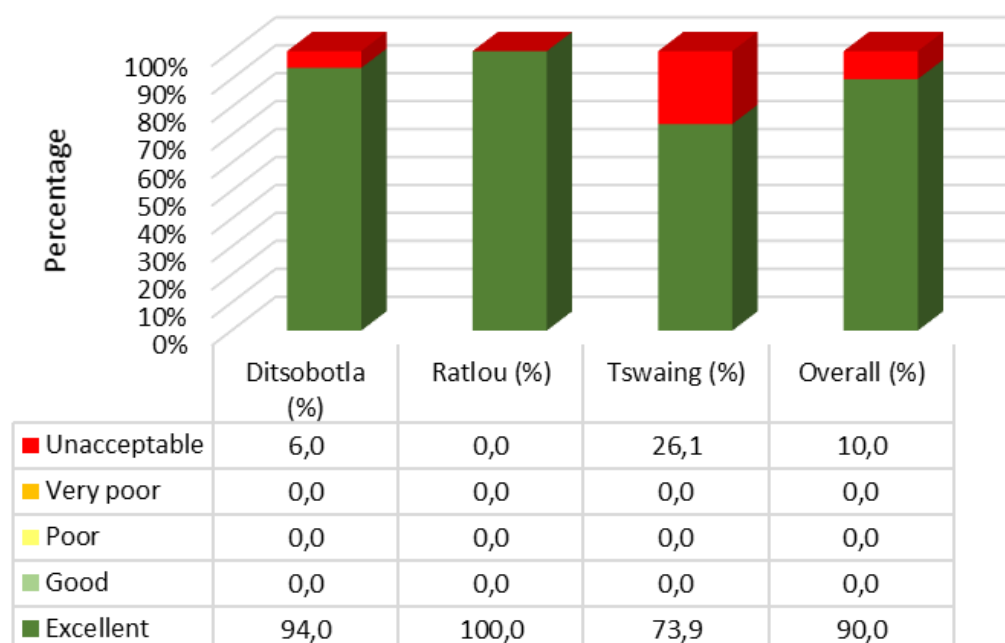


**Figure 29:** Livestock water quality statuses of boreholes according to the WQI.

#### 4.1.2.1 Ditsobotla

For the Ditsobotla LM area, 94% of the evaluated boreholes fell within the Class I classification for livestock use. Only 6% of the boreholes needed to be improved by water purification methods or technologies, as they were classified as Class V.

#### 4.1.2.2 Ratlou

The water quality in the Ratlou LM area was suitable for livestock use, as 100% of the investigated boreholes were classified as Class I. Therefore, no intervention strategies were required for the improvement of water quality. Compared to the other LM areas investigated, Ratlou had the best water quality for livestock purposes.

#### 4.1.2.3 Tswaing

73.9% of the investigated boreholes in the Tswaing LM area were regarded as suitable for livestock use, as they were classified as Class I. This was, however, poor in comparison to

the Ditsobotla and Ratlou LM areas, as 26.1% of the investigated boreholes were Class V and would need to be improved before use.

#### **4.1.2.4 Overall water quality**

The overall water quality status is suitable for livestock use, as 90% fell within the Class I classification. The remaining boreholes were classified as Class V and therefore intervention strategies would be required before use. The water quality of the investigated boreholes for livestock use was either classified as Class I or Class V, with none in between.

Overall, the water quality of the NMMD area was excellent for livestock use. It is, however, recommended that municipalities frequently evaluate the water quality, as either fluctuations in different seasons or the deterioration of water quality may occur. For the boreholes with a Class V water quality classification, purification would be required before use. Further investigation of the Class V boreholes is also recommended to determine what the cause might be for the poor water quality.

#### **4.1.2.5 WQI quality distribution of groundwater for livestock purposes**

The groundwater quality for livestock purposes distribution maps of the Ditsobotla, Ratlou, and Tswaing LM areas are presented in Figure 30, Figure 31, and Figure 32, respectively.

.

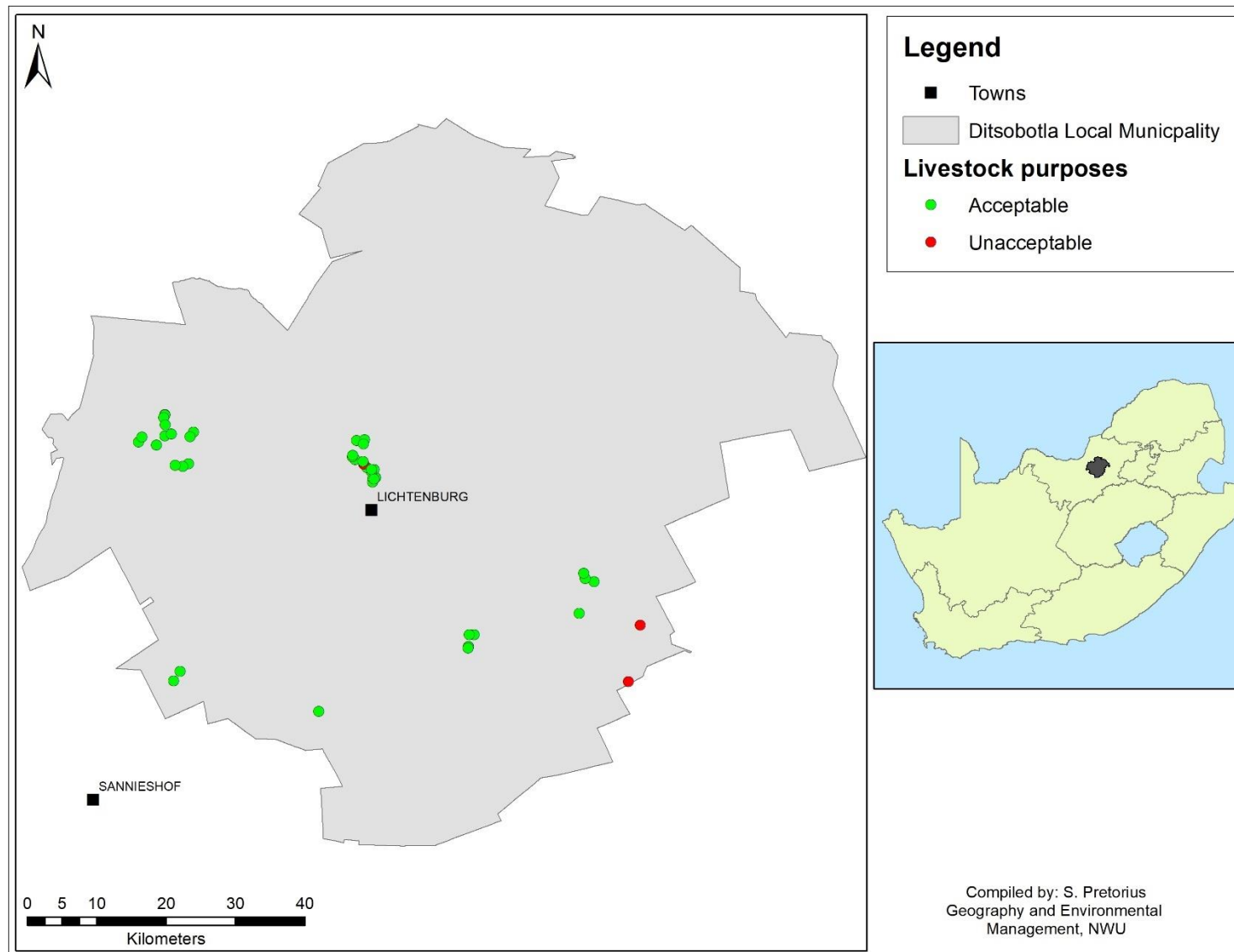


**Figure 30:** Livestock water quality classification of each borehole located in the Ditsobotla LM.

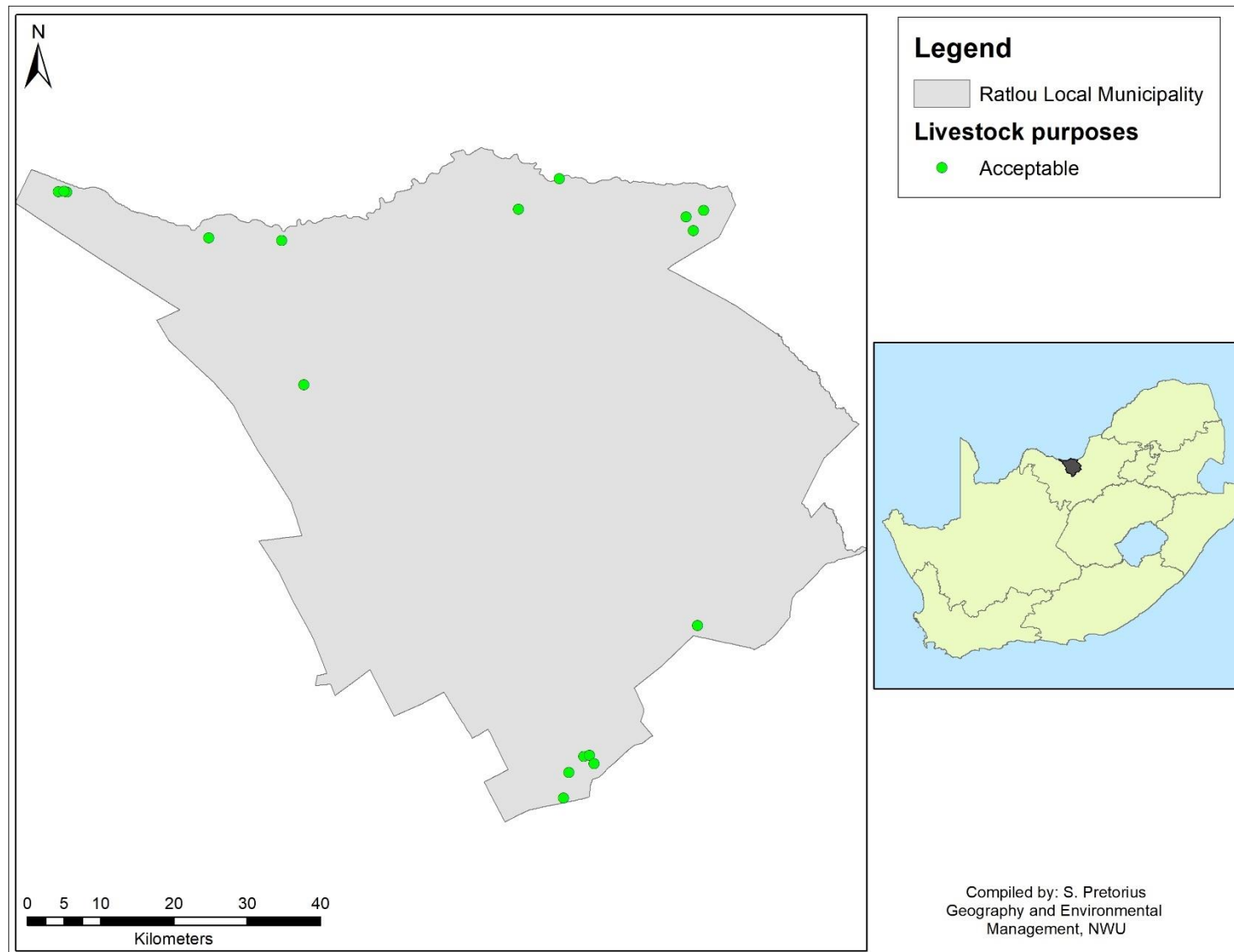


**Figure 31:** Livestock water quality classification of each borehole located in the Ratlou LM.

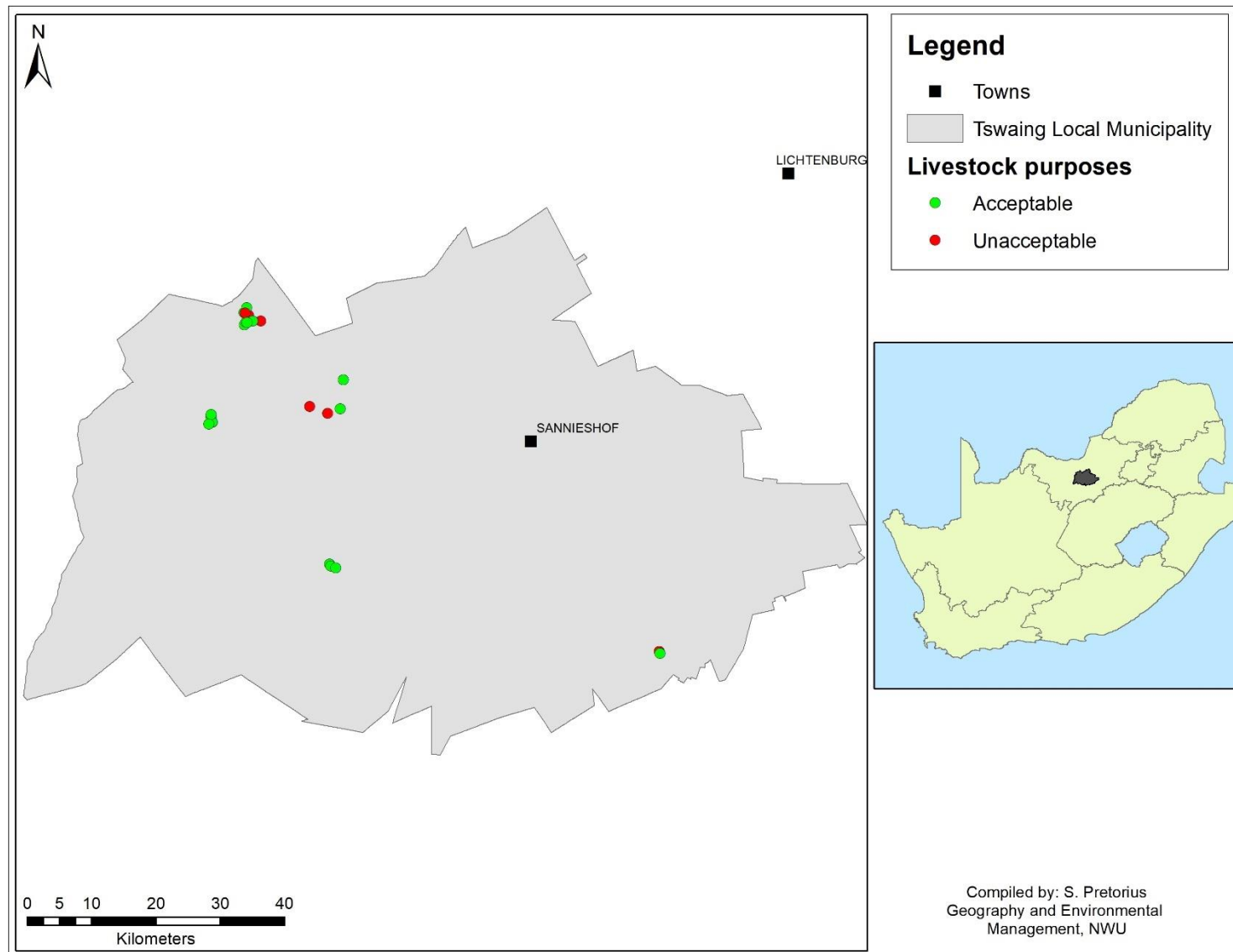


**Figure 32:** Livestock water quality classification of each borehole located in the Tswaing LM.

### 4.1.3 Irrigation purposes

An overview of the water quality for irrigation purposes, according to the WQI, is presented in Figure 33.

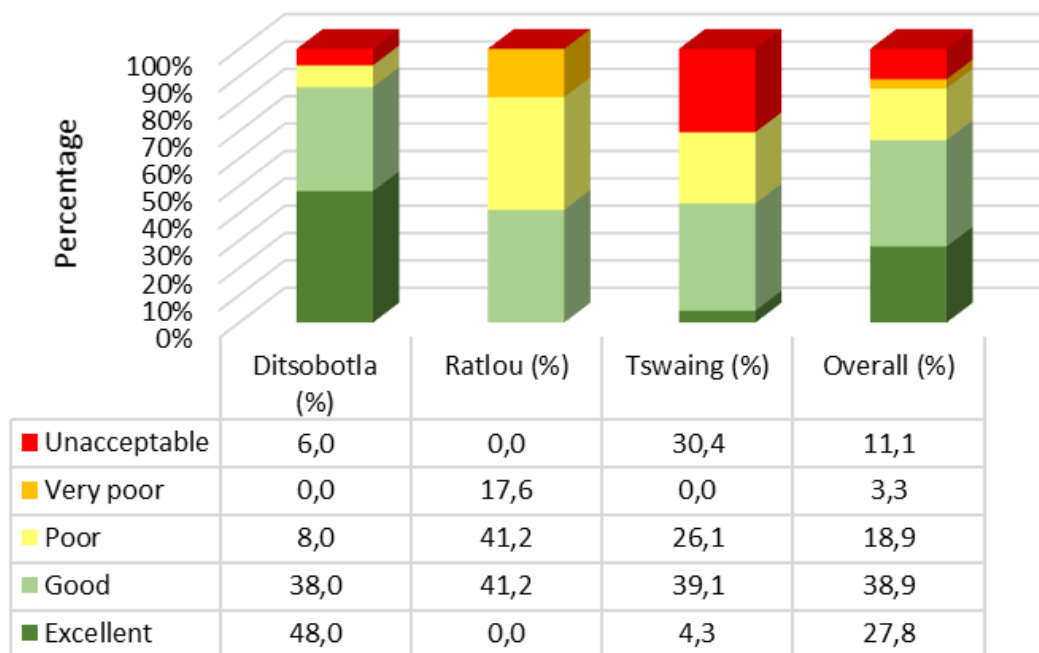


**Figure 33:** The irrigation water quality statuses of boreholes according to the WQI model.

#### 4.1.3.1 Ditsobotla

Overall, the water quality for the Ditsobotla LM area was acceptable for irrigation purposes. 48% and 38% of the investigated boreholes were classified as Class I and Class II, respectively. The percentage of boreholes classified as Class III were 8%. Therefore, 94% of the boreholes were classified as acceptable for irrigation purposes. The remaining 6% were classified as Class V.

#### 4.1.3.2 Ratlou

Only 41.2% of the boreholes that were investigated in the Ratlou LM area were Class II, while another 41.2% were classified as Class III. 17.6 % of the boreholes were classified as Class IV. All the boreholes in the area were acceptable for irrigation use, as there were no Class V boreholes. The Ratlou LM area had the best water quality for irrigation purposes.

#### **4.1.3.3 Tswaing**

The Tswaing LM area had the poorest water quality of the three investigated areas in the NMMD, as 30.4% of the boreholes were classified as Class V. Further investigation is required as to which parameters caused the low WQI value and it is required that the groundwater from these boreholes need to be treated before use. The remaining 69.6 % of the boreholes were suitable for irrigation, with 4.3%, 39.1%, and 26.1% thereof classified as Class I, II, and III, respectively.

#### **4.1.3.4 Overall water quality**

Overall, the water quality for irrigation purposes in the NMMD area was suitable for use, as only 11.1% was classified as Class V. However, 18.9 and 3.3% of the investigated boreholes were classified as Class III and IV, respectively, which raises concerns of further deterioration.

For Class III and IV boreholes, it is recommended that the water is monitored frequently, as fluctuations as well as deterioration of the water quality may occur. For all the boreholes that were classified as V for irrigation use, it is recommended that a further investigation be conducted to determine the reason for the poor water quality. Intervention strategies to improve the water quality, as well as purifying the water before use, are of utmost importance.

#### **4.1.3.5 Groundwater quality for irrigation purposes distribution according to the WQI**

The groundwater irrigation quality distribution maps of the Ditsobotla, Ratlou, and Tswaing LM areas are presented in Figure 34, Figure 35, and Figure 36, respectively.

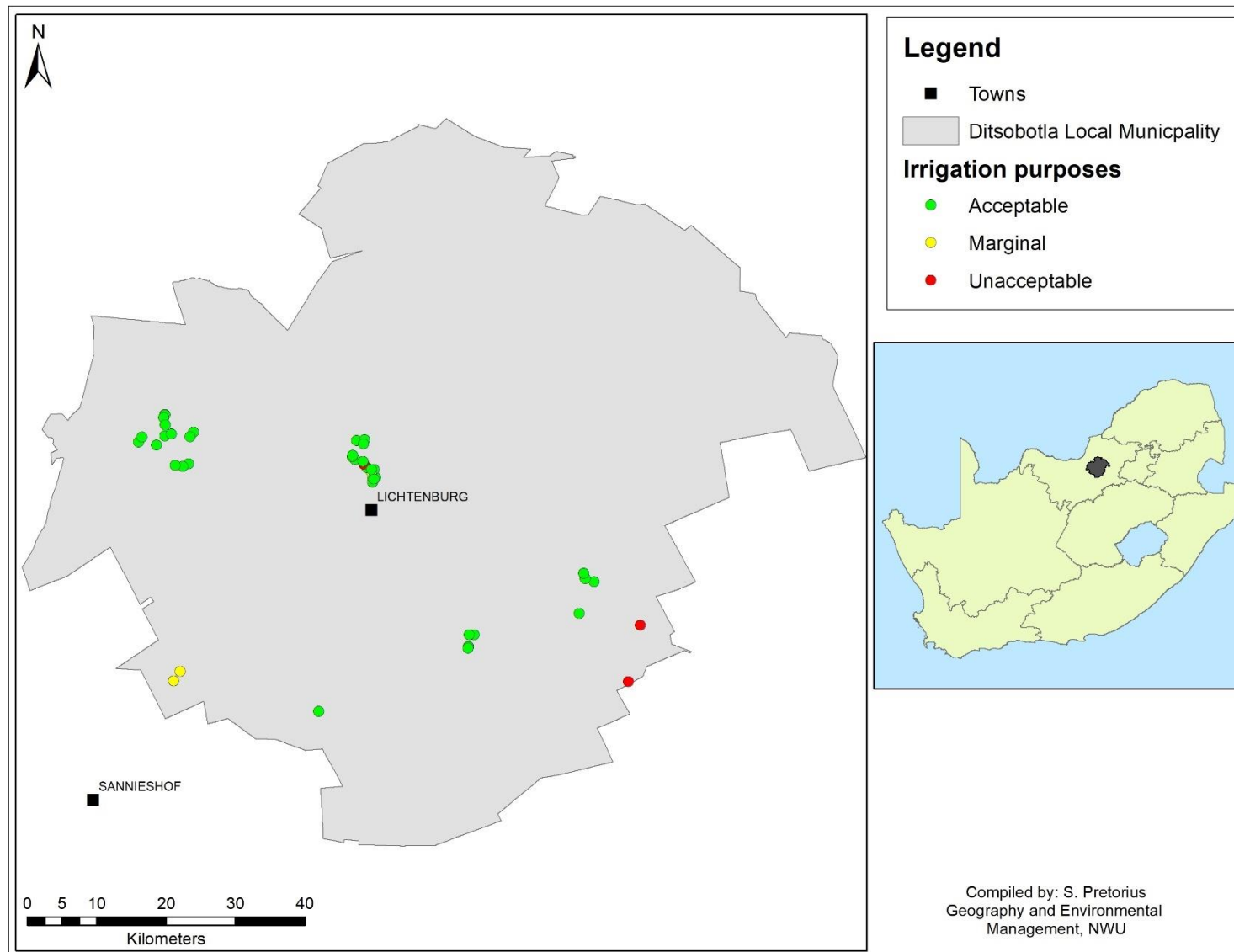


**Figure 34:** Irrigation water quality classification of each borehole located in the Ditsobotla LM.

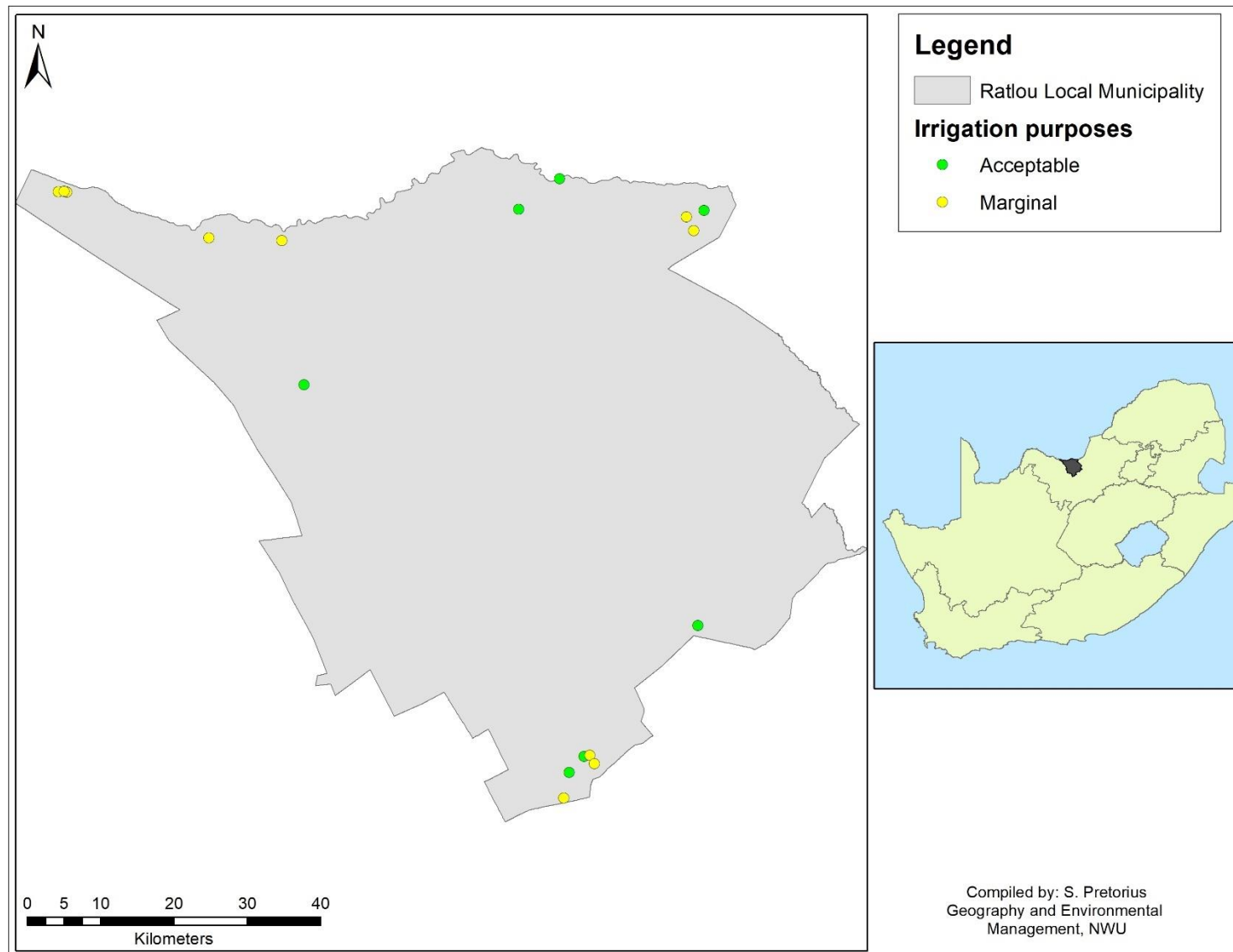


**Figure 35:** Irrigation water quality classification of each borehole located in the Ratlou LM.

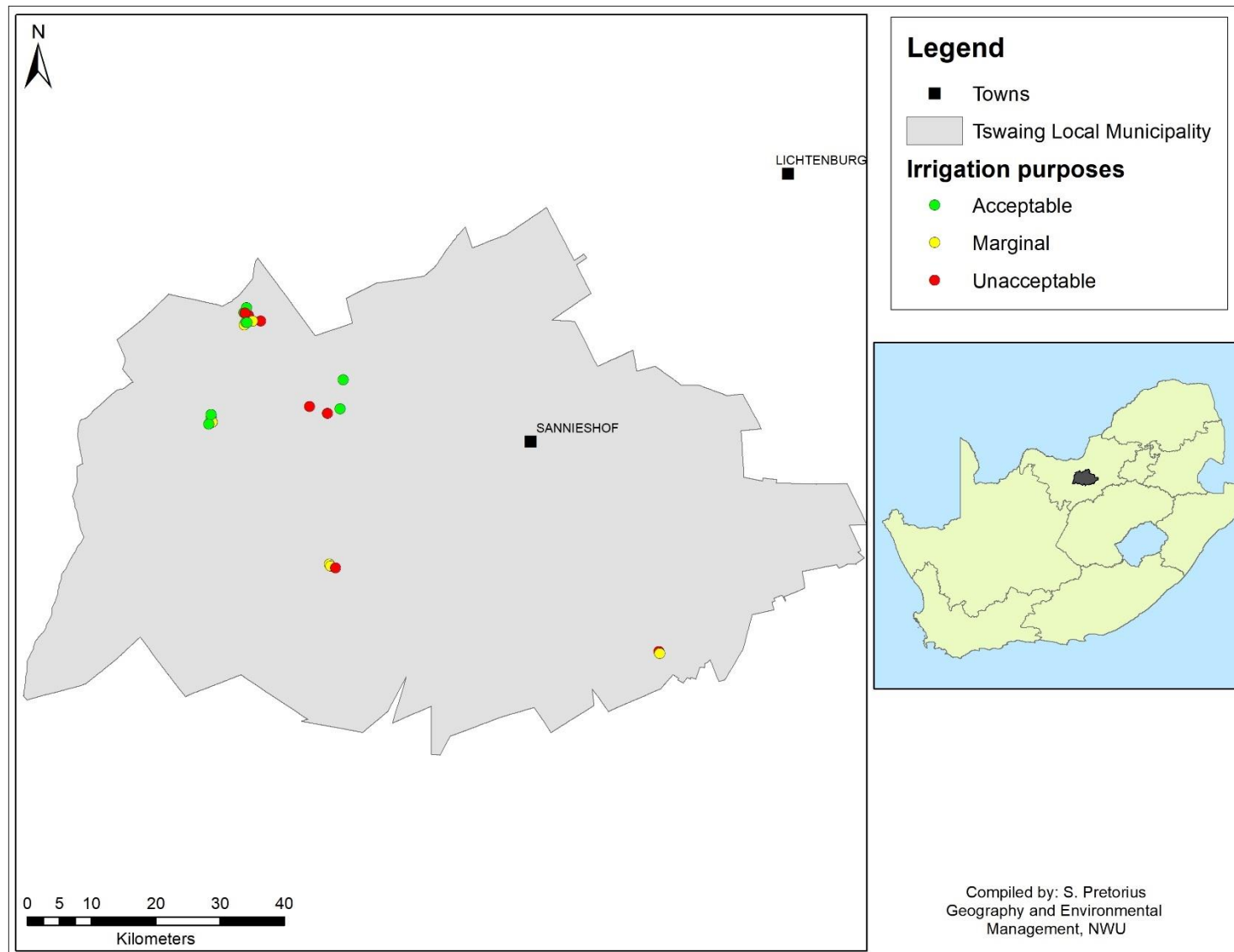


**Figure 36:** Irrigation water quality classification of each borehole located in the Tswaing LM.

## 4.2 Groundwater quality parameters

The groundwater quality parameters were investigated individually to determine what the cause might be for some boreholes having a higher WQI value than others.

Data tables are presented below with more detail on the suitability of the boreholes for drinking, livestock and irrigation purposes. Information on the percentage and number of boreholes which are deemed acceptable and unacceptable for each of the investigated areas are presented. Table 33, Table 34, and Table 35 serve as data tables for drinking, livestock and irrigation purposes, respectively.

A further investigation was conducted for each water quality parameters that did not meet the quality standard requirement, to provide a clear understanding as to what the causes might be for the high levels in the water source.

For drinking purposes, the following parameters had elevated levels, namely; *Faecal coliform*, *E. coli*, EC, and the concentrations of nitrate, fluoride, iron and manganese. Only EC had elevated levels for livestock purposes in the investigated boreholes. Lastly, for irrigation purposes, EC, pH, PI, KR, %Na, and PS had elevated levels.

Only the parameters that had elevated levels beyond the recommended standard were investigated further. The other parameters were not included in the additional analyses, as it would have been redundant.

**Table 33:** Water quality status of each parameter for drinking purposes in Ditsobotla, Ratlou and Tswaing LM areas.

| Parameter               | Ditsobotla |        |              |        | Ratlou     |        |              |        | Tswaing    |        |              |        |
|-------------------------|------------|--------|--------------|--------|------------|--------|--------------|--------|------------|--------|--------------|--------|
|                         | Acceptable |        | Unacceptable |        | Acceptable |        | Unacceptable |        | Acceptable |        | Unacceptable |        |
|                         | (%)        | Number | (%)          | Number | (%)        | Number | (%)          | Number | (%)        | Number | (%)          | Number |
| <i>Faecal coliform</i>  | 56.0       | 28     | 44.0         | 22     | 41.2       | 7      | 58.8         | 10     | 73.9       | 17     | 26.1         | 6      |
| <i>E. coli</i>          | 82.0       | 41     | 18.0         | 9      | 58.8       | 10     | 41.2         | 7      | 73.9       | 17     | 26.1         | 6      |
| EC at 25 °C             | 94.0       | 47     | 6.00         | 3      | 100        | 17     | 0.00         | 0      | 73.9       | 17     | 26.1         | 6      |
| TDS                     | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| pH at 25 °C             | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Nitrate ( $NO_3^-$ )    | 22.0       | 11     | 78.0         | 39     | 52.9       | 9      | 47.1         | 8      | 43.5       | 10     | 56.5         | 13     |
| Sulfate ( $SO_4^{2-}$ ) | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Fluoride ( $F^-$ )      | 94.0       | 47     | 6.00         | 3      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Chloride ( $Cl^-$ )     | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Zink ( $Zn$ )           | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Copper ( $Cu$ )         | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Iron ( $Fe$ )           | 96.0       | 48     | 4.00         | 2      | 94.1       | 16     | 5.90         | 1      | 100        | 23     | 0.00         | 0      |
| Manganese ( $Mn^{2+}$ ) | 84.0       | 42     | 16.0         | 8      | 88.2       | 15     | 11.8         | 2      | 73.9       | 17     | 26.1         | 6      |

**Table 34:** Water quality status of each parameter for livestock purposes in the Ditsobotla, Ratlou and Tswaing LM areas.

| Parameter               | Ditsobotla |        |              |        | Ratlou     |        |              |        | Tswaing    |        |              |        |
|-------------------------|------------|--------|--------------|--------|------------|--------|--------------|--------|------------|--------|--------------|--------|
|                         | Acceptable |        | Unacceptable |        | Acceptable |        | Unacceptable |        | Acceptable |        | Unacceptable |        |
|                         | (%)        | Number | (%)          | Number | (%)        | Number | (%)          | Number | (%)        | Number | (%)          | Number |
| EC at 25 °C             | 94.0       | 47     | 6.00         | 3      | 100        | 14     | 0.00         | 0      | 69.6       | 16     | 30.4         | 7      |
| TDS                     | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 4.35         | 0      |
| pH at 25 °C             | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Nitrate ( $NO_3^-$ )    | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Sulfate ( $SO_4^{2-}$ ) | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Chloride ( $Cl^-$ )     | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Calcium ( $Ca^{2+}$ )   | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Magnesium ( $Mg^{2+}$ ) | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Sodium ( $Na^+$ )       | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Copper ( $Cu$ )         | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |

**Table 35:** Water quality status of each parameter for irrigation purposes for Ditsobotla, Ratlou and Tswaing LM areas.

| Parameter           | Ditsobotla |        |              |        | Ratlou     |        |              |        | Tswaing    |        |              |        |
|---------------------|------------|--------|--------------|--------|------------|--------|--------------|--------|------------|--------|--------------|--------|
|                     | Acceptable |        | Unacceptable |        | Acceptable |        | Unacceptable |        | Acceptable |        | Unacceptable |        |
|                     | (%)        | Number | (%)          | Number | (%)        | Number | (%)          | Number | (%)        | Number | (%)          | Number |
| EC at 25 °C         | 94.0       | 47     | 6.00         | 3      | 100        | 17     | 0.00         | 0      | 73.9       | 17     | 26.1         | 6      |
| TDS                 | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| pH at 25 °C         | 98.0       | 49     | 2.00         | 1      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| Chloride ( $Cl^-$ ) | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| PI                  | 40.0       | 20     | 60.0         | 30     | 100        | 17     | 0.00         | 0      | 91.3       | 21     | 8.70         | 2      |
| KR                  | 98.0       | 49     | 2.00         | 1      | 64.7       | 11     | 35.3         | 6      | 95.7       | 22     | 4.30         | 1      |
| %Na                 | 98.0       | 49     | 2.00         | 1      | 82.4       | 14     | 17.6         | 3      | 100        | 23     | 0.00         | 0      |
| SAR                 | 98.0       | 49     | 2.00         | 1      | 70.6       | 12     | 29.4         | 5      | 95.7       | 22     | 4.30         | 1      |
| MAR                 | 100        | 50     | 0.00         | 0      | 100        | 17     | 0.00         | 0      | 100        | 23     | 0.00         | 0      |
| PS                  | 46.0       | 23     | 54.0         | 27     | 5.90       | 1      | 94.1         | 16     | 8.7        | 2      | 91.30        | 21     |

### 4.2.1 *Faecal coliform* and *Escherichia coli*

According to the SANS 241-1 drinking water quality standards, there should be no traces of *Faecal coliform* or *E. coli* in drinking water (SANS, 2015). The effect of *Faecal coliform* and *E. coli* present in drinking has been discussed in **Section 2.5.2.2**.

#### 4.2.1.1 Degree of contamination

##### Ditsobotla

Concerning *Faecal coliform*, 44% of the investigated boreholes in the Ditsobotla LM area have been reported to have elevated levels. Furthermore, 18% of the investigated boreholes were unacceptable for drinking purposes due to the presence of *E. coli*.

In Figure 37 and Figure 38, the extent to which the limit was exceeded, as well as the number of boreholes that fell within the elevated range, are presented for *Faecal coliform* and *E. coli*, respectively. It can be seen that the limit was greatly exceeded for *Faecal coliform* as nine of the 50 investigated boreholes had a *Faecal coliform* count of 80 or higher. Similar to *Faecal coliform*, three of the investigated boreholes had an *E. coli* count that falls within that range. It is clear that the limits for both *Faecal coliform* and *E. coli* were significantly exceeded by some boreholes.

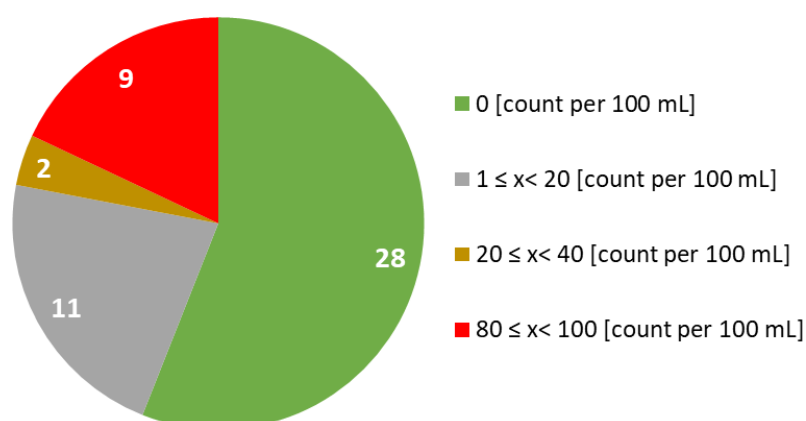


**Figure 37:** The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific *Faecal coliform* count range for drinking purposes.

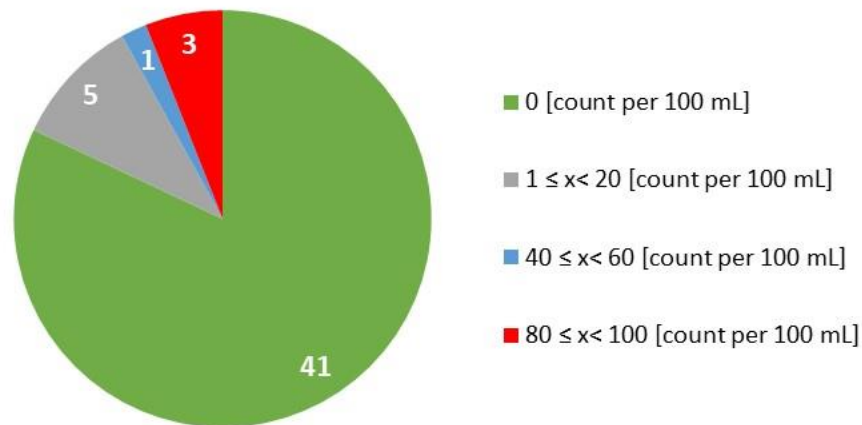


**Figure 38:** The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific *E. coli* count range for drinking purposes.

### Ratlou

Over half (58.8%) of the investigated boreholes in the Ratlou LM area have been recorded as “unacceptable” due to the presence of *Faecal coliform*. It can be seen in Figure 39 that three of the 17 investigated boreholes had a *Faecal coliform* count of 80 per 100 mL or higher. Concerning *E. coli*, 41.2% of investigated boreholes have been reported to have elevated levels. The number of boreholes, along with the extent to which they exceeded the limit, can be seen in Figure 40.

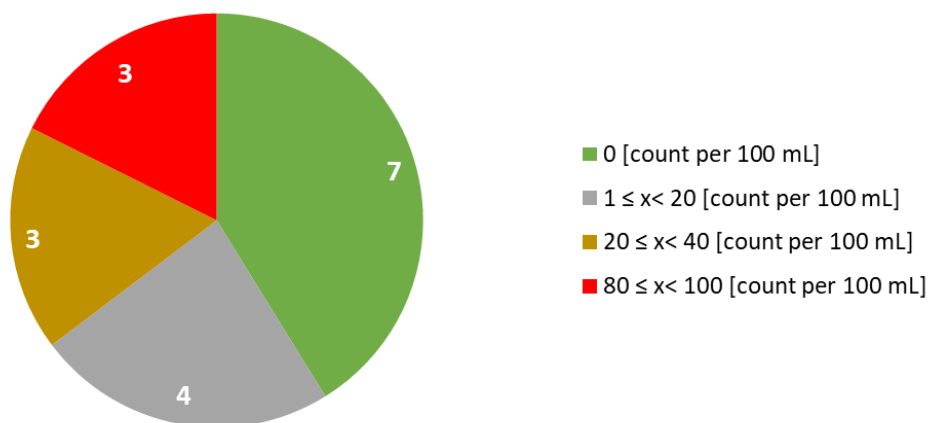


**Figure 39:** The number of investigated boreholes located in the Ratlou LM area that fell within a specific *Faecal coliform* count range for drinking purposes.

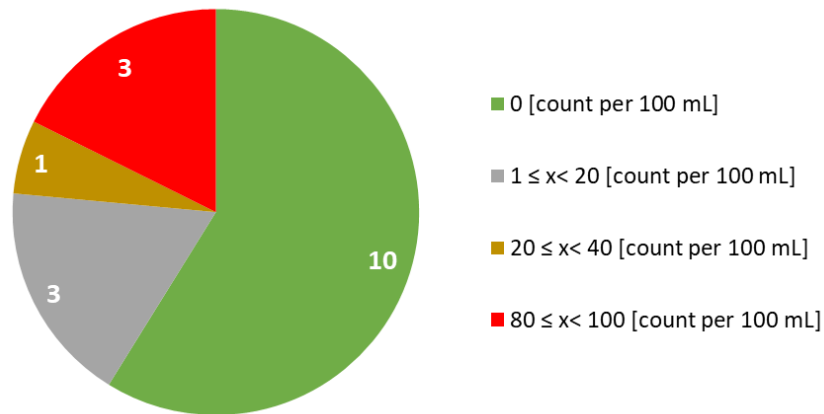


**Figure 40:** The number of investigated boreholes located in the Ratlou LM area that fell within a specific *E. coli* count range for drinking purposes.

### Tswaing

For the Tswaing LM area, 26.1% of the investigated boreholes have been reported to have elevated levels of both *Faecal coliform* and *E. coli*.

The extent to which the limit was exceeded, along with the number of boreholes that fell within the elevated range for *Faecal coliform* and *E. coli*, is presented in Figure 41 and Figure 42, respectively. Two of the 23 investigated boreholes in the Tswaing LM area had extremely high *Faecal coliform* count of higher or equal to 80 per 100 mL. Three boreholes fell within the 80 to 100 count per 100 mL range for *E. coli*, which is drastically higher than the limit.

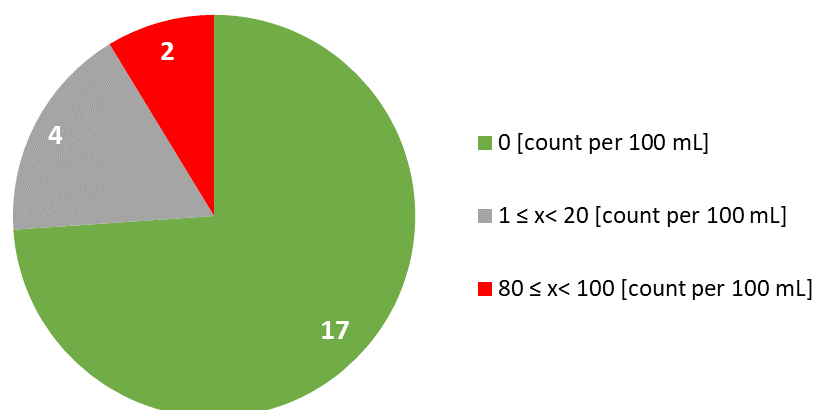


**Figure 41:** The number of investigated boreholes located in the Tswaing LM area that fell within a specific *Faecal coliform* count range for drinking purposes.

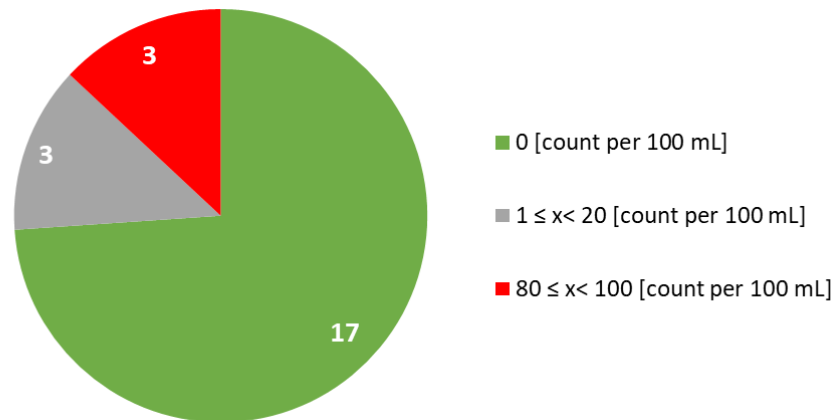


**Figure 42:** The number of investigated boreholes located in the Tswaing LM area that fell within a specific *E. coli* count range for drinking purposes.

#### 4.2.1.2 Possible cause and intervention strategies

The presence of *Faecal coliform* and *E. coli* is an indication of faecal pollution, which can be caused by domestic sewage, direct waste discharge of animals and agricultural runoff from livestock farms (Dangi *et al.*, 2017; Oram, 2020). It is recommended that the water be treated before consumption, as the presence of these microbial contaminants poses a significant risk to the health of consumers (SANS, 2015).

The water can be treated with the use of UV technology, ozonation (Ahmad & Azam, 2019; Gelete *et al.*, 2020), chlorine (Cheng *et al.*, 2020; Elder & Budd, 2011; Gelete *et al.*, 2020), chloramine (Gelete *et al.*, 2020; Yuan *et al.*, 2019) or chlorine dioxide (Cheng *et al.*, 2020; Elder & Budd, 2011; Gelete *et al.*, 2020). For water with high turbidity, chlorine, chloramine, chlorine dioxide or ozonation is suggested for disinfection (Lenntech, 2021e). However, the water can also be treated with the use of coagulation, flocculation and then filtration, before UV disinfection.

Another factor that needs to be considered is whether residual disinfection would be required. For a residual effect that will last longer than five hours, chlorine, chloramine or chlorine dioxide is recommended (Lenntech, 2021e). Ozone decays fast in water (Mao *et al.*, 2018), and will therefore only last up to five hours (Lenntech, 2021e).

Furthermore, it is recommended that an investigation is conducted in the area where the boreholes are situated in order to determine what the cause of the high *Faecal coliform* and *E. coli* count.

## 4.2.2 Electrical conductivity

In **Section 2.4.2.3**, the effects that elevated levels of EC have on drinking, livestock and irrigation water, are mentioned, along a summary of the limits in Table 2.

### 4.2.2.1 Degree of contamination

Only the Ditsobotla and Tswaing LM areas were shown to have elevated levels of EC for drinking, livestock and irrigation purposes. The EC levels of these two LM areas were investigated further.

#### Ditsobotla

Only three of the 54 investigated boreholes in the Ditsobotla LM area were recorded to have elevated EC levels for drinking, livestock, and irrigation purposes. In Figure 43, it can be seen that the EC levels of these three boreholes drastically exceeded the limits. The first, second and third range indicates the EC limits for livestock, drinking and irrigation purposes, respectively. The majority of the boreholes for the Ditsobotla LM area fell within the first range, indicating that they had an acceptable EC level for all three uses. However, one borehole fell within the range of 20 mS/cm to 40 mS/cm, another in the 60 mS/cm to 80 mS/cm range, and the last one in the 80 mS/cm to 100 mS/cm range.

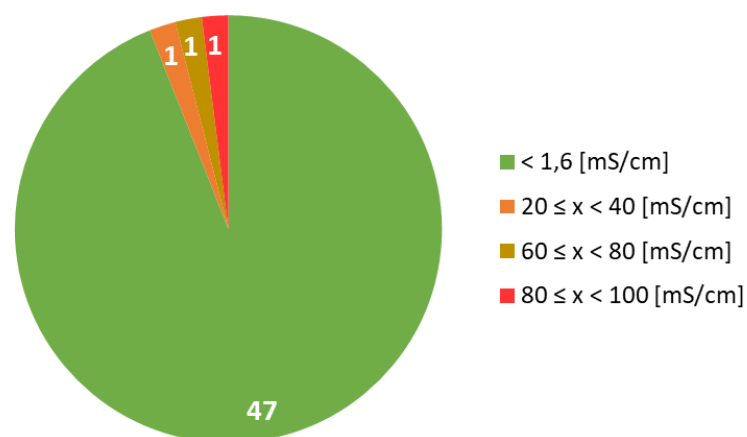


**Figure 43:** The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific EC range for drinking, livestock and irrigation purposes.

The high EC levels were, however, only a problem for a small number of boreholes in the Ditsobotla LM area, which is not a big concern for the overall water quality for that area.

## Tswaing

For the Tswaing LM area, six of the 23 investigated boreholes had elevated EC levels for drinking and irrigation purposes. Seven boreholes were unsuitable for livestock use. Borehole number 18 had an EC value of 1.64 mS/cm, which was above the EC limit for livestock, but below the EC limit for drinking and irrigation purposes.

In Figure 44, the extent to which the EC limit was exceeded, as well as the number of boreholes that fell within the elevated range, are presented. Two of the investigated boreholes fell within the 120 mS/cm to 14 mS/cm range, which was drastically higher than the recommended limits for livestock, drinking, and irrigation purposes.

Overall, EC is not a problem in the NMMD area, only for specific boreholes where intervention strategies need to be put into place. The NMMD had low (0 - 0.7 mS/cm) to moderate (1.5 – 3.7 mS/cm) EC levels (Department of Water and Sanitation, 2019), which correlates with the obtained data for this study.

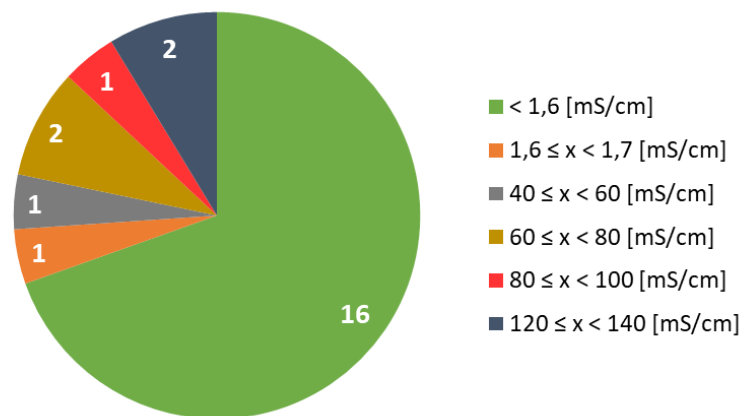


**Figure 44:** The number of investigated boreholes located in the Tswaing LM area that fell within a specific EC range for drinking, livestock and irrigation purposes.

### 4.2.2.2 Possible causes and intervention strategies

A further investigation was conducted on the boreholes with elevated EC levels. The high EC levels can be due to either microbial contamination (Fondriest Environmental Inc., 2020a) or a high concentration of TDS (Rusydi, 2018; Shrestha & Basnet, 2018).

For the boreholes listed in Table 37, the *E. coli* count was beyond the recommended limit, indicating the presence of faecal contamination, which can be due to domestic sewage

leakage or direct waste discharge of animals from livestock farms (Dangi *et al.*, 2017; Oram, 2020).

**Table 37:** The borehole numbers with elevated EC and *E. coli* levels.

| District      | Borehole Number | EC value | <i>E. coli</i> |
|---------------|-----------------|----------|----------------|
|               |                 | [mS/cm]  | [count/100 mL] |
| Ditsobotla LM | 34              | 84.40    | 11             |
| Tswaing LM    | 9               | 71.80    | 1              |
|               | 11              | 63.00    | 93             |
|               | 19              | 52.10    | 1              |
|               | 20              | 98.90    | 10             |

With regard to TDS, as mentioned in **Section 2.4.2.3**, there was a strong correlation between EC and TDS (Shrestha & Basnet, 2018). For borehole number 34 of the Ditsobotla LM area, and borehole numbers 10, 12 and 20 of the Tswaing LM area, the high EC levels could be related to the relatively high TDS levels in comparison to the other boreholes. The high TDS value could be due to geogenic sources (Khanoranga, 2019; Safe Drinking Water Foundation, 2020a; World Health Organization, 2013), human activities, industrial waste or urban runoff (Safe Drinking Water Foundation, 2020a; World Health Organization, 2013).

The groundwater of the abovementioned boreholes need to be purified prior to use for drinking, livestock, and irrigation purposes as the EC levels were highly elevated. The recommended treatment option for EC is RO (Atlas Scientific, 2021), as it effectively removes organic and inorganic elements (Albergamo *et al.*, 2020; Yuan *et al.*, 2019), as well as NF (Lenntech, 2021e). Furthermore, ion exchange can also be used, as it effectively removes dissolved inorganics (Lenntech, 2021e; Mazille & Spuhler, 2020d) such as heavy metals, calcium, and magnesium from water (Lenntech, 2021e).

It is recommended that a further investigation be conducted to find solutions to the pollution or prevent further deterioration of the specific groundwater source.

### 4.2.3 pH

Elevated levels of pH were only found for irrigation purposes, as the pH levels were within the recommended limits for drinking and livestock purposes.

The pH limit along with the effects that elevated levels of pH have on irrigation water have been discussed in **Section 2.4.2.5**.

#### **4.2.3.1 Degree of contamination**

For the Ditsobotla LM area, only one borehole had an elevated pH level. The pH value of Borehole 17 exceeded the pH limit of 8.5 with only 0.08. Overall, pH was not a problem in the NMMD area, as only one of the 90 investigated boreholes had an elevated pH level and also to a low extent.

#### **4.2.3.2 Possible causes and intervention strategy**

The high pH level can be due to the presence of limestone and/or fluctuation in temperature (Fondriest Environmental Inc., 2020b). It is recommended that borehole number 18 is monitored regularly, as a too high pH level can lead to the accumulation of calcium carbonates (Al-Assaf *et al.*, 2020). Furthermore, the pH of the specific borehole should be improved before use. It is recommended that water with a high pH level be treated through acidification of the water source with either sulfuric acid (Buendia *et al.*, 2018; Lenntech, 2021f), phosphoric acid, or nitric acid (Buendia *et al.*, 2018).

Furthermore, borehole numbers six and 22 each had a pH value of 8.45. It is therefore recommended to also frequently monitor the pH, as fluctuations may occur, leading to an increase in pH beyond the recommended level.

#### **4.2.4 Nitrate concentration**

Elevated levels of nitrate were only found for drinking purposes. For livestock purposes, the nitrate concentration was within the recommended limit. Nitrate concentration was not an evaluated parameter for irrigation purposes.

The nitrate concentration limits, along with the effect thereof beyond the recommended limit were discussed in **Section 2.4.2.6**.

##### **4.2.4.1 Degree of contamination**

###### **Ditsobotla**

78% of the investigated boreholes in the Ditsobotla LM area had high nitrate concentrations. In Figure 45, it can be seen that the majority of the boreholes greatly exceed the SANS 241-

1 (2015) limit. Only 11 boreholes fell within the acceptable range of below 11 mg/L, while four boreholes fell within the highest range of 50 mg/L to 60 mg/L.

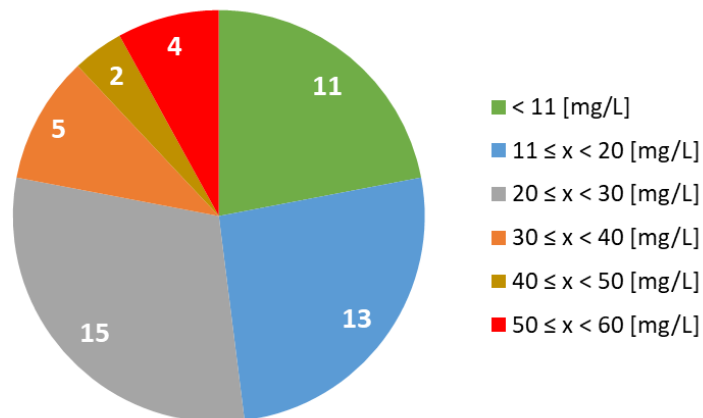


**Figure 45:** The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific nitrate concentration range for drinking purposes.

## Ratlou

For the investigated boreholes in the Ratlou LM area, 47.1 % of the boreholes were documented to have elevated levels of nitrate concentration. The extent to which the SANS 241-1 (2015) limit was exceeded, as well as the number of boreholes within the elevated range, is shown in Figure 46. Compared to the Ditsobotla and Tswaing LM areas, the contaminated boreholes in the Ratlou LM did not exceed the limit to a great extent.

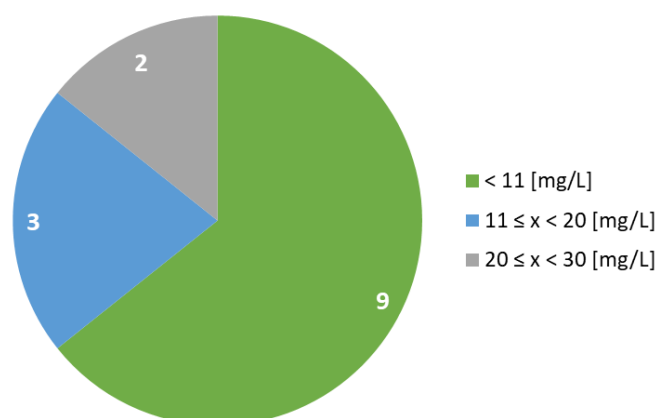


**Figure 46:** The number of investigated boreholes located in the Ratlou LM area that fell within a specific nitrate concentration range for drinking purposes.

## Tswaing

56.5 % of the investigated boreholes in the Tswaing LM area had high nitrate concentrations. In Figure 47, it can be seen to what extent the SANS 241-1 limit was exceeded. Three boreholes fell within the 30 mg/L to 40 mg/L range and two boreholes fell within the highest recorded range of 50 to 60 mg/L.

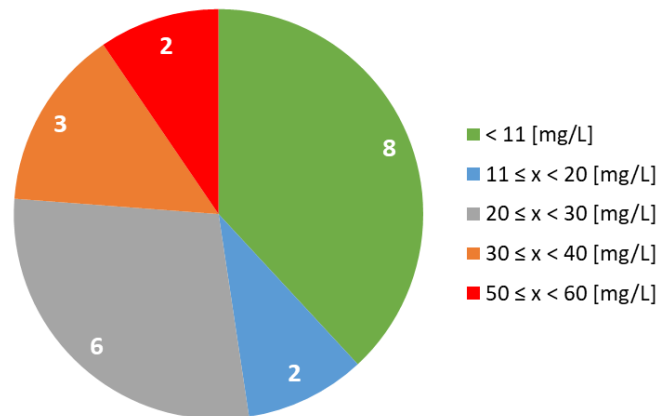


**Figure 47:** The number of investigated boreholes located in the Tswaing LM area that fell within a specific nitrate concentration range for drinking purposes.

It is clear that not only did a large number of boreholes not comply with the SANS 241-1 drinking water standards for the concentration of nitrate, but also that the exceeded amount is high. The extremely high nitrate levels could be the cause of the extremely high WQI score rating – leading to the water being “unacceptable”.

### 4.2.4.2 Possible causes and intervention strategies

The high nitrate concentrations could be due to faecal contamination from humans and/or animals, as well as agricultural runoff or leaching (World Health Organization, 2017). For the majority of the boreholes, the high nitrate concentration could be due to faecal contamination, as the *Faecal coliform* and *E. coli* counts were above the recommended limit for the majority of the boreholes.

It is recommended that the water be purified before consumption. The recommended water purification technologies are NF, RO (Crooks, 2020; Yuan *et al.*, 2019), electrodialysis (Yuan *et al.*, 2019), or ion exchange (Ahmad & Azam, 2019; Crooks, 2020; Yuan *et al.*, 2019).

It is further suggested that an investigation be conducted to determine what the cause of the elevated levels of nitrate for the indicated boreholes might be. Intervention strategies are needed to prevent further water quality deterioration, as well as to stop pollution.

#### 4.2.5 Fluoride concentration

Elevated levels of fluoride were only investigated for drinking purposes, as it was not an evaluated parameter for livestock or irrigation purposes.

The recommended fluoride concentration limit, along with the effect thereof beyond the recommended limit have been discussed in **Section 2.4.2.8**.

##### 4.2.5.1 Degree of contamination

###### Ditsobotla

As seen in Figure 48, only three of the investigated boreholes had elevated levels of fluoride. However, these boreholes had exceedingly high fluoride concentrations, which pose a chronic health risk to consumers. Two boreholes fell within the 2 mg/L to 3 mg/L range, while only one borehole fell within the 4 mg/L to 5 mg/L range, as seen in Figure 48.

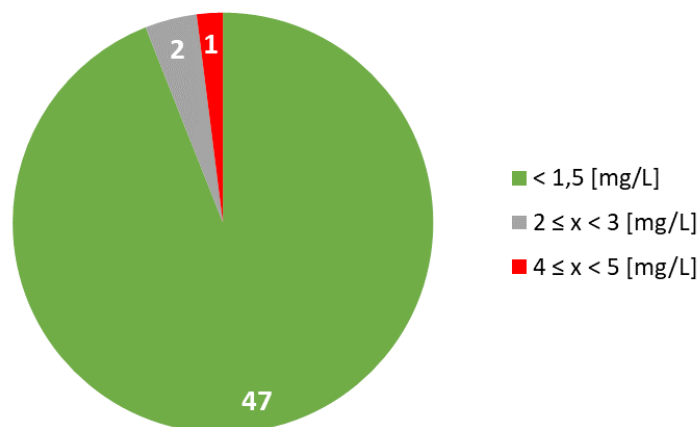


**Figure 48:** The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific fluoride concentration range for drinking purposes.

##### 4.2.5.2 Possible causes and intervention strategies

The high fluoride concentration could be due to the area's geology, agricultural fertilisers or coal combustion (Brindha & Elango, 2011). Water purification technologies that can be used

for fluoride reduction are activated carbon filters (ACF) (Antony *et al.*, 2021; Mazille & Spuhler, 2020b; Pedroza *et al.*, 2021) and ion exchange (Ahmad & Azam, 2019).

Overall, high fluoride concentration was not a problem in the NMMD area, as only three of the 90 investigated boreholes had elevated levels thereof.

#### **4.2.6 Iron concentration**

Elevated levels of iron were only investigated for drinking purposes, as it was not an evaluated parameter for livestock or irrigation purposes.

The iron concentration limit, along with the effect of iron concentrations beyond the recommended limit have been discussed in **Section 2.4.2.12**.

##### **4.2.6.1 Degree of contamination**

###### **Ditsobotla**

Only two of the investigated boreholes were recorded to have elevated levels of iron for drinking purposes in the Ditsobotla LM area. Borehole number 7 had an iron concentration of 0.93 mg/L and borehole number 28 had a concentration of 1.66 mg/L, which greatly exceeded the recommended limit.

###### **Ratlou**

Only one of the investigated boreholes was recorded to have elevated levels of iron in the Ratlou LM area. Borehole number 11 had an iron concentration of 0.96 mg/L, which greatly exceeded the limit of 0.3 mg/L.

For the boreholes with an elevated iron concentration, located in both the Ditsobotla and Ratlou LMs, the colour and turbidity might be undesirable (World Health Organization, 2017), as it greatly exceeded the limit for aesthetic risks. However, there are no chronic health-based concerns, as the iron concentrations of these boreholes were less than 2 mg/L.

##### **4.2.6.2 Possible causes and intervention strategies**

The amount of iron present in groundwater is dependent on the area's geology (Sharma & Bhattacharya, 2017). However, iron can also be present in drinking water due to the corrosion of cast iron or steel pipes (World Health Organization, 2017). It is recommended that the water

quality of these boreholes with elevated iron concentrations be purified before use. The water purification technologies which are recommended for the removal of iron from source water are SSF (Crooks, 2020; Verma *et al.*, 2017), AC (Crooks, 2020; Ketsela *et al.*, 2020), RO (Albergamo *et al.*, 2020; Crooks, 2020; Yuan *et al.*, 2019), ozonation (Ahmad & Azam, 2019; Cheng *et al.*, 2020; Elder & Budd, 2011; Mao *et al.*, 2018) or coagulation and flocculation (Crooks, 2020).

Further investigation is recommended to determine what the cause of the elevated iron might be in the three boreholes.

#### **4.2.7 Manganese concentration**

Elevated levels of manganese were only investigated for drinking purposes, as it was not an evaluated parameter for livestock and irrigation purposes.

The manganese concentration limit, along with the effect thereof beyond the recommended limit have been discussed in **Section 2.4.2.13**.

##### **4.2.7.1 Degree of contamination**

###### **Ditsobotla**

16% of the investigated boreholes in the Ditsobotla LM exceeded the SANS 241-1 manganese concentration limit for drinking water. The extent to which the limit was exceeded, as well as the number of boreholes within that elevated range, can be seen in Figure 49.

Two of the boreholes exceeded the second SANS 241-1 limit of 0.4 mg/L, at which chronic health risks are involved for the consumers (SANS, 2015). For the boreholes that had a manganese concentration of between 0.1 and 0.4 mg/L, only the taste was undesirable (SANS, 2015). It was, however, still unacceptable for drinking, as per the SANS 241-1 (2015) drinking water standards. It is therefore recommended that the water be purified before use.

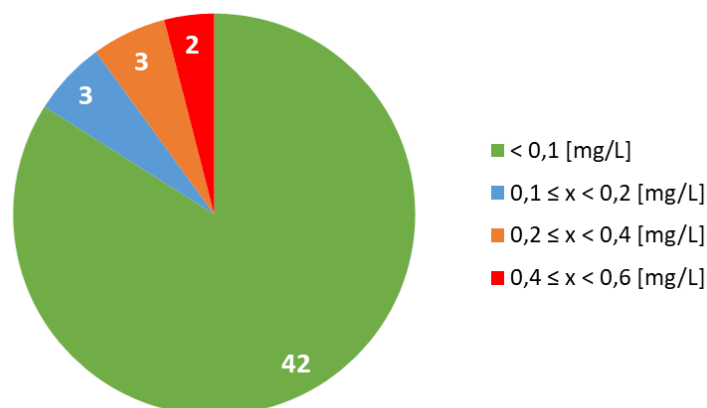


**Figure 49:** The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific manganese concentration range for drinking purposes.

### Ratlou

In the Ratlou LM area, only two boreholes were recorded to have elevated levels of manganese. The extent to which the limit was exceeded can be seen in Figure 50. For these two boreholes, which fell within the 0.1 mg/L to 0.2 mg/L range, aesthetic risks were to be expected (SANS, 2015; World Health Organization, 2017).

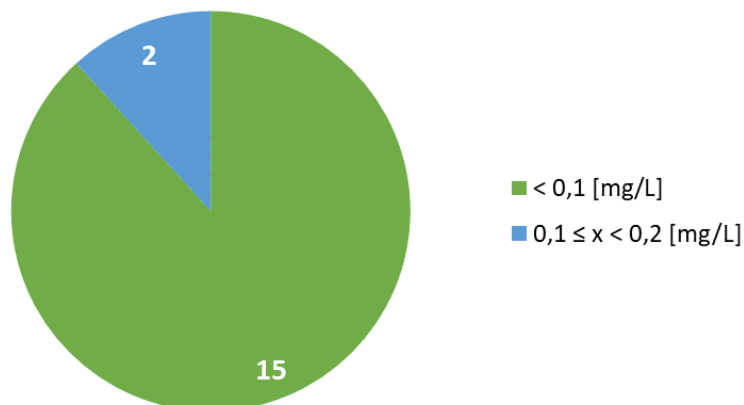


**Figure 50:** The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific manganese concentration range for drinking purposes.

### Tswaing

As seen in Figure 51, 26.1% of the investigated boreholes fell exactly on the SANS 241-1 manganese concentration limit of 0.1 mg/L for drinking water. The six boreholes that were documented to have an elevated manganese concentration fell within the 0.1 mg/L to 0.2 mg/L

range and were at risk of having an undesired taste (SANS, 2015; World Health Organization, 2017).

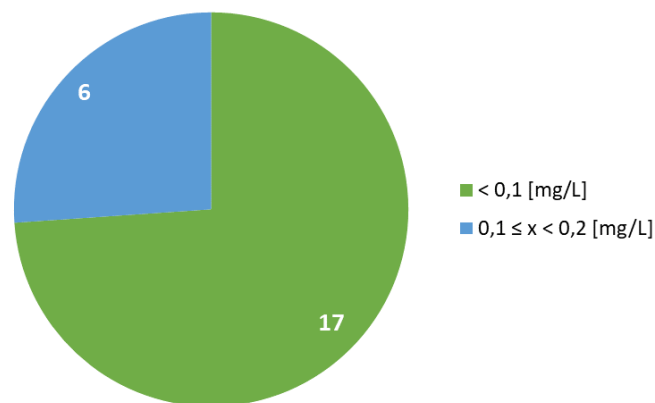


**Figure 51:** The number of investigated boreholes located in the Tswaing LM area that fell within a specific manganese concentration range for drinking purposes.

#### 4.2.7.2 Possible causes and intervention strategies

Manganese is commonly found in soil and therefore the amount thereof present in groundwater is dependent on the area's geology (Zhang *et al.*, 2020). Water purification is required for the improvement of the water quality.

For the removal of manganese, ACF, NF, RO, ion exchange (Crooks, 2020; Yuan *et al.*, 2019), electrodialysis (Yuan *et al.*, 2019), or ozone (Ahmad & Azam, 2019; Cheng *et al.*, 2020; Elder & Budd, 2011; Mao *et al.*, 2018) is recommended.

#### 4.2.8 Permeability index

A PI limit, along with the effect thereof beyond the recommended limit have been discussed in **Section 2.4.2.17**.

##### 4.2.8.1 Degree of contamination

Only the Ditsobotla and Tswaing LM areas were shown to have boreholes with undesirable PI values.

## Ditsobotla

For the Ditsobotla LM area, 60% of the investigated boreholes were shown to have an undesirable PI value of below or equal to 25%. The extent to which it exceeded the limit, as well as the number of boreholes that fell within the elevated range, are presented in Figure 52.

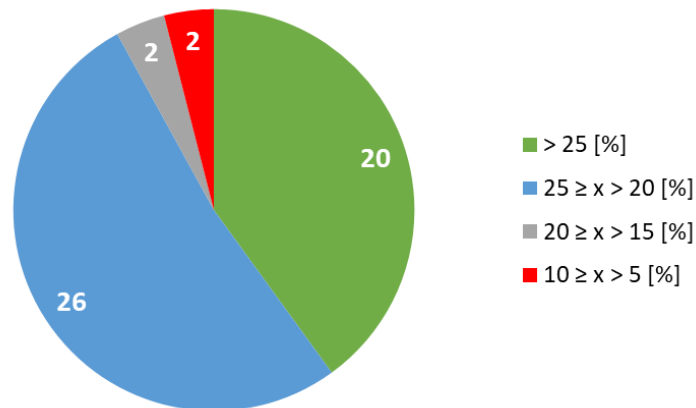


**Figure 52:** The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific PI range for irrigation purposes.

## Tswaing

Only two of the investigated boreholes in the Tswaing LM area had a PI value that was unsuitable for irrigation use. Borehole numbers 8 and 12 had PI values of 25.0 and 24.8%, respectively. These two boreholes only slightly exceeded the PI limit. Tswaing LM area had an overall good PI and was overall suitable for irrigation.

### 4.2.8.2 Possible causes and intervention strategies

The boreholes that were below or equal to 25% had very high calcium and magnesium concentrations as well as very low sodium concentrations compared to the other boreholes, leading to a low PI value. Magnesium and calcium are naturally present in some rocks, like dolomite rock, which can cause a high concentration thereof in groundwater sources. Pollution from chemical industries, livestock feed, as well as agricultural runoff can also cause an increase in calcium and magnesium concentrations in groundwater sources (Lenntech, 2021b).

To improve the PI value of the boreholes, the calcium and magnesium concentrations need to be reduced. Ion exchange, NF (Lenntech, 2021e) or RO can be used for the removal of calcium and magnesium from water (Crooks, 2020; Lenntech, 2021e).

#### **4.2.9 Kelly ratio, percentage sodium, and sodium adsorption rate**

The KR, %Na, and SAR are influenced by the amount of sodium present in water. For this reason, the possible causes, as well as the recommended intervention strategies, will be the same for these three irrigation indices.

##### **4.2.9.1 Degree of contamination for KR**

A KR limit, along with the effect thereof beyond the recommended limit have been mentioned in **Section 2.4.2.17**.

#### **Ditsobotla**

Only one of the 54 investigated boreholes in the Ditsobotla LM area exceeded the KR limit. Borehole number 16 greatly exceeded the KR limit, as it had a value of 1.59. The high KR value was due to the relatively high sodium concentration of 70.99 mg/L and the relatively low calcium and magnesium concentrations of 34.19 mg/L and 10.57 mg/L, respectively.

#### **Ratlou**

Six of the 17 investigated boreholes had a KR that exceeded the recommended limit. In Figure 53, it can be seen to what extent the KR limit was exceeded, as well as the number of boreholes that fell within the elevated KR range. Of the 17 investigated boreholes in the Ratlou LM area, two fell within the 1 to 1.25 range, one in the 1.25 to below 1.5 and in the 1.5 to below 1.75 range. Lastly, two boreholes had a KR that fell within the 1.75 to below 2 range, which is extremely high for a ratio.

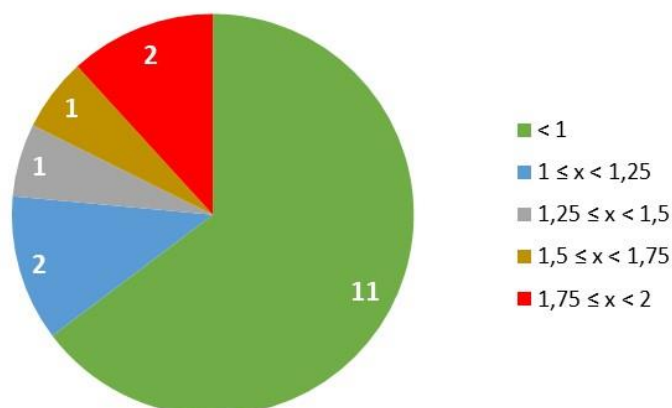


**Figure 53:** The number of investigated boreholes located in the Ratlou LM area that fell within a specific KR range for irrigation purposes.

Borehole numbers 8, 10, 11, 12, 14 and 16 had extremely high sodium concentrations, and relatively low calcium and magnesium concentrations, causing the high KRs.

Compared to the other LM areas, Ratlou LM area had a very high sodium concentration, which raises concerns for irrigational purposes. It is recommended that a further investigation should be conducted to understand what the causes might be for the high sodium concentrations.

### Tswaing

Only one of the investigated boreholes in the Tswaing LM area had a KR value above one. The KR limit was only slightly exceeded by borehole number 18, which had a KR value of 1.05.

Borehole number 18 had an extremely high sodium concentration of 159.9 mg/L. However, due to the high calcium (98.59 mg/L) and magnesium (54.20 mg/L) concentrations, the KR value did not exceed the limit of 1 by too far.

#### 4.2.9.2 Degree of contamination for %Na

The %Na limit, along with the effect thereof beyond the recommended limit have been discussed in **Section 2.4.2.17**.

### Ditsobotla

Only one of the investigated boreholes in the Ditsobotla LM area was shown to have a high %Na. The %Na of the borehole only exceeded the limit by 0.79%.

Borehole number 16 was recorded to have an extremely high sodium concentration level in comparison to the other elements that were taken into consideration. Although the %Na did not exceed the limit with a too high amount, the borehole was unsuitable for use and needs to be purified before use.

## Ratlou

For the Ratlou LM area, three boreholes had high %Na, while one, borehole number 11, was borderline, as it had a %Na of 58.4%. The extent to which it exceeded the limit, as well as the number of boreholes that fell within a specific elevated range can be seen in Figure 54.

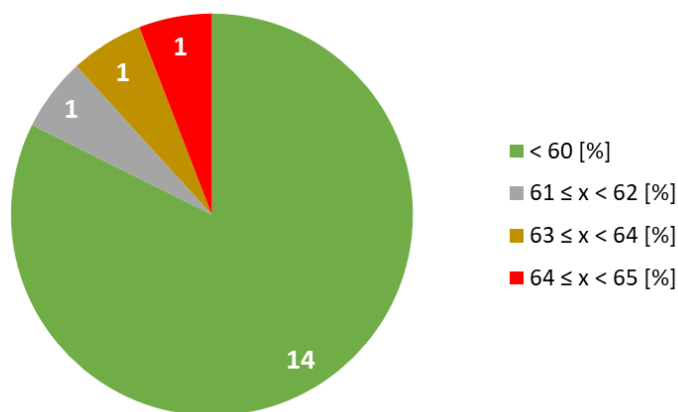


**Figure 54:** The number of investigated boreholes located in the Ratlou LM area that fell within a specific %Na range for irrigation purposes.

Borehole numbers 10, 12 and 16 had extremely high sodium concentrations relative to the calcium and magnesium concentrations. The relatively high potassium concentration also contributed to the high %Na for these three boreholes.

### 4.2.9.3 Degree of contamination for SAR

The SAR limit, along with the effect thereof beyond the recommended limit have been mentioned in **Section 2.4.2.17**.

## Ditsobotla

Only one borehole in the Ditsobotla LM area had a SAR that was above the recommended limit. Borehole number 16 had a SAR value of 21.22, which was due to the high sodium

concentration and low calcium and magnesium concentrations. The sodium concentration will have to be reduced to improve the borehole.

## Ratlou

Five of the investigated boreholes in the Ratlou LM area were shown to have a high SAR value. The extent to which these boreholes exceeded the limit is presented in Figure 55.

Due to the high sodium concentrations of borehole numbers 10, 11, 12, 14, and 16 compared to the calcium and magnesium concentrations, these boreholes had high SAR. The sodium concentration will have to be reduced.

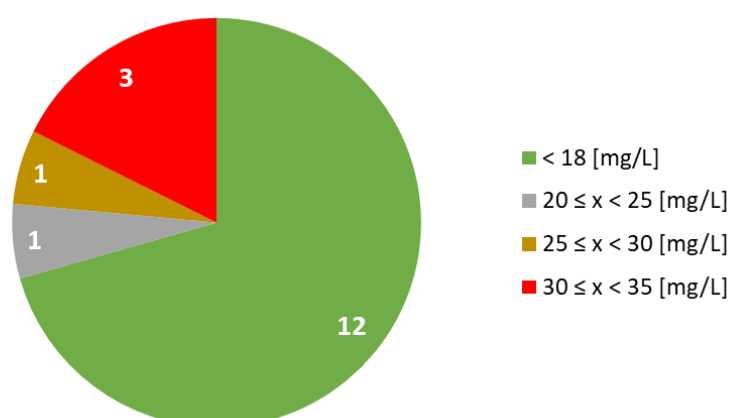


**Figure 55:** The number of investigated boreholes located in the Ratlou LM area that fell within a specific SAR range for irrigation purposes.

## Tswaing

For the Tswaing LM area, only one borehole had an undesirable SAR value. Borehole number 18 had a SAR value of 25.87 mg/L, which was due to the high sodium concentration of 159.9 mg/L. Due to high calcium and magnesium values, the KR and %Na were within the recommended limits.

The water of these boreholes with elevated SAR values was unsuitable for use and will have to undergo water purification, whereby the sodium concentration needs to be reduced.

### 4.2.9.4 Possible causes and intervention strategies

The high nitrate concentration can be due to faecal contamination from humans and/or animals, as well as agricultural runoff or leaching (World Health Organization, 2017). It is

recommended that the water is treated prior to irrigational use. The recommended water purification technologies for the reduction of nitrate in water are NF, RO (Crooks, 2020; Yuan *et al.*, 2019), electrodialysis (Yuan *et al.*, 2019), or ion exchange (Ahmad & Azam, 2019; Crooks, 2020; Yuan *et al.*, 2019).

#### 4.2.10 Potential salinity

The PS limit, along with the effect thereof beyond the recommended limit have been discussed in **Section 2.4.2.17**.

##### 4.2.10.1 Degree of contamination

###### Ditsobotla

For the Ditsobotla LM area, 51.9% of the investigated boreholes had undesirable PS values, making them unsuitable for irrigation purposes. In Figure 56, the extent to which some boreholes exceeded the limit, as well as the number of boreholes that fell within the elevated range, is presented.

For the boreholes that exceeded the limit, the high PS values were due to a combination of high sulfate and high chloride concentrations. However, for borehole number 29, the sulfate concentration was almost triple that of chloride, leading to an extremely high PS value.

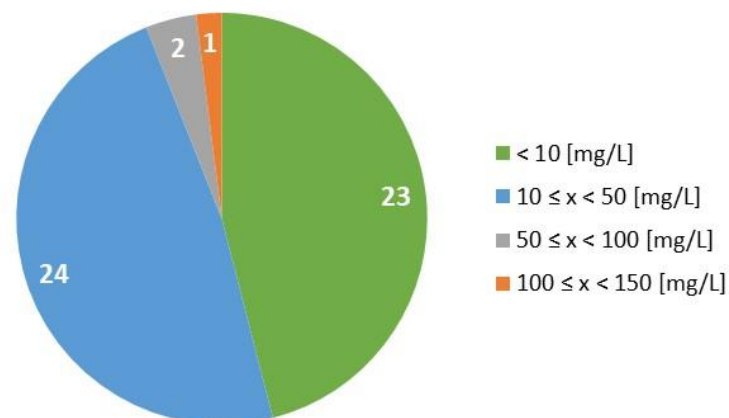


**Figure 56:** The number of investigated boreholes located in the Ditsobotla LM area that fell within a specific PS range for irrigation purposes.

## Ratlou

94.1% of the investigated boreholes in the Ratlou LM area were unsuitable for use, as the PS exceeded the recommended limit. In Figure 57, the extent to which they exceeded the limit can be seen.

For the Ratlou LM area, the high PS value was due to a combination of high sulfate and high chloride concentrations. For some boreholes, the sulfate concentration was dominant, whereas with other boreholes, the chloride concentration was dominant.

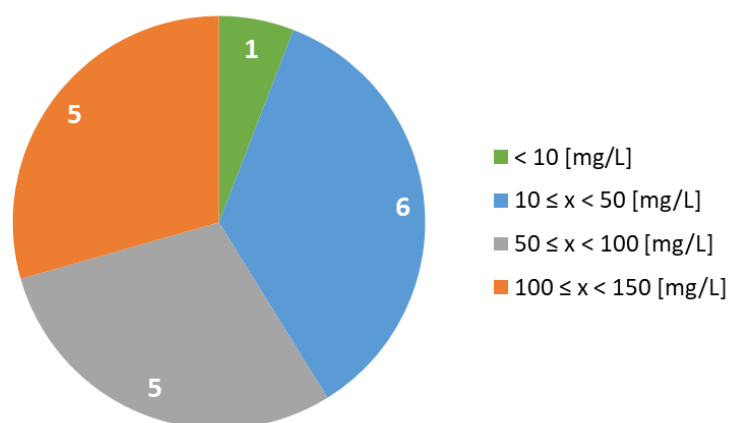


**Figure 57:** The number of investigated boreholes located in the Ratlou LM area that fell within a specific PS range for irrigation purposes.

## Tswaing

For the Tswaing LM area, 91.3% of the investigated boreholes had a PS value that was beyond the recommended limit. In Figure 58, the extent to which the boreholes exceeded the PS limit is presented, as well as the number of boreholes that fell within the elevated range.

For the Tswaing LM area, both chloride and sulfate had high concentrations, however, the chloride concentration was shown to be more in excess compared to sulfate. Borehole number 18 had an extremely high chloride concentration of 275.47 mg/L.

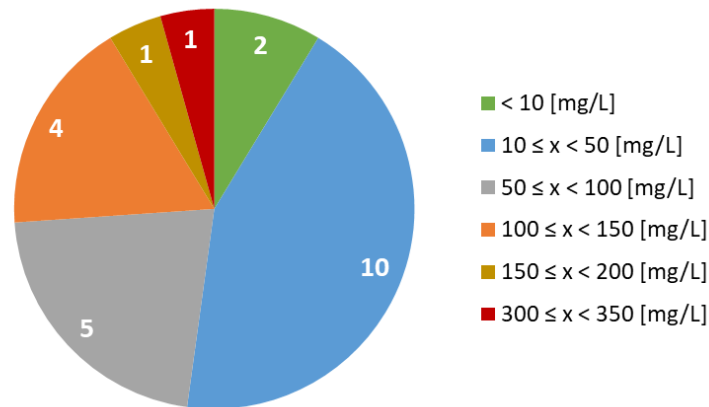


**Figure 58:** The number of investigated boreholes located in the Tswaing LM area that fell within a specific PS range for irrigation purposes.

#### 4.2.10.2 Possible causes and remediation strategies

The presence of sulfate in water can be due to natural sources as well as industrial waste. Chloride is also naturally found in water and the increase thereof can be due to urban runoff or industrial effluent (World Health Organization, 2017).

The sulfate and chloride concentrations present in the investigated boreholes do not pose a big risk to the health of humans or livestock, as the concentrations were not beyond the recommended limits. However, the combination thereof poses a great risk for plants, as it exceeded the PS limit, leading to a salinity hazard. Water purification technologies or methods to reduce the sulfate and chloride concentrations are therefore required before use. The recommended water purification methods for the reduction in chloride concentration are ACF (Antony *et al.*, 2021; Mazille & Spuhler, 2020b; Pedroza *et al.*, 2021; Yuan *et al.*, 2019), NF (Franke *et al.*, 2019; Yuan *et al.*, 2019), RO and electrodialysis (Yuan *et al.*, 2019). For the reduction in sulfate concentration, NF, RO, and ion exchange are recommended (Crooks, 2020; Sharma & Kumar, 2020).

#### 4.2.11 Overall

##### 4.2.11.1 Drinking purposes

An overview of the overall water quality parameter status for drinking water for the NMMD area is presented in Figure 59. For this analysis, the data from the Ditsobotla, Ratlou and Tswaing LM areas were combined to provide an overall view. The percentage of boreholes

that complied with the SANS 241-1 standard for a specific parameter are indicated, along with the percentage which did not comply.

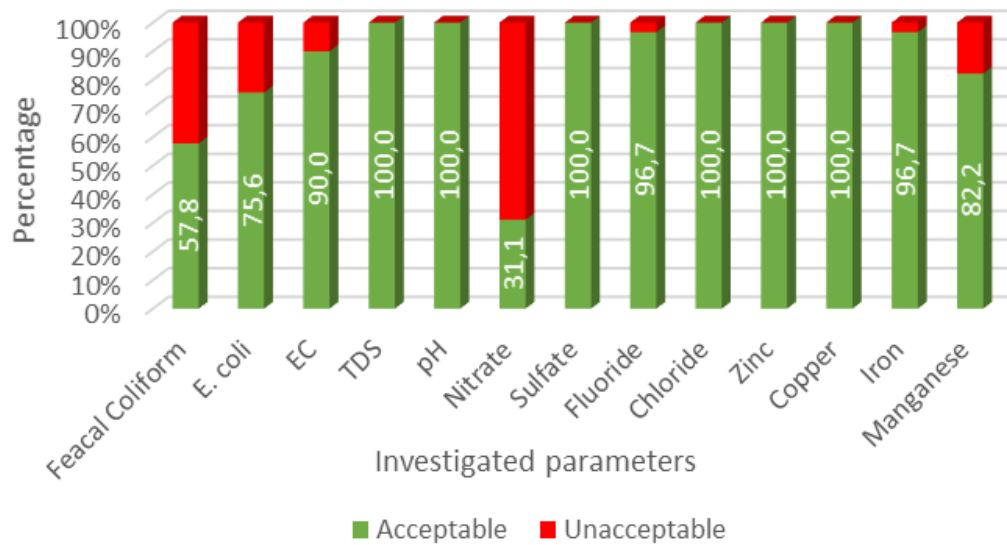


**Figure 59:** Overall status of the water quality parameters for the NMMD area for drinking purposes.

The biggest concern for the water quality status of the boreholes in the NMMD area was the elevated nitrate concentrations. 68.9% of all investigated boreholes were recorded to have a nitrate concentration that was beyond the recommended SANS 241-1 limit. In a previous study conducted by Bezuidenhout (2011), concerns of elevated nitrate concentrations in groundwater in the North West Province was reported.

Another problem that needs to be addressed is the presence of *Faecal coliform* and *E. coli* in 42.2 and 24.4% of the boreholes, respectively. The presence thereof is an indication of faecal contamination, which was shown to be a problem in groundwater sources in the North West Province (Nkwe *et al.*, 2015).

#### 4.2.11.2 Livestock purposes

An overview of the overall water quality parameter status for livestock use in the NMMD area is presented in Figure 60.

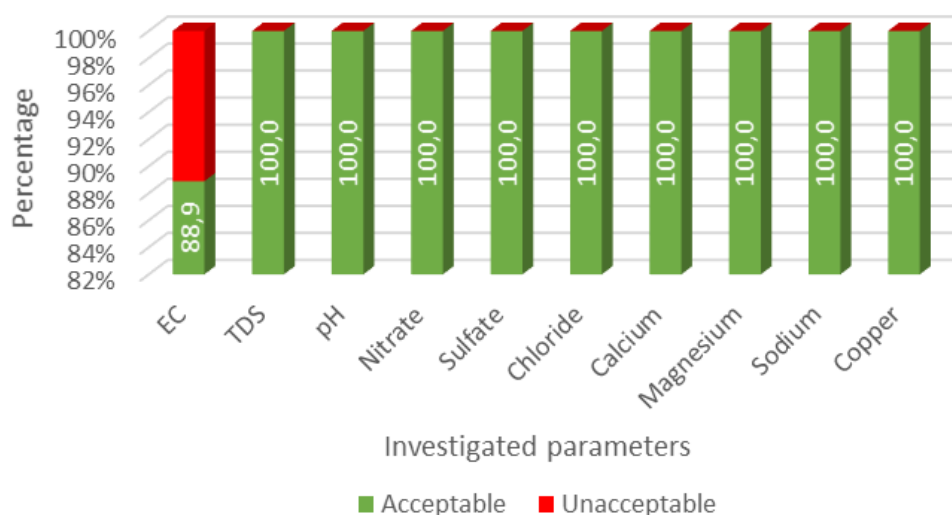


**Figure 60:** Overall status of the water quality parameters for the NMMD area for livestock purposes.

Overall, the water quality for livestock use in the NMMD area was suitable, with the only parameter of concern was EC. Only 11.1% of the investigated boreholes in the NMMD area were unsuitable for livestock use due to the elevated EC. It is clear the groundwater in the NMMD area was of excellent quality for livestock use.

#### 4.2.11.3 Irrigation purposes

An overview of the overall water quality parameter status for irrigation purposes in the NMMD area is presented in Figure 61.

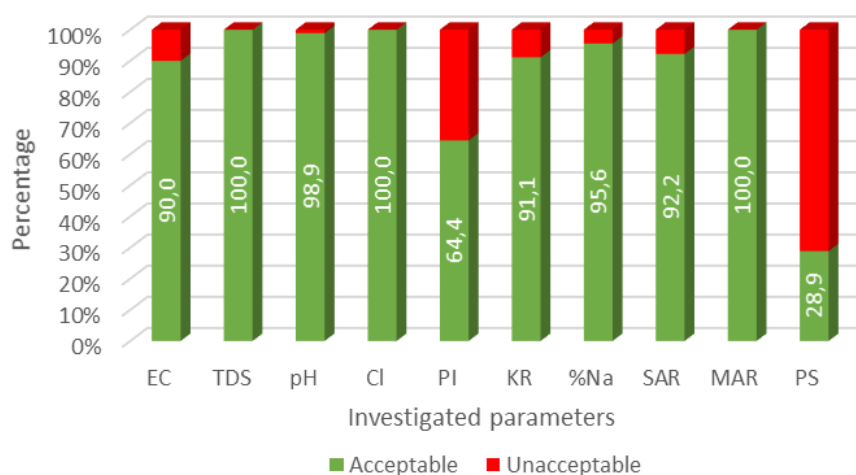


**Figure 61:** Overall status of the water quality parameters for the NMMD area for irrigation purposes.

For irrigational use in the NMMD area, the greatest concern is the salinity hazard as indicated by the low percentage of boreholes which comply to the PS limit. Only 28.9% of the boreholes complied with the PS limit. Another problem that needs to be addressed was the high sodium and bicarbonate to calcium and magnesium ratios, which negatively affects the PI value of the borehole water. 35.6% of the investigated boreholes had an undesirable PI value. The KR, %Na and SAR indicated the sodium present in water, as mentioned in **Section 2.5.2.17**. The amount of sodium present in some boreholes in the NMMD area needs to be reduced before use. Sodium was, however, not a major concern in the NMMD area as a whole. It is recommended that the boreholes which have elevated levels of PS and PI are treated prior to use.

Water treatment methods or technologies need to be utilized for the improvement of the specific parameters which have proven to be unacceptable. This is important, especially for the improvement of microbial contaminants and high nitrate levels for drinking purposes as well as for high salinity and sodium levels for irrigational purposes.

### **4.3 Water purification technology decision tree**

For this study, a water treatment technology decision tree was developed, which is presented in Figure 62. The decision tree can be used to determine which water treatment technology will be suitable for the improvement of a specific parameter. The parameters that were included in the decision tree were microbial contaminants, TDS, EC, pH, nitrate, sulfate, fluoride, chloride, manganese, iron, zinc, copper, sodium, potassium, calcium, and magnesium.

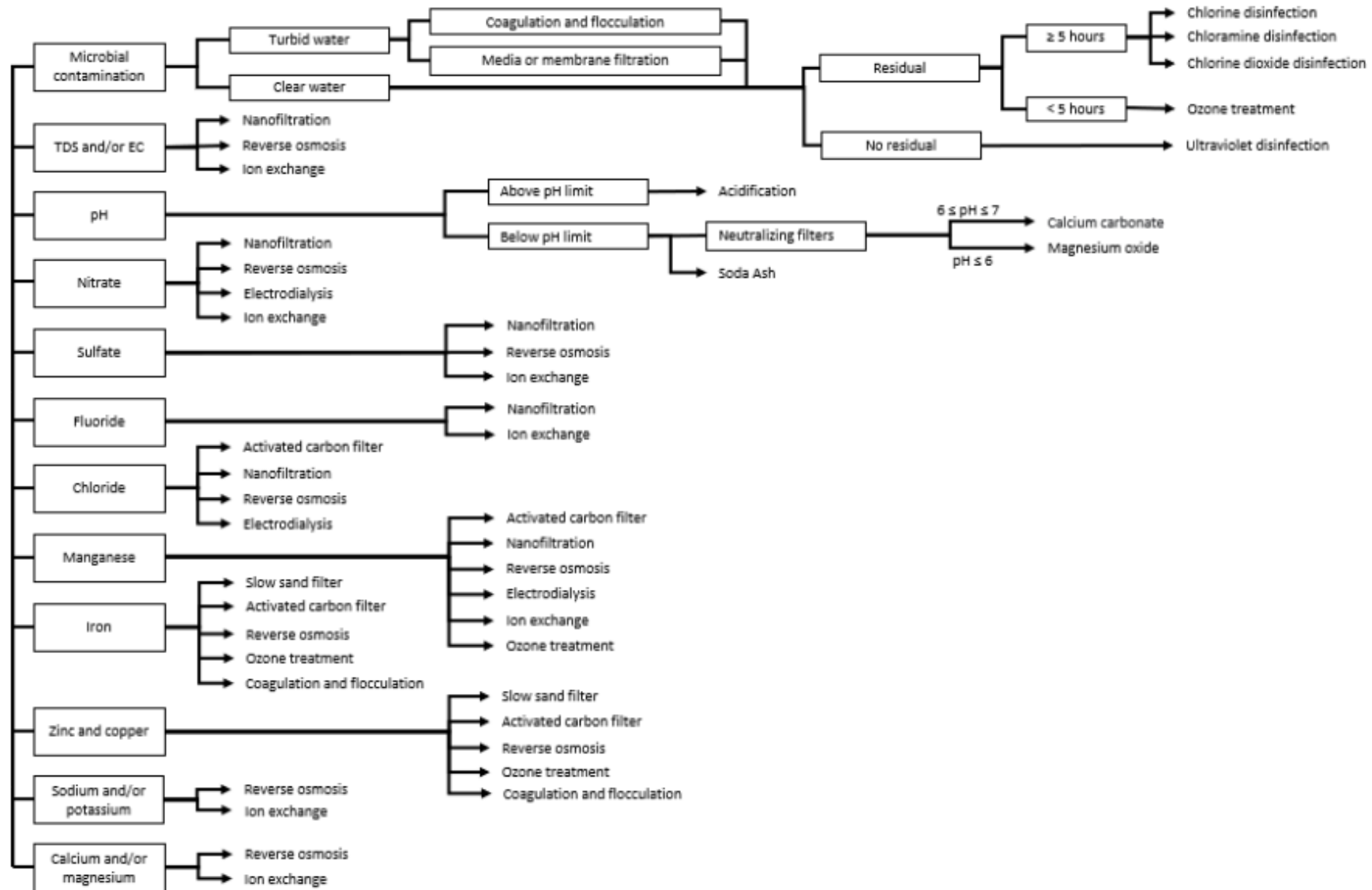


Figure 62: Water purification technology decision tree.

For the 90 investigated boreholes, the decision tree was used to determine which water purification technology would be suitable to improve the water quality for drinking, livestock, and irrigation purposes. In order to ensure that the recommended treatment tables are not redundantly long, codes were allocated for each water treatment technology. The water treatment technology codes are presented in Table 38.

**Table 38:** Water treatment technology code

| <b>Code</b> | <b>Treatment technology</b>  |
|-------------|------------------------------|
| D1          | UV                           |
| D2          | Ozone                        |
| D3          | Chlorine                     |
| D4          | Chloramine                   |
| D5          | Chlorine dioxide             |
| F1          | ACF                          |
| F2          | HSSF                         |
| F3          | SSF                          |
| F4          | MF                           |
| F5          | UF                           |
| F6          | NF                           |
| F7          | RO                           |
| F8          | Electrodialysis              |
| IX          | Ion exchange                 |
| CF          | Coagulation and flocculation |

In Table 48, Table 49, and Table 50 in Appendix B, the water quality classes, along with the parameters that exceeded the standard limit, are individually presented for drinking, livestock and irrigation purposes.

## CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

In Chapter 5, the main outcomes as defined by the objectives of this study in **Chapter 1**, along with a summary of the obtained results are stated. In **Section 5.1**, the primary conclusion drawn from the study is presented. Recommendations for future studies specifically in the NMMD area are presented in **Section 5.1.1** and recommendations for general future studies are presented in **Section 5.1.2**.

### 5.1 Conclusion

The study aimed to assess the groundwater quality of different boreholes located in the NMMD area, more specifically the Ratlou, Ditsobotla, and Tswaing LM areas, for drinking, livestock, and irrigation purposes and to present the obtained information, coupled with the treatment technology recommendations, simply and understandably. In effect, it was aimed to broaden the spectrum of people able to understand and use the obtained results.

The WQI was used to evaluate the groundwater quality of the specified LM areas for the given purposes and was proven to be an effective method. Policymakers and/or concerned citizens would be able to easily see whether the water quality of a borehole is up to standard and suitable for use by only considering the allocated WQI class rating of the specific borehole. However, if the groundwater quality is proven to be not on the acceptable standard according to the WQI, the user may find it difficult to plot a course of action if not a water expert. For this reason, the developed water purification technology decision tree has proven to be a good solution to the problem, as it will easily guide the user to see which parameter is elevated and which water treatment technology is recommended.

For the evaluation of the groundwater quality for drinking purposes, chemical, physical, and microbial water quality parameters were taken into consideration. It was found that the majority of the boreholes shifted from Class I to V when microbial contaminants, namely *E. coli* and *Faecal coliform*, were added to the chemical and physical parameters in the evaluation. Overall, the majority of the investigated boreholes poses a significant risk to the health of the consumers drinking the microbially contaminated water. Furthermore, elevated parameters, which influenced the WQI rating for the investigated boreholes, included nitrate, manganese, fluoride, and EC. In conclusion regarding the groundwater quality for drinking purposes, the recommended water purification technologies need to be used before consumption to avoid any health risks.

Concerning the groundwater quality for livestock use, 90% of the investigated boreholes were classified as Class I. The only parameter which influenced the WQI rating, resulting in a Class V score for livestock purposes, was EC. Hence, the conclusion was drawn that the overall groundwater quality is suitable for livestock use and only a few boreholes would have to be treated prior to use.

For the evaluation of the groundwater quality for irrigation purposes, the majority of the boreholes were proven to be acceptable. The undesirable WQI ratings were due to elevated levels of EC, calcium, magnesium, nitrate, sulfate, and chloride, which in effect negatively influenced the irrigation indices. In conclusion, the groundwater quality of the majority of the boreholes are suitable for irrigation purposes. However, for the remaining boreholes, the recommended water treatment technologies need to be used before use.

For each of the elevated parameters, possible causes were suggested and recommended water purification technologies were presented. The developed water purification technology decision tree was used for this section in the study. Since different water purification technologies are required for different parameters in most cases, the suggested combination for each of the investigated boreholes was included in the study. This was done individually for drinking, livestock, and irrigation purposes.

In conclusion, it is evident that the absence of a water management plan, coupled with irregular and ineffective groundwater monitoring has negatively affected the groundwater quality for drinking purposes, as it was proven that the majority of the boreholes are classified as unsuitable. In affect the health of consumers will be greatly affected if the problem is not properly addressed. There is however a significant need for information to solve the abovementioned problem for the NMMD area, which can be addressed in future studies.

## **5.2 Recommendations**

The goal for the near future is to provide an adequate water management plan, for the protection of the health of the users, livestock and the production of crops, as well as the protection of valuable groundwater resources. Therefore, the following recommendations are made for future studies specifically for the NMMD area, as well as for general future studies.

### **5.2.1 Future studies for the specific area**

The following recommendations are given for future studies to be conducted in the NMMD area. As mentioned in **Chapter 1** (Introduction), The NMMD area lacks a water management

plan, irregular and ineffective groundwater monitoring is taking place and the current information is outdated. The following recommendations will benefit the NMMD area, as the obtained results and recommendations thereof will contribute to the development and/or improvement of an effective water management plan. The possible research prospects include:

- To conduct a study on the groundwater quality of the NMMD area where Mahikeng and Ramotswa LM areas are included. The inclusion of the two LM areas will provide a better understanding as to what the overall water quality status of the NMMD area is.
- An in-depth investigation into the individual boreholes with an undesirable WQI rating to determine what the sources of pollution are. Such a study will help to identify intervention strategies that will be useful for the elimination of pollution sources to prevent further deterioration of the groundwater resource.
- To conduct a study on the groundwater stock volume and mean recharge rate of the available boreholes in the region to determine whether the available amount of water is suitable for the number of people relying on it. The stress on groundwater resources should also be considered in the study for the specific region. The obtained results from the study will be a great contribution to the management of the groundwater resources in the NMMD area, as both the water demand and the protection of water resources will be addressed.
- To conduct a seasonal variation study on the investigated boreholes of the current study to observe the water quality and quantity trend during different seasons within a year. Information regarding the change in water quality and quantity during the year will provide information needed for the necessary decision making in water resource management throughout the year in the NMMD area. In effect, the health of consumers, livestock, as well as crop production, will benefit.
- To conduct an in-depth study on the groundwater in the NMMD area where the aquifer depth as well as the area's geology is taken into consideration, as this will affect the groundwater quality. This will help to effectively adapt the water management plan for specific regions in the NMMD area.

- To conduct a nitrate specific study for the groundwater sources in the NMMD area. It is recommended that the area's fertiliser discharge rate and sanitation status of the human settlements near the boreholes are considered.
- To include the analysis of biological oxygen demand (BOD) and chemical oxygen demand (COD) in the analysis of the groundwater quality, due to the high agricultural activities in the area.

### 5.2.2 Future studies in general

The following recommendations are made for future studies in general. These recommendations include:

- The use of existing groundwater quality databases, obtained over a few years, to observe whether groundwater quality degradation is taking place in the North West Province, and if so, to what extent.
- As mentioned in **Chapter 3** (Methodology), there are some limitations to the WQI, as microbial parameters, such as *E. coli*, *Faecal coliform*, total coliforms and heterotrophic plate counts are not included in the water quality analysis method for drinking water (Olasoji *et al.*, 2019). It was also excluded in studies where the WQI was used for the evaluation of water quality for livestock and irrigation purposes. It is recommended that a study be conducted to determine how microbial contaminants can be included in the WQI model for the evaluation of water quality.
- To conduct a techno-economical study in which the costs of a wide range of water treatment technologies are compared to one another, along with a projection of expected water treatment costs for different flow rates. A study that lists the expected treatment costs of different treatment technologies would greatly benefit municipalities, as well as citizens, when deciding on a water treatment process.

Whilst the dissertation proved to be useful in evaluating the groundwater quality of the investigated boreholes, identifying elevated parameters and presenting the required treatment technologies, it is clear that groundwater challenges exist in the NMMD area. The development of a water management plan and the implementation of regular and effective

groundwater monitoring has proven to be of importance and should be considered as a pressing goal for the near future.

## REFERENCE LIST

- Abbasnia, A., Radfard, M., Mahvi, A.H., Nabizadeh, R., Yousefi, M., Alimohammadi, M. 2018. Groundwater quality assessment for irrigation purposes based on irrigation water quality index and its zoning with GIS in the villages of Chabahar, Sistan and Baluchistan, Iran. *Data in Brief*. 19:623–631.
- Acumen group. 2021. *Disinfection: Chlorine dioxide*. [https://www.acugrp.com/disinfection?qclid=CjwKCAjwvuGJBhB1EiwACU1Aia-nwwGvxd3sWSIZHV4NmO54vzXTkGZW01gDOaghYI\\_aJ5\\_mM375PBoCkqIQAvD\\_BwE](https://www.acugrp.com/disinfection?qclid=CjwKCAjwvuGJBhB1EiwACU1Aia-nwwGvxd3sWSIZHV4NmO54vzXTkGZW01gDOaghYI_aJ5_mM375PBoCkqIQAvD_BwE) Date of access: 08 Sep. 2021.
- AGES (Africa Geo-Environment Engineering and Science). 2019. *Water*. <https://ages-group.com/water/> Date of access: 15 Jul. 2020.
- Ahdab, Y.D., Rehman, D., Schücking, G., Barbosa, M. & Lienhard, J.H. 2021. Treating Irrigation Water Using High-Performance Membranes for Monovalent Selective Electrodialysis. *ACS ES&T Water*. 1(1):117–124.
- Ahmad, A. & Azam, T. 2019. Water Purification Technologies. In: A.M. Grumezescu & A.M. Holban, eds. *Bottled and Packaged Water*. Woodhead Publishing. pp. 83–120.
- Al Sinjari, W.E., Al-Saffawi, A.-A.Y.T. & Al-Taee, Y.A.J. 2019. Application of WQI model to assessment of water for irrigation and livestock drinking purpose: The case study, ground water quality of Gleewkhan Village Southeastern of Mosul City Iraq. *Journal of Engineering and Applied Sciences*. 14(9):10706–10710.
- Al-Assaf, A.Y.R., Talat, R.A. & Al-Saffawi, A.A.Y.T. 2020. Suitability of water for irrigation and livestock watering purpose using iwqi model: The case study groundwater quality of some quarters of mosul city, Iraq. *Plant Archives*. 20:1797–1802.
- Al-Omran, A., Al-Barakah, F., Altuquq, A., Aly, A. & Nadeem, M. 2015. Drinking water quality assessment and water quality index of Riyadh, Saudi Arabia. *Water Quality Research Journal of Canada*. 50(3):287–296.
- Al-Saffawi, A.Y.T., Al Sinjari, W.E. & Al-Taee, Y.A.J. 2018. Assessment of groundwater quality using the WQI in Gleewkhan village northeastern of Iraq. *International Journal of Enhanced Research in Science, Technology and Engineering*. 7(5):1–7.
- Al-Saffawi, A.Y.T., Al-Shanoona, R.A.A. & Alobidy, O.M.S. 2021. Application weight mathematical model to assess water quality for irrigation: A case study of Tigris river in Nineveh governorate. *IOP Conference Series: Earth and Environmental Science*.

735(1):1-7.

- Al-Saffawi, A.Y.T., Ibn Abubakar, B.S, Al-Asaat, A.Y, Hussaini, M. & Ibrahim, U. 2020. Groundwater Quality Assessment of Nimrod for Livestock and Poultry Consumption. *Uniport Journal of Engineering and Scientific Research*. 5:120–127.
- Al-Saffawi, A.Y.T., Ibn Abubakar, B.S.U., Abbass, L.Y. & Monguno, A.K. 2020. Assessment of groundwater quality for irrigation using water quality index in Al-Kasik subdistrict Northwestern, Iraq. *Nigerian Journal of Technology*. 39(2):632–638.
- Al-Saffawi, A.Y.T., Al-Assaf, A.Y.R. & Talat, R.A. 2020. Valuation of water quality for livestock and poultry watering: a case study of groundwater in some areas of Mosul city, Iraq. *Nippon Journal of Environmental Science*. 1(2):1006.
- Alam, M.Z., Carpenter-Boggs, L., Mitra, S., Haque, M.M., Halsey, J., ... Moniruzzaman, M. 2017. Effect of salinity intrusion on food crops, livestock, and fish species at Kalapara Coastal Belt in Bangladesh. *Journal of Food Quality*. 23:1-23.
- Alaviani, F., Sedghi, H., Moghaddam, A.A. & Babazadeh, H. 2018. Adopting GMS–PSO model to reduce groundwater withdrawal by integrated water resources management. *International Journal of Environmental Research*. 12:619–629.
- Albergamo, V., Blankert, B., Cornelissen, E.R., Hofs, B., Knibbe, W.J., ... De Voogt, P. 2019. Removal of polar organic micropollutants by pilot-scale reverse osmosis drinking water treatment. *Water Research*. 148:535–545.
- Albergamo, V., Escher, B.I., Schymanski, E.L., Helmus, R., Dingemans, M.M.L., ... De Voogt, P. 2020. Evaluation of reverse osmosis drinking water treatment of riverbank filtrate using bioanalytical tools and non-target screening. *Environmental Science: Water Research and Technology*. 6(1):103–116.
- Ali, A., Quist-Jensen, C.A., Drioli, E. & Macedonio, F. 2018. Evaluation of integrated microfiltration and membrane distillation/crystallization processes for produced water treatment. *Desalination*. 434:161–168.
- Alkherraz, A.M., Ali, A.K. & Elsherif, K.M. 2020. Removal of Pb (II), Zn (II), Cu (II) and Cd (II) from aqueous solutions by adsorption onto olive branches activated carbon: Equilibrium and thermodynamic studies. *Journal of Chemistry International*. 6(1):11–20.
- Andreoli, F.C. & Sabogal-Paz, L.P. 2020. Household slow sand filter to treat groundwater with microbiological risks in rural communities. *Water Research*. 186:116352.
- Ang, M.B.M.Y., Tang, C.L., De Guzman, M.R., Maganto, H.L.C., Caparanga, A.R., ... Lai, J.Y.

2020. Improved performance of thin-film nanofiltration membranes fabricated with the intervention of surfactants having different structures for water treatment. *Desalination*. 481:114352.
- Antony, A., Silvester, R., Alikunju, A.P. & Francis, B. 2021. Efficacy of a closed water depuration system with charcoal filter on the bacteriological quality of *Villorita cyprinoides* ( Hanley , 1866 ). *Fishery Technology*. 58:160–165.
- Atlas Scientific. 2021. Why Measuring Conductivity In Water Is Important For All Applications. <https://atlas-scientific.com/blog/why-is-conductivity-important-in-water/> Date of access: 02 Oct. 2021.
- Badeenezhad, A., Reza, H., Nikbakht, H., Radfard, M., Abbasnia, A., ... Alhamd, M. 2020. Groundwater for sustainable development estimation of the groundwater quality index and investigation of the affecting factors their changes in Shiraz drinking groundwater , Iran. *Groundwater for Sustainable Development*. 11:100435.
- Banda, T.D. & Kumarasamy, M.V. 2020a. Development of a universal water quality index (UWQI) for South African river catchments. *Water*. 12(6):1534.
- Banda, T.D. & Kumarasamy, M.V. 2020b. Development of water quality indices (WQIs): A review. *Polish Journal of Environmental Studies*. 29(3):2011–2021.
- Ben, W., Shi, Y., Li, W., Zhang, Y. & Qiang, Z. 2017. Oxidation of sulfonamide antibiotics by chlorine dioxide in water: Kinetics and reaction pathways. *Chemical Engineering Journal*. 327:743–750.
- Bezuidenhout, C.C. 2011. *A scoping study on the environmental water (groundwater and surface water) quality and management in the North West Province, South Africa*.
- Bierkens, M.F.P. & Wada, Y. 2019. Non-renewable groundwater use and groundwater depletion: A review. *Environmental Research Letters*. 14(6):3002.
- Block, J. 2020. Nitrate poisoning of livestock. *North Dakota State University Extension*. 839.
- Brindha, K. & Elango, L. 2011. Fluoride in groundwater: Causes, implications and mitigation measures. *Fluoride Properties, Applications and Environmental Management*. 1:113–136.
- Bruni, M.A. & Spuhler, D. 2020. *Slow sand filtration factsheet. Sustainable sanitation and water management*. <https://sswm.info/sswm-university-course/module-6-disaster-situations-planning-and-preparedness/further-resources-0/slow-sand-filtration> Date of access: 09 Sep. 2021.

- Buendia, J.A., Perez-Lopez, E. & Venkattraman, A. 2018. System-level model and experiments for irrigation water alkalinity reduction and enrichment using an atmospheric pressure dielectric barrier discharge. *Water Research*. 144:728–739.
- Campinas, M., Viegas, R.M.C., Silva, C., Lucas, H. & Rosa, M.J. 2021. Operational performance and cost analysis of PAC/ceramic MF for drinking water production: Exploring treatment capacity as a new indicator for performance assessment and optimization. *Separation and Purification Technology*. 255:117443.
- CDC (Centers for disease Control and Prevention). 2020. *Water disinfection with chlorine and chloramine*. [https://www.cdc.gov/healthywater/drinking/public/water\\_disinfection.html](https://www.cdc.gov/healthywater/drinking/public/water_disinfection.html) Date of access: 07 Sept. 2021.
- Cheng, L.H., Xiong, Z.Z., Cai, S., Li, D.W. & Xu, X.H. 2020. Aeration-manganese sand filter-ultrafiltration to remove iron and manganese from water: Oxidation effect and fouling behavior of manganese sand coated film. *Journal of Water Process Engineering*. 38:101621.
- Chourasia, L.P. 2018. Assessment of groundwater quality using water quality index in and around Korba City, Chhattisgarh, India. *American Journal of Software Engineering and Applications*. 7(1):15.
- Cobbing, J.E. 2018. An updated water balance for the Grootfontein aquifer near Mahikeng. *Water SA*. 44(1):54–64.
- Colvin, C., Muruven, D., Lindley, D., Gordon, H. & Schachtschneider, K. 2016. *Water: Facts and Futures*. Cape Town, South Africa.
- Commercial Filtration Supply. 2021. *Membrane filtration vs media filtration: Which one does your business need?* <https://www.commercialfiltrationsupply.com/education/membrane-vs-media-filtration-differences.html> Date of access: 08 Sep. 2021.
- Crooks, A. 2020. *Understanding Limits for Livestock Water*. Wels Labs.
- Dangi, P.L., Sharma, B. & Uppadhyay, B. 2017. BOD, Total and *Faecal coliform* bacterial status of Lake Pichhola, Udaipur, Rajasthan. *International Journal of Fisheries and Aquatic Studies*. 5(3):176–180.
- De Graaf, E.M., Gleeson, T., Van Beek, L.P.H., Sutanudjaja, E.H. & Bierkens, M.F.P. 2019. Environmental flow limits to global groundwater pumping. *Nature*. 574:90–94.
- Denchak, M. 2018. *Water pollution: Everything you need to know*. Natural Resources Defense Council. <https://www.nrdc.org/stories/water-pollution-everything-you-need-know> Date of

access: 17 Oct. 2021.

Department of Rural Development and Land Reform (South Africa). 2016. *District rural development plan: Ngaka Modiri Molema District Municipality*. Pretoria.

Department of Water Affairs and Forestry (South Africa). 1996. *South African water quality guidelines. Agricultural use: livestock watering*. Second ed. Vol. 5. Pretoria: Department of Water Affairs and Forestry.

Department of Water and Sanitation (South Africa). 2019. *Groundwater: Water sector public education and outreach programme booklet*. Pretoria: Department of Water and Sanitation.

Drinking Water. 2019. *Drinking water treatment - pH adjustment*. <https://drinking-water.extension.org/drinking-water-treatment-ph-adjustment/> Date of access: 20 Sep. 2021.

Du, Z., Jia, R., Li, C., Cui, P., Song, W. & Liu, J. 2020. Pilot-scale UV/H<sub>2</sub>O<sub>2</sub>-BAC process for drinking water treatment – Analysis and comparison of different activated carbon columns. *Chemical Engineering Journal*. 382:123044.

Du Preez, C.C. & Van Huyssteen, C.W. 2020. Threats to soil and water resources in South Africa. *Environmental Research*. 183:109015.

Edokpayi, J.N., Rogawski, E.T., Kahler, D.M., Hill, C.L., Reynolds, C., ... Dillingham, R. 2018. Challenges to sustainable safe drinking water: A case study of water quality and use across seasons in rural communities in Limpopo Province, South Africa. *Water*. 10(2):159–167.

Edokpayi, J.N., Odiyo, J.O., Msagati, T.A.M. & Potgieter, N. 2015. Temporal variations in physico-chemical and microbiological characteristics of Mvudi River , South Africa. *International Journal of Environmental Research and Public Health*. 3(12):4128–4140.

Elangovan, K. & Rani, R. 2017. Study on suitability of groundwater for irrigation purpose in Parambikulam Aliyar project area, India. *Indian Journal of Geo-Marine Sciences*. 46(5):1052–1060.

Elder, D. & Budd, G.C. 2011. Overview of water treatment processes. In: J.K. Edzwald, ed. Sixth ed. *Water Quality & Treatment: A Handbook on Drinking Water*. Denver, Colorado: American Water Works Association, American Society of Civil Engineers, McGraw-Hill.

Elshall, A.S., Arik, A.D., El-Kadi, A.I., Pierce, S., Ye, M., ... Chun, G. 2020. Groundwater sustainability: A review of the interactions between science and policy. *Environmental*

*Research Letters*. 15(9):3004.

- Ememu, A.J. & Nwankwoala, H.O. 2018. Application of Water Quality Index ( WQI ) for agricultural and irrigational use around Okpoko, Southeastern Nigeria. *Engineering Heritage Journal*. 2(1):14–18.
- Enitan-Folami, A.M., Mutileni, N., Odiyo, J.O., Swalaha, F.M. & Edokpayi, J.N. 2019. Hydrochemical, bacteriological assessment, and classification of groundwater quality in Thulamela Municipality, South Africa: potential health risk. *Human and Ecological Risk Assessment: An International Journal*, <https://doi.org/10.1080/10807039.2019.1644153>.
- Evans, A.E., Mateo-Sagasta, J., Qadir, M., Boelee, E. & Ippolito, A. 2019. Agricultural water pollution: key knowledge gaps and research needs. *Current Opinion in Environmental Sustainability*. 36:20–27.
- Falconer, L., Telfer, T.C. & Ross, L.G. 2018. Modelling seasonal nutrient inputs from non-point sources across large catchments of importance to aquaculture. *Aquaculture*. 495:682–692.
- Fondriest Environmental Inc. 2020a. *Conductivity, salinity and total dissolved solids*. <https://www.fondriest.com/environmental-measurements/parameters/water-quality/conductivity-salinity-tds/> Date of access: 17 Dec. 2020.
- Fondriest Environmental Inc. 2020b. *pH of water*. <https://www.fondriest.com/environmental-measurements/parameters/water-quality/ph/> Date of access: 19 Dec. 2020.
- Franke, V., McCleaf, P., Lindegren, K. & Ahrens, L. 2019. Efficient removal of per- and polyfluoroalkyl substances (PFASs) in drinking water treatment: Nanofiltration combined with active carbon or anion exchange. *Environmental Science: Water Research and Technology*. 5(11):1836–1843.
- Gaikwad, S.K., Kadam, A.K., Ramgir, R.R., Kashikar, A.S., Wagh, V.M., ... Kamble, K.D. 2020. Assessment of the groundwater geochemistry from a part of west coast of India using statistical methods and water quality index. *HydroResearch*. 3:48–60.
- Gao, Y., Qian, H., Ren, W., Wang, H. & Liu, F. 2020. Hydrogeochemical characterization and quality assessment of groundwater based on integrated-weight water quality index in a concentrated urban area. *Journal of Cleaner Production*. 260:121006.
- Garg, T., Hamilton, S.E., Hochard, J.P., Plous, E. & Talbot, J. 2018. (Not so) gently down the stream: River pollution and health in Indonesia. *Journal of Environmental Economics and Management*. 92:35–53.

- Gelete, G., Gokcekus, H., Ozsahin, D.U., Uzun, B. & Gichamo, T. 2020. Evaluating disinfection techniques of water treatment. *Desalination and Water Treatment*. 177:408–415.
- German, D., Thiex, N. & Wright, C. 2008. *Interpretation of water analysis for livestock suitability*. South Dakota State University. <https://www.thecattlesite.com/articles/1503/interpretation-of-water-analysis-for-livestock-suitability/> Date of access: 03 Aug. 2021.
- Government, N.W.P. 2017. *North West Spatial Development Framework 2017*.
- Government of Western Australia: Department of Health. 2016. *Copper in drinking water*. [https://ww2.health.wa.gov.au/Articles/A\\_E/Copper-in-drinking-water](https://ww2.health.wa.gov.au/Articles/A_E/Copper-in-drinking-water) Date of access: 29 Dec. 2020.
- Grandjean, P. & Landrigan, P.J. 2015. Neurobehavioural effects of developmental toxicity. *The Lancet Neurology*. 13(3):330–338.
- Grazuleviciene, R., Nadisauskiene, R., Buinauskiene, J. & Grazulevicius, T. 2009. Effects of Elevated Levels of Manganese and Iron in Drinking Water on Birth Outcomes. *Polish Journal of Environmental Studies*. 18(5):819–825.
- Han, J., Zhang, X., Li, W. & Jiang, J. 2021. Low chlorine impurity might be beneficial in chlorine dioxide disinfection. *Water Research*. 188:116520.
- Hanasaki, N., Yoshikawa, S., Pokhrel, Y. & Kanae, S. 2018. A global hydrological simulation to specify the sources of water used by humans. *Hydrology and Earth System Sciences*. 22(1):789–817.
- Hansima, M.A.C.K., Makehelwala, M., Jinadasa, K.B.S.N., Wei, Y., Nanayakkara, K.G.N., ... Weerasooriya, R. 2021. Fouling of ion exchange membranes used in the electrodialysis reversal advanced water treatment: A review. *Chemosphere*. 263:127951.
- Hasan, M., Begum, L., Hosain, S., Poddar, P., Chowdhury, A. & Ali, F. 2017. Study on heavy metals (zinc and lead) in drinking water of tannery area, adjacent areas and outside village areas. *Journal of Environmental & Analytical Toxicology*. 7(2):1000433.
- Heeb, M.B., Kristiana, I., Trogolo, D., Arey, J.S. & Von Gunten, U. 2017. Formation and reactivity of inorganic and organic chloramines and bromamines during oxidative water treatment. *Water Research*. 110:91–101.
- Helmenstine, A.M. 2019. *pH definition and equation in chemistry*. <https://www.thoughtco.com/definition-of-ph-in-chemistry-604605> Date of access: 12 Oct.

2019.

- Hendrawati, H., Yuliasri, I.R., Nurhasni, Rohaeti, E., Effendi, H. & Darusman, L.K. 2016. The use of Moringa Oleifera seed powder as coagulant to improve the quality of wastewater and ground water. *IOP Conference Series: Earth and Environmental Science*. 31(1):2033.
- Hussain, M., Al-hasnawi, S.S. & Al-shamma, A.M. 2018. Assessment of index for aquifer water quality for irrigstion and livestock purposes of Dammam aquifer in Najaf Area of Iraq. *Journal University of Kerbala*. 16(3):77–89.
- Ibrahim, M.N. 2019. Assessing groundwater quality for drinking purpose in Jordan: Application of water quality index. *Journal of Ecological Engineering*. 20(3):101–111.
- Ivanets, I., Azarova, Agabekov, V.E., Azarov, S., Batsukh, C., ... Rat'ko, A.A. 2016. Effect of phase composition of natural quartz raw material on characterization of microfiltration ceramic membranes. *Ceramics International*. 42(15):16571–16578.
- Jalil, A.A., Luyun, R.A., Delos Reyes, A.A. & Bato, V.A. 2020. Assessment of groundwater quality for irrigation at Malamawi Island, Basilan, Philippines. *Jurnal Penelitian Pengelolaan Daerah Aliran Sungai*. 4(2):187–200.
- Jiang, C., Tian, L., Hou, Y. & Niu, Q.J. 2019. Nanofiltration membranes with enhanced microporosity and inner-pore interconnectivity for water treatment: Excellent balance between permeability and selectivity. *Journal of Membrane Science*. 586:192–201.
- Jung, B., Menk, D., Watts, M.J. & Jassby, D. 2021. Evaluation and optimization of treatment technologies treating groundwater from the Arbuckle-Timbered Hills Aquifer in Oklahoma. *ACS ES&T Water*. 1(6):1380–1389.
- Ketsela, G., Animen, Z. & Talema, A. 2020. Adsorption of lead (II), cobalt (II) and iron (II) from aqueous solution by activated carbon prepared from white Lupine (GIBITO) HUSK. *Journal of Thermodynamics and Catalysis*. 11(2):1000203.
- Khajouei, G., Park, H. II, Finklea, H.O., Ziemkiewicz, P.F., Peltier, E.F. & Lin, L.S. 2021. Produced water softening using high-pH catholyte from brine electrolysis: reducing chemical transportation and environmental footprints. *Journal of Water Process Engineering*. 40:101911.
- Khanoranga, S.K. 2019. An assessment of groundwater quality for irrigation and drinking purposes around brick kilns in three districts of Balochistan province, Pakistan, through water quality index and multivariate statistical approaches. *Journal of Geochemical Exploration*. 197:14–26.

- Kumar, P.S. & Balamurugan, P. 2019. Suitability of ground water for irrigation purpose in Omalur Taluk, Salem, Tamil Nadu, India. *Indian Journal of Ecology*. 46(1):1–6.
- Kunrath, C.C.N., Patrocínio, D.C., Siqueira Rodrigues, M.A., Benvenuti, T. & Amado, F.D.R. 2020. Electrodialysis reversal as an alternative treatment for producing drinking water from brackish river water: A case study in the dry season, northeastern Brazil. *Journal of Environmental Chemical Engineering*. 8:103719.
- Lenntech. 2021a. Calcium (Ca) and water. <https://www.lenntech.com/periodic/water/calcium/calcium-and-water.htm> Date of access: 06 Aug. 2021.
- Lenntech. 2021b. Magnesium (Mg) and water. <https://www.lenntech.com/periodic/water/magnesium/magnesium-and-water.htm> Date of access: 06 Aug. 2021.
- Lenntech. 2021c. Sodium (Na) and water. <https://www.lenntech.com/periodic/water/sodium/sodium-and-water.htm> Date of access: 07 Aug. 2021.
- Lenntech. 2021d. Disinfectants: Chlorine Dioxide. <https://www.lenntech.com/processes/disinfection/chemical/disinfectants-chlorine-dioxide.htm> Date of access: 08 Sep. 2021.
- Lenntech. 2021e. Water treatment decision path tutorial. <https://www.lenntech.com/decision/water-treatment-decision-path.htm> Date of access: 01 Oct. 2021.
- Lenntech. 2021f. Carbonates and bicarbonates hazard of irrigation water. <https://www.lenntech.com/applications/irrigation/bicarbonate/bicarbonate-hazard-of-irrigation-water.htm> Date of access: 18 Sep. 2021.
- Levchuk, I., Rueda Márquez, J.J. & Sillanpää, M. 2018. Removal of natural organic matter (NOM) from water by ion exchange – A review. *Chemosphere*. 192:90–104.
- Li, H.Y., Osman, H., Kang, C.W. & Ba, T. 2017. Numerical and experimental investigation of UV disinfection for water treatment. *Applied Thermal Engineering*. 111:280–291.
- Liu, B., Zhu, T., Liu, W., Zhou, R., Zhou, S., Van der Bruggen, B. 2020. Ultrafiltration pre-oxidation by boron-doped diamond anode for algae-laden water treatment: membrane fouling mitigation, interface characteristics and cake layer organic release. *Water Research*. 187:116435.

- Mahmud, Z.H., Islam, S., Imran, K.M., Hakim, I., Worth, M., ... Ahmed, N. 2019. Occurrence of *Escherichia coli* and *Faecal coliform* in drinking water at source and household point-of-use in Rohingya camps, Bangladesh. *Gut Pathogens*. 11(52):1–11.
- Malkoske, T.A., Bérubé, P.R. & Andrews, R.C. 2020. Coagulation/flocculation prior to low pressure membranes in drinking water treatment: A review. *Environmental Science: Water Research and Technology*. 6(11):2993–3023.
- Mao, Y., Guo, D., Yao, W., Wang, X., Yang, H., ... Wang, Y. 2018. Effects of conventional ozonation and electro-peroxone pretreatment of surface water on disinfection by-product formation during subsequent chlorination. *Water Research*. 130:322–332.
- Maphela, B. & Cloete, F. 2020. Johannesburg's implementation of the National Water Act, 1998 in Soweto, South Africa. *Development Southern Africa*. 37(4):535–552.
- Mary River Catchment Coordinating Committee. 2013. *Water quality standards*. <http://mrccc.org.au/wp-content/uploads/2013/10/Water-Quality-Salinity-Standards.pdf> Date of access: 12 Oct. 2019.
- Masoud, A.M. & Ali, M.H. 2020. Coupled multivariate statistical analysis and WQI approaches for groundwater quality assessment in Wadi El-Assiuty downstream area, Eastern Desert, Egypt. *Journal of African Earth Sciences*. 172:103982.
- Mathivha, F.I., Nkosi, M. & Mutoti, M.I. 2021. Evaluating the relationship between hydrological extremes and groundwater in Luvuvhu River catchment, South Africa. *Journal of Hydrology: Regional Studies*. 37:100897.
- Mazhar, M.A., Khan, N.A., Ahmed, S., Khan, A.H., Hussain, A., ... Vambol, V. 2020. Chlorination disinfection by-products in municipal drinking water – A review. *Journal of Cleaner Production*. 273:123159.
- Mazille, F. & Spuhler, D. 2020a. *Coagulation-flocculation. sustainable sanitation and water management*. <https://sswm.info/sswm-university-course/module-6-disaster-situations-planning-and-preparedness/further-resources-0/coagulation-flocculation> Date of access: 14 Sep. 2021.
- Mazille, F. & Spuhler, D. 2020b. *Adsorption (activated carbon). Sustainable sanitation and water management*. [https://sswm.info/sswm-university-course/module-6-disaster-situations-planning-and-preparedness/further-resources-0/adsorption-\(activated-carbon\)](https://sswm.info/sswm-university-course/module-6-disaster-situations-planning-and-preparedness/further-resources-0/adsorption-(activated-carbon)) Date of access: 09 Sep. 2021.
- Mazille, F. & Spuhler, D. 2020c. *Membrane filtration. Slow sand filtration factsheet*. <https://sswm.info/sswm-university-course/module-6-disaster-situations-planning-and->

- [preparedness/further-resources-0/membrane-filtration](#) Date of access: 09 Sep. 2021.
- Mazille, F. & Spuhler, D. 2020d. *Ion exchange. Sustainable sanitation and water management.* <https://sswm.info/sswm-university-course/module-6-disaster-situations-planning-and-preparedness/further-resources-0/ion-exchange> Date of access: 14 Sep. 2021.
- Medeiros, R.C., De, N., Freitas, B.L.S., Sabogal-Paz, L.P., Hoffmann, M.T., ... Byrne, J.A. 2020. Drinking water treatment by multistage filtration on a household scale: Efficiency and challenges. *Water Research*. 178:115816.
- Medical News Today. 2018. *Why do we have fluoride in our water?* <https://www.medicalnewstoday.com/articles/154164#uses> Date of access: 20 Dec. 2020.
- Meehan, M.A., Stokka, G. & Mostrom, M. 2020. *Livestock Water Quality*. Fargo: North Dakota State University. (Study guide, AS1764).
- Mehl, V. & Johannsen, K. 2018. Calculating chemical speciation, pH, saturation index and calcium carbonate precipitation potential (CCPP) based on alkalinity and acidity using OpenModelica. *Journal of Water Supply: Research and Technology - AQUA*. 67(1):1–11.
- Mohamad Mazuki, N.I., Teow, Y.H., Ho, K.C. & Mohammad, A.W. 2020. Techno-economic analysis of single disinfection units and integrated disinfection systems for sewage effluent reclamation. *Journal of Water Process Engineering*. 36:101398.
- Moona, N., Murphy, K.R., Bondelind, M., Bergstedt, O. & Pettersson, T.J.R. 2018. Partial renewal of granular activated carbon biofilters for improved drinking water treatment. *Environmental Science: Water Research and Technology*. 4(4):529–538.
- Mung, C.C. 2017. Evaluation, modelling and control of ultrafiltration membrane water treatment systems. University of Malaya Kuala Lumpur.
- NanoTech. 2021. *Chloramines.* [https://www.nanotech.co.za/product/chloramines/?gclid=CjwKCAjwvuGJBhB1EiwACU1AiUDW\\_11CjGkTn-sSTjhjcp0zaXG6Ab19oQlf19Fgu1bCnrGzmDbKeBoCnB8QAvD\\_BwE](https://www.nanotech.co.za/product/chloramines/?gclid=CjwKCAjwvuGJBhB1EiwACU1AiUDW_11CjGkTn-sSTjhjcp0zaXG6Ab19oQlf19Fgu1bCnrGzmDbKeBoCnB8QAvD_BwE) Date of access: 08 Sep. 2021.
- Ngaka Modiri Molema District Municipality. 2018. *Annual Report 2017/18*. North West
- Ngaka Modiri Molema District Municipality. 2019. *Integrated Development Plan Report 2019/20*.
- Ngaka Modiri Molema District Municipality. 2020a. *Profile and analysis district development model*.

- Ngaka Modiri Molema District Municipality. 2020b. *Ngaka Modiri Molema District Municipality overview*. <https://www.nmmdm.gov.za/overview> Date of access: 27 Sep. 2021.
- Nkwe, K.I., Ateba, C.N., Sithebe, N.P. & Bezuidenhout, C.C. 2015. Enumeration of somatic and F-RNA phages as an indicator of fecal contamination in potable water from rural areas of the North West Province. *Pathogens*. 4(3):503–512.
- Noulas, C., Tziouvalekas, M. & Karyotis, T. 2018. Zinc in soils, water and food crops. *Journal of Trace Elements in Medicine and Biology*. 49:252–260.
- NRC (National Research Council). 2006. *Fluoride in Drinking Water: A Scientific Review of EPA's Standards*. T.N.A. Press, ed. Washington, DC.
- Olasoji, S.O., Oyewole, N.O., Abiola, B. & Edokpayi, J.N. 2019. Water quality assessment of surface and groundwater sources using a water quality index method: A case study of a peri-urban town in southwest, Nigeria. *Environments - MDPI*. 6(23):1-11.
- Oram, B. 2020. *Fecal coliform bacteria in water*. Water Research Center. <https://www.water-research.net/index.php/fecal-coliform-bacteria-in-water> Date of access: 03 Jan. 2020.
- Padhi, R.K., Subramanian, S. & Satpathy, K.K. 2019. Formation, distribution, and speciation of DBPs during treatment of different source water with chlorine and chlorine dioxide. *Chemosphere*. 218:540–550.
- Park, C. & Allaby, M. 2017. *A dictionary of environment and conservation*. 3rd ed. Oxford University Press.
- Pedroza, M.M., Neves, L.H.D., Paz, E.C.S., Silva, F.M., Rezende, C.S.A., ... Arruda, M.G. 2021. Activated charcoal production from tree pruning in the Amazon region of Brazil for the treatment of gray water. *Journal of Applied Research and Technology*. 19(1):49–65.
- Pullin, H., Crane, R.A., Morgan, D.J. & Scott, T.B. 2017. The effect of common groundwater anions on the aqueous corrosion of zero-valent iron nanoparticles and associated removal of aqueous copper and zinc. *Journal of Environmental Chemical Engineering*. 5(1):1166–1173.
- Pure-H2O. 2021. *ULO3. Pure-H2O Blended Learning*. <https://pure-h2o-learning.eu/units-of-learning-outcomes/ulo3/358-chapter-7?showall=&start=2> Date of access: 17 Sep. 2021.
- Qaderi, F. & Babanezhad, E. 2017. Prediction of the groundwater remediation costs for drinking use based on quality of water resource, using artificial neural network. *Journal of Cleaner Production*. 161:840–849.
- Qian, H., Chen, J. & Howard, K.W.F. 2020. Assessing groundwater pollution and potential

- remediation processes in a multi-layer aquifer system. *Environmental Pollution*. 263:114669.
- Ramakrishnaiah, C.R., Sadashivaiah, C. & Ranganna, G. 2009. Assessment of water quality index for the groundwater in Tumkur taluk, Karnataka state, India. *E-Journal of Chemistry*. 6(2):523–530.
- Rusydi, A.F. 2018. Correlation between conductivity and total dissolved solid in various type of water: A review. *IOP Conference Series: Earth and Environmental Science*. 118(1):2019.
- Safe Drinking Water Foundation. 2020a. *TDS and pH*. <https://www.safewater.org/fact-sheets-1/2017/1/23/tds-and-ph> Date of access: 16 Dec. 2020.
- Safe Drinking Water Foundation. 2020b. *Ultrafiltration, Nanofiltration and Reverse Osmosis*. <https://www.safewater.org/fact-sheets-1/2017/1/23/ultrafiltrationnanoandro> Date of access: 16 Dec. 2020.
- Safe Drinking Water Foundation. 2021. *Conventional water treatment: coagulation and filtration*. <https://www.safewater.org/fact-sheets-1/2017/1/23/conventional-water-treatment> Date of access: 16 Dec. 2020.
- SAHRC (South African Human Rights Commission). 2018. *The right to water and sanitation*. Johannesburg.
- Saikrishna, K., Purushotham, D., Sunitha, V., Reddy, Y.S., Linga, D. & Kumar, B.K. 2020. Data for the evaluation of groundwater quality using water quality index and regression analysis in parts of Nalgonda district, Telangana, Southern India. *Data in Brief*. 32(2020):106235.
- SANS (South African National Standards). 2015. Drinking water Part 1: Microbiological , physical , aesthetic and chemical determinands. Pretoria: SABS Standards Division. (SANS 241-1).
- Saucedo-Terán, R.A., Holguín- Licón, C., Jurado-Guerra, P., Ochoa-Rivero, J.M. & Rubio-Arias, H.O. 2017. Cattle drinking water quality in the cow-calf beef operation in southern Chihuahua, Mexico. *Ecosistemas y Recursos Agropecuarios*. 4(11):331.
- Shahriari, H.R. & Hosseini, S.S. 2020. Experimental and statistical investigation on fabrication and performance evaluation of structurally tailored PAN nanofiltration membranes for produced water treatment. *Chemical Engineering and Processing: Process Intensification*. 147:107766.

- Sharma, M.K. & Kumar, M. 2020. Sulphate contamination in groundwater and its remediation: an overview. *Environmental Monitoring and Assessment*. 192:74.
- Sharma, S. & Bhattacharya, A. 2017. Drinking water contamination and treatment techniques. *Applied Water Science*. 7(3):1043–1067.
- Sheep Connect SA. 2021. *Water quality for livestock*. <https://www.sheepconnectsa.com.au/management/water/water-for-livestock/water-quality-for-livestock> Date of access: 04 Aug. 2021.
- Shrestha, A.K. & Basnet, N. 2018. The Correlation and regression analysis of physicochemical parameters of river water for the evaluation of percentage contribution to electrical conductivity. *Journal of Chemistry*. 2018:1-9
- Sipple, S., Meinshausen, N., Fischer, E.M., Szekely, E. & Knutti, R. 2020. Climate change now detectable from any single day of weather at global scale. *Nature Climate Change*. 10:35–41.
- Soleimani, H., Nasri, O., Ojaghi, B., Palarari, H., Hosseini, M., ... Kiani, G. 2018. Data on drinking water quality using water quality index (WQI) and assessment of groundwater quality for irrigation purposes in. *Data in Brief*. 20:375–386.
- Stats SA (Statistics South Africa). 2018. *Provincial profile: North West. Community Survey 2016*. Pretoria.
- Stats SA (Statistics South Africa). 2019. *General Household Survey 2018*. <http://www.statssa.gov.za/publications/P0318/P03182018.pdf> Date of access: 13 Jun. 2020.
- Tahaikt, M., El-Ghzizel, S., Essafi, N., Hafsi, M., Taky, M. & Elmidaoui, A. 2021. Technical-economic comparison of nanofiltration and reverse osmosis in the reduction of fluoride ions from groundwater: Experimental, modeling, and cost estimate. *Desalination and Water Treatment*. 216:83–95.
- United Nations General Assembly. 2016. *The human rights to safe drinking water and sanitation: A/RES/70/169*.
- Van der Meulen, E.S., Sutton, N.B., Van de Ven, F.H.M., Van Oel, P.R. & Rijnaarts, H.H.M. 2020. Trends in demand of urban surface water extractions and in situ use functions. *Water Resources Management*. 34(15):4943–4958.
- Verlicchi, P. & Grillini, V. 2020. Surface water and groundwater quality in South Africa and Mozambique — Analysis of the most critical pollutants for drinking purposes and

- challenges in water treatment selection. *Water*. 12:305.
- Verma, S., Daverey, A. & Sharma, A. 2017. Slow sand filtration for water and wastewater treatment – a review. *Environmental Technology Reviews*. 6(1):47–58.
- Von Gunten, U. 2018. Oxidation processes in water treatment: Are we on track? *Environmental Science and Technology*. 52(9):5062–5075.
- Wanda, E.M.M., Mamba, B.B. & Msagati, T.A.M. 2016. Determination of the water quality index ratings of water in the Mpumalanga and North West Provinces, South Africa. *Physics and Chemistry of the Earth*. 92:70–78.
- Wang, J. & Wu, K. 2015. *The design for ion exchange column*. The Hague University.
- World Bank. 2017. *Water resource management: Strategy*. World Bank Water. <https://www.worldbank.org/en/topic/waterresourcesmanagement#2> Date of access: 21 Sep. 2021.
- World Health Organization. 2011. *Guidelines for drinking-water quality*. 4th ed. Geneva.
- World Health Organization. 2013. *Household Household Water Water Treatment Treatment and Safe Storage: Manual for the participant*. Geneva.
- World Health Organization. 2017. *Guidelines for drinking-water quality*. 4th ed. Geneva.
- World Health Organization. 2019. *Drinking-water*. <https://www.who.int/en/news-room/fact-sheets/detail/drinking-water> Date of access: 02 Jun. 2020.
- World Health Organization & United Nations-Water. 2019. *National systems to support drinking-water, sanitation and hygiene: Global status report 2019. UN-Water global analysis and assessment of sanitation and drinking- water (GLAAS) 2019 report*. Geneva.
- (WRC) Water Research Commission. 2018. *The South Africa mine water atlas*. Gezina.
- Yuan, J., Van Dyke, M.I. & Huck, P.M. 2019. Selection and evaluation of water pretreatment technologies for managed aquifer recharge (MAR) with reclaimed water. *Chemosphere*. 236:124886.
- Zahedi, S. 2017. Modification of expected conflicts between Drinking Water Quality Index and Irrigation Water Quality Index in water quality ranking of shared extraction wells using Multi Criteria Decision Making techniques. *Ecological Indicators*. 83:368–379.
- Zhang, Z., Xiao, C., Adeyeye, O., Yang, W. & Liang, X. 2020. Source and mobilization mechanism of iron, manganese and arsenic in groundwater of Shuangliao City, Northeast

China. *Water*. 12:534.

## APPENDIX A: RAW DATA

**Table 39:** Borehole coordinates of Ditsobotla LM area.

| Borehole | Date      | Sample                  | Latitude  | Longitude |
|----------|-----------|-------------------------|-----------|-----------|
| 1        | 29/5/2019 | Bodibe BH01             | -26,02871 | 25,89756  |
| 2        | 29/5/2019 | Bodibe BH02             | -26,02877 | 25,89766  |
| 3        | 29/5/2019 | Bodibe BH03             | -26,03222 | 25,89610  |
| 4        | 1/7/2019  | Bodibe BH06             | -26,06425 | 25,86349  |
| 5        | 14/5/2019 | Bodibe BH07             | -26,05757 | 25,86818  |
| 6        | 1/7/2019  | Bodibe BH08             | -26,04187 | 25,89801  |
| 7        | 1/7/2019  | Coligny - Scotland BH01 | -26,31430 | 26,29868  |
| 8        | 28/6/2019 | Coligny - Scotland BH02 | -26,31415 | 26,29220  |
| 9        | 14/5/2019 | Coligny BH09            | -26,32973 | 26,29137  |
| 10       | 14/5/2019 | Coligny BH12            | -26,32954 | 26,29118  |
| 11       | 29/5/2019 | Coligny BH13            | -26,33137 | 26,29079  |
| 12       | 29/5/2019 | Driestaat BH02          | -26,28644 | 26,43476  |
| 13       | 14/5/2019 | Ga-Maloka BH02          | -26,41310 | 26.10548  |
| 14       | 14/5/2019 | Ga-Maloka BH03          | -26,42775 | 26.10703  |
| 15       | 14/5/2019 | Ga-Maloka BH04          | -26,42662 | 26.10152  |
| 16       | 28/6/2019 | Ga-Maloka BH06          | -26,41696 | 26.10627  |
| 17       | 29/5/2019 | Ga-Maloko BH03          | -26,42775 | 26.10703  |
| 18       | 29/5/2019 | Ga-Maloko BH05          | -26,4139  | 26,09707  |
| 19       | 28/6/2019 | Itekeng BH06            | -26,37419 | 25,90924  |
| 20       | 28/6/2019 | Itekeng BH07            | -26,36187 | 25,91745  |
| 21       | 1/7/2019  | Itsoseng BH01           | -26,09218 | 25,92836  |
| 22       | 14/5/2019 | Itsoseng BH10           | -26,06806 | 25,88698  |
| 23       | 13/6/2019 | Itsoseng BH13           | -26,05604 | 25,89781  |

| <b>Borehole</b> | <b>Date</b> | <b>Sample</b>       | <b>Latitude</b> | <b>Longitude</b> |
|-----------------|-------------|---------------------|-----------------|------------------|
| 24              | 14/5/2019   | Itsoseng BH14       | -26,05353       | 25,90630         |
| 25              | 13/6/2019   | Lichtenburg C1      | -26,11590       | 26,16690         |
| 26              | 28/6/2019   | Lichtenburg Pump 01 | -26,11034       | 26,17117         |
| 27              | 7/5/2019    | Lichtenburg Pump 02 | -26,11199       | 26,16902         |
| 28              | 28/6/2019   | Lichtenburg Pump 03 | -26,09967       | 26,16913         |
| 29              | 28/6/2019   | Lichtenburg Pump 08 | -26,10259       | 26,16585         |
| 30              | 28/6/2019   | Lichtenburg Pump 09 | -26,11093       | 26,16775         |
| 31              | 28/6/2019   | Lichtenburg Pump 10 | -26,11199       | 26,16902         |
| 32              | 28/6/2019   | Lichtenburg Pump 11 | -26,09753       | 26,15953         |
| 33              | 14/5/2019   | Lichtenburg Pump 22 | -26,08681       | 26,14437         |
| 34              | 16/04/2019  | Lichtenburg Pump 23 | -26,09294       | 26,15574         |
| 35              | 13/6/2019   | Lichtenburg Pump 38 | -26,08335       | 26,14067         |
| 36              | 13/6/2019   | Lichtenburg Pump 39 | -26,08168       | 26,14156         |
| 37              | 13/6/2019   | Lichtenburg Pump 4  | -26,09975       | 26,16558         |
| 38              | 28/6/2019   | Lichtenburg Pump 40 | -26,08952       | 26,15463         |
| 39              | 13/6/2019   | Lichtenburg Pump 44 | -26,06238       | 26,14606         |
| 40              | 1/7/2019    | Lichtenburg Pump 45 | -26,06109       | 26,15687         |
| 41              | 1/7/2019    | Lichtenburg Pump 46 | -26,06679       | 26,15525         |
| 42              | 30/04/2019  | Opraap BH01         | -26,37515       | 26,49866         |
| 43              | 7/5/2019    | Putfontein BH02     | -26,24551       | 26,45407         |
| 44              | 14/5/2019   | Putfontein BH04     | -26,24150       | 26,44284         |
| 45              | 14/5/2019   | Putfontein BH07     | -26,23443       | 26,44086         |
| 46              | 29/5/2019   | Shiela BH01         | -26,05149       | 25,93490         |
| 47              | 13/6/2019   | Shiela BH02         | -26,05704       | 25,93023         |
| 48              | 30/04/2019  | Stompie BH01        | -26,30203       | 26,51418         |
| 49              | 29/5/2019   | Verdwaal BH01       | -26,09589       | 25,92095         |

| <b>Borehole</b> | <b>Date</b> | <b>Sample</b> | <b>Latitude</b> | <b>Longitude</b> |
|-----------------|-------------|---------------|-----------------|------------------|
| 50              | 14/5/2019   | Verdwaal BH02 | -26,09412       | 25,91098         |

**Table 40:** Borehole coordinates of Ratlou LM area.

| <b>Borehole</b> | <b>Date</b> | <b>Sample</b>         | <b>Latitude</b> | <b>Longitude</b> |
|-----------------|-------------|-----------------------|-----------------|------------------|
| 1               | 1/7/2019    | Moshawane BH2         | -26,01371       | 24,81932         |
| 2               | 13/6/2019   | Disaneng BH1          | -25,79975       | 25,31022         |
| 3               | 13/6/2019   | Disaneng BH02         | -25,80750       | 25,28851         |
| 4               | 13/6/2019   | Ditlounge BH1         | -25,79836       | 25,08272         |
| 5               | 13/6/2019   | Madibogo Pan BH02     | -26,47036       | 25,16276         |
| 6               | 13/6/2019   | Madibogo Pan BH05     | -26,48963       | 25,14472         |
| 7               | 13/6/2019   | Madibogo Pan BH11     | -26,46858       | 25,16984         |
| 8               | 13/6/2019   | Madibogo Pan BH12     | -26,47928       | 25,17565         |
| 9               | 13/6/2019   | Madibogo Station BH08 | -26,52131       | 25,13823         |
| 10              | 20/6/2019   | Dingateng BH3         | -25,77667       | 24,51796         |
| 11              | 20/6/2019   | Disaneng BH3          | -25,82462       | 25,29756         |
| 12              | 20/6/2019   | Mabule BH4            | -25,77698       | 24,52864         |
| 13              | 20/6/2019   | Makgobistad BH3       | -25,76076       | 25,13294         |
| 14              | 20/6/2019   | Tshidilamolomo BH2    | -25,83323       | 24,70254         |
| 15              | 28/6/2019   | Kraaipan BH03         | -26,30929       | 25,30252         |
| 16              | 29/5/2019   | Dingateng BH01        | -25,77620       | 24,52517         |
| 17              | 29/5/2019   | Makgori BH06          | -25,83664       | 24,79226         |

**Table 41:** Borehole coordinates of Tswaing LM area.

| <b>Borehole</b> | <b>Date</b> | <b>Sample</b>  | <b>Latitude</b> | <b>Longitude</b> |
|-----------------|-------------|----------------|-----------------|------------------|
| 1               | 13/6/2019   | Jachtkraal BH1 | -26,70042       | 25,52275         |
| 2               | 13/6/2019   | Sione BH12     | -26,34783       | 25,40263         |

| <b>Borehole</b> | <b>Date</b> | <b>Sample</b>              | <b>Latitude</b> | <b>Longitude</b> |
|-----------------|-------------|----------------------------|-----------------|------------------|
| 3               | 13/6/2019   | Skierlik (Ganaalagte) BH11 | -26,44205       | 25,54205         |
| 4               | 13/6/2019   | Vlektes (Ganalaagte) BH12  | -26,48265       | 25,53778         |
| 5               | 14/5/2019   | Atameleng BH09             | -26,49422       | 25,35687         |
| 6               | 14/5/2019   | Sione BH08                 | -26,36488       | 25,40339         |
| 7               | 14/5/2019   | Sione BH10                 | -26,36146       | 25,40556         |
| 8               | 15/04/2019  | Ganalaagte BH01            | -26,47949       | 25,49488         |
| 9               | 22/5/2019   | Atameleng BH06             | -26,50146       | 25,35859         |
| 10              | 23/04/2019  | Ganaalagte BH06 (T177180B) | -26,48930       | 25,52013         |
| 11              | 26/04/2019  | Sione BH 01 (10-74877)     | -26,35938       | 25,42641         |
| 12              | 26/04/2019  | Sione BH03                 | -26,35158       | 25,40939         |
| 13              | 28/6/2019   | Sione BH13                 | -26,34097       | 25,40635         |
| 14              | 29/5/2019   | Atamaleng BH06             | -26,50146       | 25,35859         |
| 15              | 29/5/2019   | Atamaleng BH08             | -26,49066       | 25,35679         |
| 16              | 29/5/2019   | Atamaleng BH10             | -26,50417       | 25,35389         |
| 17              | 29/5/2019   | Jachtkraal BH02            | -26,70296       | 25,52413         |
| 18              | 29/5/2019   | Jachtkraal BH03            | -26,70583       | 25,53123         |
| 19              | 30/04/2019  | Letsopa BH01               | -26,82286       | 25,98456         |
| 20              | 30/04/2019  | Sione BH06                 | -26,34830       | 25,40442         |
| 21              | 7/5/2019    | Letsopa BH02               | -26,82573       | 25,98568         |
| 22              | 7/5/2019    | Sione BH02                 | -26,35980       | 25.41523         |
| 23              | 7/5/2019    | Sione BH09                 | -26,36168       | 25.40705         |

**Table 42:** Raw data of the measured water quality parameters for the Ditsobotla LM area.

| Nr | Date      | Ca    | Mg    | K    | Na    | SO <sub>4</sub> | NO <sub>3</sub> | Cl    | HCO <sub>3</sub> | Fe   | Mn   | Cu   | Zn   | pH   | EC   | TDS    | F    | <i>E. coli</i> | FC    |
|----|-----------|-------|-------|------|-------|-----------------|-----------------|-------|------------------|------|------|------|------|------|------|--------|------|----------------|-------|
| 1  | 29/5/2019 | 70,33 | 26,01 | 1,53 | 4,59  | 1,25            | 16,42           | 4,42  | 335,59           | 0,00 | 0,00 | 0,04 | 0,08 | 7,64 | 0,59 | 383,50 | 0,04 | 0,00           | 14,00 |
| 2  | 29/5/2019 | 70,25 | 26,25 | 1,52 | 4,52  | 1,24            | 16,74           | 4,47  | 335,59           | 0,00 | 0,00 | 0,02 | 0,03 | 7,38 | 0,59 | 383,50 | 0,04 | 0,00           | 6,00  |
| 3  | 29/5/2019 | 72,14 | 27,95 | 1,67 | 5,77  | 1,11            | 15,65           | 4,64  | 353,89           | 0,00 | 0,00 | 0,03 | 0,01 | 7,26 | 0,62 | 403,00 | 0,04 | 0,00           | 17,00 |
| 4  | 1/7/2019  | 76,55 | 39,04 | 1,56 | 6,67  | 19,22           | 48,30           | 16,26 | 350,84           | 0,00 | 0,00 | 0,01 | 0,01 | 7,41 | 0,74 | 481,00 | 0,06 | 0,00           | 80,00 |
| 5  | 14/5/2019 | 79,76 | 39,06 | 1,35 | 5,94  | 26,79           | 53,40           | 17,69 | 341,69           | 0,01 | 0,00 | 0,02 | 0,01 | 7,15 | 0,75 | 487,50 | 0,03 | 0,00           | 23,00 |
| 6  | 1/7/2019  | 56,91 | 32,18 | 0,93 | 4,38  | 1,58            | 12,65           | 4,62  | 326,44           | 0,00 | 0,00 | 0,02 | 0,01 | 8,46 | 0,57 | 370,50 | 0,04 | 0,00           | 80,00 |
| 7  | 1/7/2019  | 8,07  | 4,62  | 3,97 | 10,81 | 1,00            | 25,47           | 3,89  | 51,86            | 0,93 | 0,22 | 0,02 | 0,06 | 7,74 | 0,14 | 91,00  | 0,01 | 0,00           | 0,00  |
| 8  | 28/6/2019 | 20,04 | 7,45  | 5,08 | 12,18 | 15,97           | 56,42           | 3,76  | 57,97            | 0,24 | 0,02 | 0,01 | 0,07 | 6,77 | 0,23 | 149,50 | 0,02 | 0,00           | 0,00  |
| 9  | 14/5/2019 | 28,05 | 9,73  | 2,02 | 17,01 | 6,13            | 29,81           | 13,90 | 122,03           | 0,01 | 0,00 | 0,02 | 0,02 | 6,97 | 0,30 | 195,00 | 0,02 | 0,00           | 0,00  |
| 10 | 14/5/2019 | 28,46 | 11,22 | 2,74 | 17,70 | 8,68            | 29,14           | 16,31 | 128,13           | 0,02 | 0,00 | 0,02 | 0,01 | 6,71 | 0,32 | 208,00 | 0,01 | 0,00           | 0,00  |
| 11 | 29/5/2019 | 18,44 | 9,76  | 1,73 | 18,91 | 6,72            | 27,28           | 11,27 | 103,73           | 0,00 | 0,00 | 0,02 | 0,06 | 7,14 | 0,26 | 169,00 | 0,08 | 0,00           | 2,00  |
| 12 | 29/5/2019 | 30,86 | 11,91 | 1,56 | 32,88 | 3,46            | 27,10           | 19,61 | 180,00           | 0,00 | 0,00 | 0,02 | 0,07 | 7,40 | 0,40 | 260,00 | 0,10 | 15,00          | 80,00 |
| 13 | 14/5/2019 | 49,70 | 10,69 | 2,87 | 17,47 | 8,12            | 4,74            | 5,27  | 231,86           | 0,05 | 0,00 | 0,02 | 0,01 | 7,65 | 0,42 | 273,00 | 0,65 | 0,00           | 7,00  |
| 14 | 14/5/2019 | 44,09 | 24,55 | 3,47 | 17,70 | 19,22           | 0,07            | 6,90  | 274,57           | 0,00 | 0,01 | 0,03 | 0,02 | 7,45 | 0,51 | 331,50 | 2,69 | 0,00           | 0,00  |
| 15 | 28/6/2019 | 54,99 | 32,34 | 1,80 | 17,45 | 9,84            | 25,90           | 8,08  | 326,44           | 0,00 | 0,01 | 0,01 | 0,03 | 7,58 | 0,62 | 403,00 | 0,66 | 0,00           | 0,00  |
| 16 | 28/6/2019 | 34,19 | 10,57 | 1,03 | 70,99 | 29,86           | 0,02            | 15,40 | 280,67           | 0,07 | 0,10 | 0,01 | 0,02 | 7,58 | 0,57 | 370,50 | 4,95 | 0,00           | 0,00  |
| 17 | 29/5/2019 | 46,89 | 22,36 | 3,33 | 33,34 | 26,44           | 1,24            | 7,12  | 298,98           | 0,00 | 0,02 | 0,03 | 0,01 | 8,58 | 0,57 | 370,50 | 2,96 | 0,00           | 0,00  |
| 18 | 29/5/2019 | 40,08 | 11,19 | 2,29 | 11,95 | 30,78           | 2,69            | 4,56  | 164,74           | 0,00 | 0,00 | 0,02 | 0,01 | 7,66 | 0,35 | 227,50 | 0,15 | 0,00           | 2,00  |
| 19 | 28/6/2019 | 60,20 | 39,10 | 1,60 | 36,30 | 33,20           | 19,20           | 64,00 | 346,50           | 0,10 | 0,56 | 0,01 | 0,04 | 7,20 | 0,83 | 560,10 | 0,25 | 0,00           | 13,00 |
| 20 | 28/6/2019 | 70,94 | 41,32 | 1,71 | 37,62 | 34,75           | 19,91           | 65,94 | 353,89           | 0,11 | 0,58 | 0,01 | 0,04 | 7,17 | 0,87 | 565,50 | 0,27 | 0,00           | 0,00  |
| 21 | 1/7/2019  | 63,32 | 30,59 | 1,56 | 4,13  | 2,08            | 25,03           | 6,44  | 320,33           | 0,00 | 0,00 | 0,01 | 0,01 | 8,46 | 0,59 | 383,50 | 0,05 | 0,00           | 0,00  |
| 22 | 14/5/2019 | 88,17 | 39,81 | 1,46 | 7,84  | 11,74           | 42,91           | 30,14 | 384,40           | 0,01 | 0,00 | 0,02 | 0,01 | 7,18 | 0,81 | 526,50 | 0,04 | 0,00           | 0,00  |

| Nr | Date       | Ca     | Mg    | K     | Na    | SO <sub>4</sub> | NO <sub>3</sub> | Cl    | HCO <sub>3</sub> | Fe   | Mn   | Cu   | Zn   | pH   | EC    | TDS    | F    | <i>E. coli</i> | FC    |
|----|------------|--------|-------|-------|-------|-----------------|-----------------|-------|------------------|------|------|------|------|------|-------|--------|------|----------------|-------|
| 23 | 13/6/2019  | 70,94  | 28,44 | 2,27  | 6,60  | 1,56            | 11,60           | 5,71  | 353,89           | 0,00 | 0,00 | 0,02 | 0,01 | 7,46 | 0,62  | 403,00 | 0,02 | 0,00           | 0,00  |
| 24 | 14/5/2019  | 54,51  | 32,11 | 1,38  | 4,45  | 2,07            | 8,13            | 4,35  | 323,38           | 0,01 | 0,09 | 0,02 | 0,02 | 7,16 | 0,56  | 364,00 | 0,02 | 0,00           | 0,00  |
| 25 | 13/6/2019  | 67,33  | 36,94 | 1,19  | 6,67  | 30,74           | 18,02           | 9,00  | 335,59           | 0,05 | 0,04 | 0,01 | 0,08 | 7,96 | 0,67  | 435,50 | 0,07 | 0,00           | 0,00  |
| 26 | 28/6/2019  | 73,52  | 38,40 | 0,74  | 3,80  | 2,77            | 30,29           | 5,04  | 384,40           | 0,00 | 0,00 | 0,01 | 0,04 | 7,31 | 0,70  | 455,00 | 0,04 | 0,00           | 0,00  |
| 27 | 7/5/2019   | 67,33  | 35,49 | 0,82  | 4,56  | 2,53            | 30,04           | 5,50  | 353,89           | 0,00 | 0,00 | 0,01 | 0,00 | 7,20 | 0,65  | 422,50 | 0,05 | 80,00          | 80,00 |
| 28 | 28/6/2019  | 70,94  | 36,94 | 0,63  | 3,55  | 1,97            | 23,55           | 4,24  | 381,35           | 1,66 | 0,00 | 0,01 | 0,01 | 7,26 | 0,68  | 442,00 | 0,05 | 0,00           | 0,00  |
| 29 | 28/6/2019  | 102,90 | 59,30 | 1,24  | 46,24 | 161,85          | 6,46            | 61,15 | 417,96           | 0,02 | 0,02 | 0,01 | 0,03 | 7,46 | 1,21  | 786,50 | 0,05 | 1,00           | 2,00  |
| 30 | 28/6/2019  | 70,47  | 36,46 | 0,73  | 3,66  | 3,59            | 29,35           | 5,07  | 366,10           | 0,00 | 0,01 | 0,02 | 0,04 | 7,13 | 0,67  | 435,50 | 0,04 | 12,00          | 80,00 |
| 31 | 28/6/2019  | 76,23  | 38,40 | 0,79  | 4,02  | 4,54            | 29,91           | 5,45  | 393,55           | 0,00 | 0,01 | 0,01 | 0,04 | 7,31 | 0,72  | 468,00 | 0,06 | 0,00           | 80,00 |
| 32 | 28/6/2019  | 72,86  | 40,10 | 0,64  | 3,35  | 5,50            | 24,94           | 4,30  | 393,55           | 0,04 | 0,02 | 0,01 | 0,04 | 7,18 | 0,71  | 461,50 | 0,06 | 0,00           | 1,00  |
| 33 | 14/5/2019  | 57,71  | 36,25 | 0,71  | 3,12  | 3,32            | 19,27           | 7,35  | 329,49           | 0,01 | 0,00 | 0,02 | 0,01 | 7,16 | 0,60  | 390,00 | 0,03 | 80,00          | 80,00 |
| 34 | 16/04/2019 | 55,00  | 36,00 | 11,00 | 10,00 | 12,00           | 0,00            | 14,00 |                  | 0,20 | 0,38 |      | 0,00 | 7,40 | 84,40 | 511,00 | 0,50 | 11,00          | 0,00  |
| 35 | 13/6/2019  | 38,78  | 25,52 | 1,71  | 4,14  | 6,32            | 1,24            | 8,51  | 237,96           | 0,00 | 0,26 | 0,03 | 0,07 | 7,58 | 0,43  | 279,50 | 0,08 | 0,00           | 0,00  |
| 36 | 13/6/2019  | 69,33  | 35,24 | 0,95  | 4,40  | 2,42            | 29,20           | 5,46  | 363,04           | 0,00 | 0,02 | 0,03 | 0,03 | 7,25 | 0,66  | 429,00 | 0,02 | 0,00           | 0,00  |
| 37 | 13/6/2019  | 69,33  | 37,67 | 0,64  | 3,45  | 5,19            | 20,88           | 5,32  | 372,20           | 0,00 | 0,00 | 0,02 | 0,01 | 7,19 | 0,67  | 435,50 | 0,04 | 0,00           | 0,00  |
| 38 | 28/6/2019  | 74,71  | 38,40 | 0,99  | 3,71  | 2,22            | 27,74           | 4,57  | 396,60           | 0,01 | 0,01 | 0,01 | 0,05 | 7,19 | 0,71  | 461,50 | 0,03 | 0,00           | 0,00  |
| 39 | 13/6/2019  | 68,53  | 35,24 | 0,60  | 3,67  | 2,90            | 18,81           | 6,98  | 359,99           | 0,00 | 0,00 | 0,01 | 0,04 | 7,24 | 0,65  | 422,50 | 0,04 | 0,00           | 0,00  |
| 40 | 1/7/2019   | 53,70  | 40,10 | 5,08  | 3,97  | 2,68            | 31,13           | 4,99  | 341,69           | 0,00 | 0,00 | 0,01 | 0,01 | 8,30 | 0,63  | 409,50 | 0,05 | 0,00           | 7,00  |
| 41 | 1/7/2019   | 54,11  | 38,98 | 0,50  | 4,35  | 2,95            | 19,56           | 4,90  | 341,69           | 0,00 | 0,00 | 0,03 | 0,01 | 8,31 | 0,61  | 396,50 | 0,14 | 0,00           | 0,00  |
| 42 | 30/04/2019 | 41,00  | 17,00 | 10,00 | 17,00 | 24,00           | 0,00            | 30,00 |                  | 0,20 | 0,10 |      | 0,00 | 7,50 | 38,50 | 238,00 | 0,50 | 0,00           | 0,00  |
| 43 | 7/5/2019   | 66,93  | 22,00 | 1,56  | 18,85 | 21,13           | 55,18           | 35,81 | 222,71           | 0,02 | 0,05 | 0,01 | 0,07 | 7,28 | 0,60  | 390,00 | 0,10 | 41,00          | 80,00 |
| 44 | 14/5/2019  | 51,70  | 14,10 | 0,89  | 21,55 | 22,04           | 33,48           | 26,18 | 180,00           | 0,02 | 0,00 | 0,01 | 0,02 | 7,33 | 0,47  | 305,50 | 0,03 | 0,00           | 0,00  |
| 45 | 14/5/2019  | 40,48  | 11,16 | 1,38  | 11,65 | 11,43           | 52,70           | 10,93 | 128,13           | 0,17 | 0,02 | 0,02 | 0,05 | 7,39 | 0,35  | 227,50 | 0,03 | 2,00           | 25,00 |

| Nr | Date       | Ca    | Mg    | K     | Na    | SO <sub>4</sub> | NO <sub>3</sub> | Cl    | HCO <sub>3</sub> | Fe   | Mn   | Cu   | Zn   | pH   | EC    | TDS    | F    | <i>E. coli</i> | FC    |
|----|------------|-------|-------|-------|-------|-----------------|-----------------|-------|------------------|------|------|------|------|------|-------|--------|------|----------------|-------|
| 46 | 29/5/2019  | 68,94 | 30,62 | 1,73  | 6,31  | 1,16            | 16,47           | 6,86  | 353,89           | 0,00 | 0,00 | 0,03 | 0,03 | 7,43 | 0,63  | 409,50 | 0,02 | 0,00           | 8,00  |
| 47 | 13/6/2019  | 69,74 | 27,71 | 1,93  | 6,90  | 1,96            | 19,90           | 11,17 | 329,49           | 0,00 | 0,00 | 0,01 | 0,01 | 7,83 | 0,61  | 396,50 | 0,00 | 0,00           | 0,00  |
| 48 | 30/04/2019 | 83,00 | 53,00 | 10,00 | 10,00 | 61,00           | 0,00            | 19,00 | 0,00             | 0,20 | 0,10 |      | 0,00 | 7,80 | 73,70 | 479,00 | 0,50 | 0,00           | 0,00  |
| 49 | 29/5/2019  | 65,73 | 25,52 | 2,72  | 17,70 | 12,35           | 27,28           | 8,27  | 320,33           | 0,00 | 0,00 | 0,02 | 0,01 | 8,36 | 0,62  | 403,00 | 0,05 | 80,00          | 80,00 |
| 50 | 14/5/2019  | 70,94 | 30,14 | 1,77  | 5,65  | 1,76            | 30,79           | 9,29  | 335,59           | 0,01 | 0,00 | 0,02 | 0,01 | 7,22 | 0,63  | 409,50 | 0,03 | 0,00           | 0,00  |

**Table 43:** Raw data of the measured water quality parameters for the Ratlou LM area.

| Nr | Date      | Ca    | Mg    | K    | Na     | SO <sub>4</sub> | NO <sub>3</sub> | Cl    | HCO <sub>3</sub> | Fe   | Mn   | Cu   | Zn   | pH   | EC   | TDS    | F    | <i>E. coli</i> | FC    |
|----|-----------|-------|-------|------|--------|-----------------|-----------------|-------|------------------|------|------|------|------|------|------|--------|------|----------------|-------|
| 1  | 1/7/2019  | 59,32 | 34,92 | 5,08 | 33,33  | 8,36            | 2,36            | 13,76 | 414,91           | 0,00 | 0,00 | 0,01 | 0,01 | 8,47 | 0,74 | 481,00 | 0,16 | 0,00           | 0,00  |
| 2  | 13/6/2019 | 28,50 | 16,28 | 2,83 | 31,21  | 3,97            | 64,22           | 31,55 | 134,23           | 0,10 | 0,02 | 0,01 | 0,05 | 7,07 | 0,42 | 273,00 | 0,03 | 80,00          | 80,00 |
| 3  | 13/6/2019 | 58,11 | 41,32 | 1,20 | 31,73  | 16,81           | 5,79            | 42,46 | 369,15           | 0,00 | 0,00 | 0,01 | 0,02 | 8,22 | 0,77 | 500,50 | 0,13 | 15,00          | 17,00 |
| 4  | 13/6/2019 | 80,96 | 24,04 | 2,74 | 29,66  | 3,63            | 0,30            | 16,41 | 417,96           | 0,00 | 0,03 | 0,01 | 0,56 | 7,39 | 0,74 | 481,00 | 0,01 | 0,00           | 0,00  |
| 5  | 13/6/2019 | 60,92 | 29,17 | 3,27 | 44,83  | 16,13           | 25,94           | 15,76 | 384,40           | 0,00 | 0,00 | 0,01 | 0,02 | 7,30 | 0,75 | 487,50 | 0,07 | 0,00           | 10,00 |
| 6  | 13/6/2019 | 29,97 | 16,70 | 4,17 | 21,29  | 4,36            | 11,58           | 9,26  | 204,40           | 0,01 | 0,00 | 0,02 | 0,07 | 7,11 | 0,39 | 253,50 | 0,07 | 22,00          | 39,00 |
| 7  | 13/6/2019 | 74,14 | 40,59 | 4,83 | 74,26  | 58,13           | 10,02           | 50,62 | 463,72           | 0,00 | 0,00 | 0,02 | 0,06 | 7,20 | 1,04 | 676,00 | 0,10 | 0,00           | 0,00  |
| 8  | 13/6/2019 | 45,05 | 24,82 | 4,25 | 71,60  | 22,16           | 70,28           | 50,61 | 274,57           | 0,00 | 0,00 | 0,02 | 0,05 | 7,18 | 0,75 | 487,50 | 0,11 | 0,00           | 0,00  |
| 9  | 13/6/2019 | 57,67 | 38,33 | 3,05 | 49,81  | 33,62           | 82,79           | 91,47 | 225,76           | 0,00 | 0,01 | 0,01 | 1,72 | 6,99 | 0,83 | 539,50 | 0,08 | 7,00           | 24,00 |
| 10 | 20/6/2019 | 47,41 | 36,10 | 7,05 | 142,30 | 84,10           | 10,44           | 73,24 | 466,77           | 0,00 | 0,00 | 0,03 | 0,02 | 7,39 | 1,14 | 741,00 | 0,00 | 0,00           | 0,00  |
| 11 | 20/6/2019 | 59,92 | 19,44 | 3,74 | 116,79 | 23,71           | 15,84           | 66,25 | 433,21           | 0,96 | 0,13 | 0,02 | 0,26 | 7,42 | 0,93 | 604,50 | 0,12 | 80,00          | 80,00 |
| 12 | 20/6/2019 | 50,73 | 29,41 | 6,46 | 151,40 | 86,47           | 8,87            | 70,62 | 460,67           | 0,00 | 0,00 | 0,02 | 0,04 | 7,46 | 1,15 | 747,50 | 0,00 | 4,00           | 23,00 |
| 13 | 20/6/2019 | 70,94 | 33,05 | 1,28 | 36,32  | 24,16           | 21,38           | 31,97 | 366,10           | 0,02 | 0,11 | 0,02 | 0,16 | 7,27 | 0,79 | 513,50 | 0,14 | 80,00          | 80,00 |
| 14 | 20/6/2019 | 57,78 | 37,67 | 7,27 | 118,10 | 58,38           | 3,83            | 57,00 | 491,18           | 0,00 | 0,00 | 0,03 | 0,03 | 7,22 | 1,06 | 689,00 | 0,06 | 0,00           | 0,00  |
| 15 | 28/6/2019 | 43,23 | 19,93 | 0,46 | 24,47  | 8,88            | 7,55            | 3,39  | 274,57           | 0,00 | 0,01 | 0,01 | 0,04 | 7,61 | 0,49 | 318,50 | 0,38 | 0,00           | 0,00  |
| 16 | 29/5/2019 | 43,44 | 31,60 | 6,75 | 147,30 | 77,81           | 12,46           | 87,62 | 433,21           | 0,00 | 0,03 | 0,02 | 0,02 | 7,58 | 1,14 | 741,00 | 0,06 | 0,00           | 19,00 |

|    |           |       |       |      |       |       |      |        |        |      |      |      |      |      |      |        |      |      |      |
|----|-----------|-------|-------|------|-------|-------|------|--------|--------|------|------|------|------|------|------|--------|------|------|------|
| 17 | 29/5/2019 | 72,94 | 43,02 | 8,56 | 66,06 | 28,49 | 3,34 | 101,94 | 411,86 | 0,00 | 0,03 | 0,02 | 0,02 | 7,05 | 1,03 | 669,50 | 0,16 | 0,00 | 1,00 |
|----|-----------|-------|-------|------|-------|-------|------|--------|--------|------|------|------|------|------|------|--------|------|------|------|

**Table 44:** Raw data of the measured water quality parameters for the Tswaing LM area.

| Nr | Date       | Ca     | Mg    | K     | Na     | SO <sub>4</sub> | NO <sub>3</sub> | Cl     | HCO <sub>3</sub> | Fe   | Mn   | Cu   | Zn   | pH   | EC     | TDS     | F    | <i>E. coli</i> | FC    |
|----|------------|--------|-------|-------|--------|-----------------|-----------------|--------|------------------|------|------|------|------|------|--------|---------|------|----------------|-------|
| 1  | 13/6/2019  | 106,40 | 33,30 | 4,65  | 67,45  | 45,94           | 72,12           | 97,85  | 381,35           | 0,02 | 0,00 | 0,01 | 0,01 | 7,14 | 1,11   | 721,50  | 0,14 | 0,00           | 0,00  |
| 2  | 13/6/2019  | 70,94  | 24,31 | 0,67  | 42,76  | 10,51           | 3,41            | 27,30  | 387,45           | 0,02 | 0,01 | 0,04 | 0,02 | 7,04 | 0,74   | 481,00  | 0,31 | 0,00           | 0,00  |
| 3  | 13/6/2019  | 23,25  | 7,78  | 1,26  | 8,28   | 1,31            | 10,54           | 5,35   | 112,88           | 0,05 | 0,05 | 0,04 | 0,02 | 7,10 | 0,22   | 143,00  | 0,06 | 0,00           | 4,00  |
| 4  | 13/6/2019  | 72,54  | 18,71 | 2,59  | 45,98  | 19,24           | 10,47           | 34,91  | 344,74           | 0,06 | 0,01 | 0,02 | 0,01 | 7,33 | 0,72   | 468,00  | 0,52 | 0,00           | 0,00  |
| 5  | 14/5/2019  | 19,24  | 8,20  | 3,44  | 13,13  | 1,77            | 32,24           | 12,41  | 85,42            | 0,02 | 0,00 | 0,02 | 0,02 | 7,09 | 0,23   | 149,50  | 0,01 | 0,00           | 0,00  |
| 6  | 14/5/2019  | 87,77  | 48,45 | 0,98  | 63,68  | 43,85           | 25,90           | 97,04  | 433,21           | 0,01 | 0,00 | 0,03 | 0,01 | 7,30 | 1,12   | 728,00  | 0,02 | 80,00          | 80,00 |
| 7  | 14/5/2019  | 63,32  | 31,28 | 1,31  | 52,74  | 7,11            | 22,78           | 16,43  | 433,21           | 0,01 | 0,01 | 0,02 | 0,02 | 7,11 | 0,81   | 526,50  | 0,07 | 0,00           | 0,00  |
| 8  | 15/04/2019 | 78,00  | 33,00 | 10,00 | 37,00  | 20,00           | 0,00            | 42,00  | 0,00             | 0,20 | 0,10 | 0,00 | 0,00 | 7,60 | 71,80  | 444,00  | 0,50 | 1,00           | 0,00  |
| 9  | 22/5/2019  | 17,63  | 10,21 | 5,47  | 14,52  | 3,84            | 35,96           | 18,08  | 79,32            | 0,00 | 0,00 | 0,04 | 0,01 | 7,05 | 0,25   | 162,50  | 0,02 | 0,00           | 3,00  |
| 10 | 23/04/2019 | 127,00 | 31,00 | 10,00 | 76,00  | 55,00           | 0,00            | 108,00 | 0,00             | 0,20 | 0,10 | 0,00 | 0,00 | 7,80 | 120,00 | 773,00  | 0,50 | ND             | 0,00  |
| 11 | 26/04/2019 | 63,00  | 29,00 | 10,00 | 35,00  | 9,20            | 0,00            | 10,00  | 0,00             | 0,20 | 0,10 | 0,00 | 0,00 | 7,10 | 63,00  | 436,00  | 0,50 | 93,00          | 0,00  |
| 12 | 26/04/2019 | 130,00 | 61,00 | 10,00 | 63,00  | 28,00           | 0,00            | 154,00 | 0,00             | 0,20 | 0,10 | 0,00 | 0,00 | 6,90 | 136,00 | 837,00  | 0,50 | ND             | 0,00  |
| 13 | 28/6/2019  | 66,61  | 39,80 | 0,43  | 31,11  | 5,85            | 0,05            | 19,50  | 445,42           | 0,12 | 0,06 | 0,01 | 0,03 | 7,42 | 0,80   | 520,00  | 0,27 | 0,00           | 0,00  |
| 14 | 29/5/2019  | 17,03  | 10,56 | 4,19  | 26,73  | 30,74           | 58,28           | 22,34  | 48,81            | 0,00 | 0,00 | 0,03 | 0,03 | 8,23 | 0,30   | 195,00  | 0,01 | 0,00           | 0,00  |
| 15 | 29/5/2019  | 12,93  | 7,29  | 3,01  | 15,48  | 3,84            | 17,98           | 8,15   | 85,42            | 0,00 | 0,00 | 0,05 | 0,02 | 7,09 | 0,20   | 130,00  | 0,04 | 0,00           | 3,00  |
| 16 | 29/5/2019  | 10,08  | 5,59  | 3,05  | 12,60  | 3,84            | 13,64           | 3,42   | 73,22            | 0,00 | 0,00 | 0,04 | 0,02 | 6,99 | 0,16   | 104,00  | 0,04 | 0,00           | 0,00  |
| 17 | 29/5/2019  | 87,37  | 35,24 | 3,29  | 84,66  | 47,12           | 50,69           | 93,91  | 396,60           | 0,00 | 0,02 | 0,01 | 0,03 | 7,20 | 1,10   | 715,00  | 0,02 | 0,00           | 2,00  |
| 18 | 29/5/2019  | 98,59  | 54,20 | 4,55  | 159,90 | 130,40          | 20,43           | 275,47 | 341,69           | 0,00 | 0,00 | 0,01 | 0,01 | 7,28 | 1,64   | 1066,00 | 0,04 | 0,00           | 0,00  |
| 19 | 30/04/2019 | 42,00  | 21,00 | 10,00 | 35,00  | 27,00           | 0,00            | 39,00  | 0,00             | 0,20 | 0,10 | 0,00 | 0,00 | 7,50 | 52,10  | 411,00  | 0,50 | 1,00           | 0,00  |
| 20 | 30/04/2019 | 100,00 | 39,00 | 10,00 | 58,00  | 16,00           | 0,00            | 74,00  | 0,00             | 0,20 | 0,10 | 0,00 | 0,00 | 7,50 | 98,90  | 662,00  | 0,50 | 10,00          | 0,00  |
| 21 | 7/5/2019   | 36,07  | 13,31 | 5,08  | 29,36  | 14,41           | 35,96           | 85,80  | 61,02            | 0,02 | 0,00 | 0,01 | 0,03 | 6,78 | 0,43   | 279,50  | 0,08 | 0,00           | 0,00  |
| 22 | 7/5/2019   | 90,98  | 37,34 | 3,52  | 84,40  | 14,80           | 90,59           | 62,75  | 475,92           | 0,02 | 0,05 | 0,02 | 0,01 | 7,05 | 1,14   | 741,00  | 0,09 | 0,00           | 0,00  |

|    |          |       |       |      |       |      |       |       |        |      |      |      |      |      |      |        |      |       |       |
|----|----------|-------|-------|------|-------|------|-------|-------|--------|------|------|------|------|------|------|--------|------|-------|-------|
| 23 | 7/5/2019 | 71,96 | 29,24 | 1,59 | 56,62 | 7,35 | 20,62 | 12,41 | 466,77 | 0,03 | 0,03 | 0,02 | 0,05 | 7,17 | 0,85 | 552,50 | 0,14 | 80,00 | 80,00 |
|----|----------|-------|-------|------|-------|------|-------|-------|--------|------|------|------|------|------|------|--------|------|-------|-------|

---

## APPENDIX B: WQI SCORES AND RECOMMENDATIONS

**Table 45:** WQI scores of the investigated boreholes for drinking, livestock, and irrigation purposes for the Ditsobotla LM area.

| Borehole<br>Nr | WQI rating |           |            | Borehole<br>Nr | WQI rating |           |            |
|----------------|------------|-----------|------------|----------------|------------|-----------|------------|
|                | Drinking   | Livestock | Irrigation |                | Drinking   | Livestock | Irrigation |
| 1              | 29,6       | 16,2      | 34,6       | 26             | 45,0       | 17,4      | 35,2       |
| 2              | 29,3       | 14,8      | 33,5       | 27             | 43,8       | 16,4      | 35,8       |
| 3              | 28,2       | 14,7      | 34,3       | 28             | 91,1       | 16,0      | 33,9       |
| 4              | 65,3       | 21,2      | 55,8       | 29             | 36,5       | 26,3      | 186,6      |
| 5              | 70,7       | 21,1      | 58,7       | 30             | 43,8       | 16,3      | 34,8       |
| 6              | 26,9       | 18,6      | 40,5       | 31             | 45,2       | 17,5      | 36,5       |
| 7              | 85,2       | 12,9      | 76,5       | 32             | 42,2       | 16,3      | 35,3       |
| 8              | 75,5       | 14,1      | 57,7       | 33             | 31,9       | 14,3      | 37,8       |
| 9              | 39,6       | 12,1      | 66,0       | 34             | 518,1      | 688,1     | 579,7      |
| 10             | 39,2       | 11,3      | 68,8       | 35             | 37,6       | 12,3      | 45,0       |
| 11             | 37,0       | 12,2      | 75,7       | 36             | 44,7       | 16,8      | 35,7       |
| 12             | 39,1       | 15,1      | 86,6       | 37             | 34,2       | 15,4      | 36,1       |
| 13             | 21,5       | 13,1      | 52,6       | 38             | 42,6       | 16,6      | 34,0       |
| 14             | 31,2       | 13,1      | 61,0       | 39             | 32,2       | 15,0      | 36,8       |
| 15             | 45,2       | 17,7      | 55,1       | 40             | 46,7       | 21,0      | 41,8       |
| 16             | 58,6       | 15,6      | 121,9      | 41             | 35,2       | 19,6      | 41,9       |
| 17             | 37,6       | 19,3      | 80,6       | 42             | 243,0      | 319,3     | 317,4      |
| 18             | 14,6       | 12,7      | 59,4       | 43             | 77,3       | 20,5      | 82,8       |
| 19             | 96,4       | 18,7      | 130,7      | 44             | 47,7       | 16,6      | 79,7       |
| 20             | 99,8       | 19,2      | 130,8      | 45             | 72,5       | 17,5      | 53,7       |
| 21             | 40,2       | 20,5      | 41,1       | 46             | 29,5       | 15,5      | 38,3       |
| 22             | 60,3       | 20,1      | 65,0       | 47             | 33,6       | 17,4      | 44,2       |
| 23             | 24,2       | 14,8      | 37,2       | 48             | 442,0      | 606,4     | 538,2      |
| 24             | 28,2       | 12,4      | 35,6       | 49             | 43,2       | 21,4      | 57,2       |
| 25             | 40,0       | 19,2      | 57,1       | 50             | 44,4       | 16,4      | 38,9       |

**Table 46:** WQI scores of the investigated boreholes for drinking, livestock, and irrigation purposes for the Ratlou LM area.

| Borehole<br>Nr | WQI rating |           |            | Borehole<br>Nr | WQI rating |           |            |
|----------------|------------|-----------|------------|----------------|------------|-----------|------------|
|                | Drinking   | Livestock | Irrigation |                | Drinking   | Livestock | Irrigation |
| 1              | 19,3       | 20,0      | 74,0       | 10             | 34,5       | 26,2      | 218,3      |
| 2              | 82,1       | 18,7      | 94,8       | 11             | 79,2       | 22,2      | 170,6      |
| 3              | 23,8       | 20,0      | 103,5      | 12             | 32,9       | 26,5      | 220,9      |
| 4              | 17,4       | 14,9      | 62,8       | 13             | 49,8       | 18,7      | 92,6       |
| 5              | 41,6       | 18,7      | 81,2       | 14             | 25,0       | 22,3      | 174,5      |
| 6              | 22,1       | 11,3      | 65,1       | 15             | 22,0       | 14,1      | 59,8       |
| 7              | 31,3       | 21,6      | 144,7      | 16             | 39,7       | 27,1      | 236,3      |
| 8              | 89,6       | 25,1      | 138,3      | 17             | 27,1       | 18,9      | 176,4      |
| 9              | 107,5      | 26,7      | 163,3      |                |            |           |            |

**Table 47:** WQI scores of the investigated boreholes for drinking, livestock, and irrigation purposes for the Tswaing LM area.

| Borehole<br>Nr | WQI rating |           |            | Borehole<br>Nr | WQI rating |           |            |
|----------------|------------|-----------|------------|----------------|------------|-----------|------------|
|                | Drinking   | Livestock | Irrigation |                | Drinking   | Livestock | Irrigation |
| 1              | 98,9       | 29,6      | 174,6      | 13             | 25,5       | 15,7      | 71,1       |
| 2              | 20,6       | 14,8      | 84,8       | 14             | 73,0       | 22,6      | 109,3      |
| 3              | 24,6       | 9,2       | 48,5       | 15             | 26,0       | 10,4      | 75,7       |
| 4              | 31,6       | 16,8      | 98,7       | 16             | 20,6       | 8,7       | 73,3       |
| 5              | 41,7       | 12,0      | 65,1       | 17             | 76,2       | 27,5      | 182,6      |
| 6              | 49,6       | 24,5      | 175,5      | 18             | 58,4       | 34,5      | 421,2      |
| 7              | 39,8       | 18,2      | 80,6       | 19             | 322,0      | 430,2     | 430,0      |
| 8              | 424,3      | 588,9     | 544,7      | 20             | 578,9      | 808,4     | 752,8      |
| 9              | 45,5       | 12,9      | 73,8       | 21             | 50,6       | 14,2      | 142,6      |
| 10             | 718,9      | 984,3     | 943,0      | 22             | 120,5      | 31,5      | 135,9      |
| 11             | 376,1      | 515,5     | 452,9      | 23             | 40,5       | 18,6      | 76,8       |
| 12             | 804,9      | 1108,7    | 1067,6     |                |            |           |            |

**Table 48:** WQI ratings and water treatment recommendation for drinking, livestock, and irrigation purposes for the Ditsobotla area.

| Borehole number | Drinking |                                 | Livestock |                    | Irrigation |                                 | Water treatment recommendation                                                                            |
|-----------------|----------|---------------------------------|-----------|--------------------|------------|---------------------------------|-----------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter              | WQI       | Elevated parameter | WQI        | Elevated parameter              |                                                                                                           |
| 1               | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | I          | PI (high calcium and magnesium) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX |
| 2               | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | I          | PI (high calcium and magnesium) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX |
| 3               | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | I          | PI (high calcium and magnesium) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX |

| Borehole number | Drinking |                                 | Livestock |                    | Irrigation |                                                                 | Water treatment recommendation                                                                                                   |
|-----------------|----------|---------------------------------|-----------|--------------------|------------|-----------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter              | WQI       | Elevated parameter | WQI        | Elevated parameter                                              |                                                                                                                                  |
| 4               | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | II         | PI (high calcium and magnesium), PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7<br><b>2)</b> IX and F1/F8 |
| 5               | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | II         | PI (high calcium and magnesium), PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7<br><b>2)</b> IX and F1/F8 |
| 6               | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | I          | PI (high calcium and magnesium)                                 | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX                        |

| Borehole number | Drinking |                                                  | Livestock |                    | Irrigation |                                | Water treatment recommendation                                                                                                         |
|-----------------|----------|--------------------------------------------------|-----------|--------------------|------------|--------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                               | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                                        |
| 7               | II       | Nitrate, Iron, manganese, <i>Faecal coliform</i> | I         | -                  | II         | -                              | <b>Drinking:</b><br><b>1)</b> D2 and F6/F7/F8/IX<br><b>2)</b> D1/D2/D3/D4/D5 and F7<br><b>3)</b> D1/D2/D3/D4/D5, F6/F8/IX and F1/F3/CF |
| 8               | II       | Nitrate                                          | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                       |
| 9               | I        | Nitrate                                          | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                       |

| Borehole number | Drinking |                                                  | Livestock |                    | Irrigation |                                | Water treatment recommendation                                                                                                                      |
|-----------------|----------|--------------------------------------------------|-----------|--------------------|------------|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                               | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                                                     |
| 10              | I        | Nitrate                                          | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><br><b>1)</b> F6/F7/F8/IX<br><br><b>Irrigation:</b><br><br><b>1)</b> F1/F8 and IX, or<br><br><b>2)</b> F6/F7                    |
| 11              | V        | Nitrate, <i>Faecal coliform</i>                  | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><br><b>1)</b> F1/F8 and IX, or<br><br><b>2)</b> F6/F7 |
| 12              | V        | Nitrate, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><br><b>1)</b> F1/F8 and IX, or<br><br><b>2)</b> F6/F7 |

| Borehole number | Drinking |                        | Livestock |                    | Irrigation |                                                                                                      | Water treatment recommendation                                                                          |
|-----------------|----------|------------------------|-----------|--------------------|------------|------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter     | WQI       | Elevated parameter | WQI        | Elevated parameter                                                                                   |                                                                                                         |
| 13              | V        | <i>Faecal coliform</i> | I         | -                  | II         | -                                                                                                    | <b>Drinking:</b><br><br>1) D1/D2/D3/D4/D5                                                               |
| 14              | I        | Fluoride               | I         | -                  | II         | PS (high sulfate and chloride)                                                                       | <b>Drinking:</b><br><br>1) F6/IX<br><br><b>Irrigation:</b><br><br>1) F1/F8 and IX, or<br>2) F6/F7       |
| 15              | I        | Nitrate                | I         | -                  | II         | PS (high sulfate and chloride)                                                                       | <b>Drinking:</b><br><br>1) F6/F7/F8/IX<br><br><b>Irrigation:</b><br><br>1) F1/F8 and IX, or<br>2) F6/F7 |
| 16              | II       | Manganese, fluoride    | I         | -                  | III        | KR (high sodium), %Na (high sodium and potassium), SAR (high sodium), PS (high sulfate and chloride) | <b>Drinking:</b><br><br>1) F6/IX<br><br><b>Irrigation:</b><br><br>1) F1/F8 and IX, or<br>2) F6/F7       |

| Borehole number | Drinking |                                               | Livestock |                    | Irrigation |                                       | Water treatment recommendation                                                                                                                     |
|-----------------|----------|-----------------------------------------------|-----------|--------------------|------------|---------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                            | WQI       | Elevated parameter | WQI        | Elevated parameter                    |                                                                                                                                                    |
| 17              | I        | Fluoride                                      | I         | -                  | II         | PS (high sulfate and chloride),<br>pH | <b>Drinking:</b><br><br><b>1)</b> F6/IX<br><br><b>Irrigation:</b><br><br><b>1)</b> F1/F8, IX, and P1, or<br><b>2)</b> F6/F7 and P1                 |
| 18              | V        | <i>Faecal coliform</i>                        | I         | -                  | II         | PS (high sulfate and chloride)        | <b>Drinking:</b><br><br><b>1)</b> D1/D2/D3/D4/D5<br><br><b>Irrigation:</b><br><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                    |
| 19              | V        | Nitrate, manganese,<br><i>Faecal coliform</i> | I         | -                  | III        | PS (high sulfate and chloride)        | <b>Drinking:</b><br><br><b>1)</b> D1/D2/D3/D4/D5 and<br>F6/F7/F8/IX<br><br><b>Irrigation:</b><br><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |

| Borehole number | Drinking |                    | Livestock |                    | Irrigation |                                                                 | Water treatment recommendation                                                                                   |
|-----------------|----------|--------------------|-----------|--------------------|------------|-----------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter | WQI       | Elevated parameter | WQI        | Elevated parameter                                              |                                                                                                                  |
| 20              | II       | Nitrate, manganese | I         | -                  | III        | PS (high sulfate and chloride)                                  | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 21              | I        | Nitrate            | I         | -                  | I          | PI (high calcium and magnesium)                                 | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F7/IX                               |
| 22              | II       | Nitrate            | I         | -                  | II         | PI (high calcium and magnesium), PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F7<br><b>2)</b> IX and F1/F8        |

| Borehole number | Drinking |                    | Livestock |                    | Irrigation |                                                                 | Water treatment recommendation                                                                         |
|-----------------|----------|--------------------|-----------|--------------------|------------|-----------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter | WQI       | Elevated parameter | WQI        | Elevated parameter                                              |                                                                                                        |
| 23              | I        | Nitrate            | I         | -                  | I          | PI (high calcium and magnesium)                                 | <b>Drinking:</b><br><b>1) F6/F7/F8/IX</b><br><br><b>Irrigation:</b><br><b>1) F7/IX</b>                 |
| 24              | I        | -                  | I         | -                  | I          | PI (high calcium and magnesium)                                 | <b>Irrigation:</b><br><b>1) F7/IX</b>                                                                  |
| 25              | I        | Nitrate            | I         | -                  | II         | PI (high calcium and magnesium), PS (high sulfate and chloride) | <b>Drinking:</b><br>1) F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1) F7</b><br><b>2) IX and F1/F8</b> |
| 26              | I        | Nitrate            | I         | -                  | I          | PI (high calcium and magnesium)                                 | <b>Drinking:</b><br><b>1) F6/F7/F8/IX</b><br><br><b>Irrigation:</b><br><b>1) F7/IX</b>                 |

| Borehole number | Drinking |                                                  | Livestock |                    | Irrigation |                                 | Water treatment recommendation                                                                                          |
|-----------------|----------|--------------------------------------------------|-----------|--------------------|------------|---------------------------------|-------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                               | WQI       | Elevated parameter | WQI        | Elevated parameter              |                                                                                                                         |
| 27              | V        | Nitrate, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | I          | PI (high calcium and magnesium) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX               |
| 28              | II       | Nitrate, Iron                                    | I         | -                  | I          | PI (high calcium and magnesium) | <b>Drinking:</b><br><b>1)</b> F7<br><b>2)</b> F1/F3/D2/CF and F6/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX     |
| 29              | V        | <i>E. coli</i> , <i>Faecal coliform</i>          | I         | -                  | III        | PS (high sulfate and chloride)  | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5<br><br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |

| Borehole number | Drinking |                                                  | Livestock |                    | Irrigation |                                 | Water treatment recommendation                                                                            |
|-----------------|----------|--------------------------------------------------|-----------|--------------------|------------|---------------------------------|-----------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                               | WQI       | Elevated parameter | WQI        | Elevated parameter              |                                                                                                           |
| 30              | V        | Nitrate, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | I          | PI (high calcium and magnesium) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX |
| 31              | V        | Nitrate, <i>Faecal coliform</i>                  | I         | -                  | I          | PI (high calcium and magnesium) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX |
| 32              | V        | Nitrate, <i>Faecal coliform</i>                  | I         | -                  | I          | PI (high calcium and magnesium) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX |

| Borehole number | Drinking |                                                  | Livestock |                    | Irrigation |                                                                     | Water treatment recommendation                                                                                                                                               |
|-----------------|----------|--------------------------------------------------|-----------|--------------------|------------|---------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                               | WQI       | Elevated parameter | WQI        | Elevated parameter                                                  |                                                                                                                                                                              |
| 33              | V        | Nitrate, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | I          | PI (high calcium and magnesium)                                     | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX                                                                    |
| 34              | V        | Manganese, EC, <i>E. coli</i>                    | V         | EC                 | V          | PI (high calcium and magnesium), PS (high sulfate and chloride), EC | <b>Drinking:</b><br><b>1)</b> F6/F7/IX and D1/D2/D3/D4/D5<br><br><b>Livestock:</b><br><b>1)</b> F6/F7/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7<br><b>2)</b> IX and F1/F8 |
| 35              | I        | Manganese                                        | I         | -                  | I          | PS (high sulfate and chloride)                                      | <b>Drinking:</b><br><b>1)</b> F1/F6/F7/F8/IX/D2<br><br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                                                   |

| Borehole<br>number | Drinking |                    | Livestock |                    | Irrigation |                                    | Water treatment<br>recommendation                                                              |
|--------------------|----------|--------------------|-----------|--------------------|------------|------------------------------------|------------------------------------------------------------------------------------------------|
|                    | WQI      | Elevated parameter | WQI       | Elevated parameter | WQI        | Elevated parameter                 |                                                                                                |
| 36                 | I        | Nitrate            | I         | -                  | I          | PI (high calcium and<br>magnesium) | <b>Drinking:</b><br><br><b>1) F6/F7/F8/IX</b><br><br><b>Irrigation:</b><br><br><b>1) F7/IX</b> |
| 37                 | I        | Nitrate            | I         | -                  | I          | PI (high calcium and<br>magnesium) | <b>Drinking:</b><br><br><b>1) F6/F7/F8/IX</b><br><br><b>Irrigation:</b><br><br><b>1) F7/IX</b> |
| 38                 | I        | Nitrate            | I         | -                  | I          | PI (high calcium and<br>magnesium) | <b>Drinking:</b><br><br><b>1) F6/F7/F8/IX</b><br><br><b>Irrigation:</b><br><br><b>1) F7/IX</b> |
| 39                 | I        | Nitrate            | I         | -                  | I          | PI (high calcium and<br>magnesium) | <b>Drinking:</b><br><br><b>1) F6/F7/F8/IX</b><br><br><b>Irrigation:</b><br><br><b>1) F7/IX</b> |

| Borehole number | Drinking |                                 | Livestock |                    | Irrigation |                                                                     | Water treatment recommendation                                                                                                                            |
|-----------------|----------|---------------------------------|-----------|--------------------|------------|---------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter              | WQI       | Elevated parameter | WQI        | Elevated parameter                                                  |                                                                                                                                                           |
| 40              | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | I          | PI (high calcium and magnesium)                                     | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX                                                 |
| 41              | I        | Nitrate                         | I         | -                  | I          | PI (high calcium and magnesium)                                     | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7/IX                                                                    |
| 42              | IV       | Manganese, EC                   | V         | EC                 | V          | PI (high calcium and magnesium), PS (high sulfate and chloride), EC | <b>Drinking:</b><br><b>1)</b> F6/F7/IX<br><br><b>Livestock:</b><br><b>1)</b> F6/F7/IX<br><br><b>Irrigation:</b><br><b>1)</b> F7<br><b>2)</b> IX and F1/F8 |

| Borehole number | Drinking |                                                  | Livestock |                    | Irrigation |                                | Water treatment recommendation                                                                                                      |
|-----------------|----------|--------------------------------------------------|-----------|--------------------|------------|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                               | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                                     |
| 43              | V        | Nitrate, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 44              | I        | Nitrate                                          | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                    |
| 45              | V        | Nitrate, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |

| Borehole number | Drinking |                                 | Livestock |                    | Irrigation |                                                                     | Water treatment recommendation                                                                                                                    |
|-----------------|----------|---------------------------------|-----------|--------------------|------------|---------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter              | WQI       | Elevated parameter | WQI        | Elevated parameter                                                  |                                                                                                                                                   |
| 46              | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | I          | PI (high calcium and magnesium)                                     | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F7/IX                                             |
| 47              | I        | Nitrate                         | I         | -                  | I          | PI (high calcium and magnesium), PS (high sulfate and chloride)     | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F7<br><b>2)</b> IX and F1/F8                                         |
| 48              | V        | Manganese, EC                   | V         | EC                 | V          | PI (high calcium and magnesium), PS (high sulfate and chloride), EC | <b>Drinking:</b><br><b>1)</b> F6/F7/IX<br><b>Livestock:</b><br><b>1)</b> F6/F7/IX<br><b>Irrigation:</b><br><b>1)</b> F7<br><b>2)</b> IX and F1/F8 |

| Borehole number | Drinking |                                                  | Livestock |                    | Irrigation |                                                                 | Water treatment recommendation                                                                                                                  |
|-----------------|----------|--------------------------------------------------|-----------|--------------------|------------|-----------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                               | WQI       | Elevated parameter | WQI        | Elevated parameter                                              |                                                                                                                                                 |
| 49              | V        | Nitrate, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride)                                  | <b>Drinking:</b><br><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 50              | I        | Nitrate                                          | I         | -                  | I          | PI (high calcium and magnesium), PS (high sulfate and chloride) | <b>Drinking:</b><br><br><b>1)</b> F6/F7/F8/IX<br><br><b>Irrigation:</b><br><br><b>1)</b> F7<br><b>2)</b> IX and F1/F8                           |

**Table 49:** WQI ratings and water treatment recommendations for drinking, livestock, and irrigation purposes for the Ratlou area.

| Borehole number | Drinking |                                                     | Livestock |                    | Irrigation |                                | Remediation recommendation                                                                                                          |
|-----------------|----------|-----------------------------------------------------|-----------|--------------------|------------|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                                  | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                                     |
| 1               | I        | -                                                   | I         | -                  | II         | PS (high sulfate and chloride) | <b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                                                                 |
| 2               | V        | Nitrate, <i>E. coli</i> ,<br><i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 3               | V        | <i>E. coli</i> , <i>Faecal coliform</i>             | I         | -                  | III        | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                 |

| Borehole number | Drinking |                                                  | Livestock |                    | Irrigation |                                | Remediation recommendation                                                                                                          |
|-----------------|----------|--------------------------------------------------|-----------|--------------------|------------|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                               | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                                     |
| 4               | I        | -                                                | I         | -                  | II         | PS (high sulfate and chloride) | <b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                                                                 |
| 5               | V        | Nitrate, <i>Faecal coliform</i>                  | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 6               | V        | Nitrate, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 7               | I        | -                                                | I         | -                  | III        | PS (high sulfate and chloride) | <b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or                                                                                    |

| Borehole number | Drinking |                                                     | Livestock |                    | Irrigation |                                                                                                      | Remediation recommendation                                                                                                          |
|-----------------|----------|-----------------------------------------------------|-----------|--------------------|------------|------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                                  | WQI       | Elevated parameter | WQI        | Elevated parameter                                                                                   |                                                                                                                                     |
|                 |          |                                                     |           |                    |            |                                                                                                      | <b>2) F6/F7</b>                                                                                                                     |
| 8               | II       | Nitrate                                             | I         | -                  | III        | KR (high sodium), PS (high sulfate and chloride)                                                     | <b>Drinking:</b><br>F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b>                              |
| 9               | V        | Nitrate, <i>E. coli</i> ,<br><i>Faecal coliform</i> | I         | -                  | III        | PS (high sulfate and chloride)                                                                       | <b>Drinking:</b><br><b>1) D1/D2/D3/D4/D5 and F6/F7/F8/IX</b><br><b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b> |
| 10              | I        | -                                                   | I         | -                  | IV         | KR (high sodium), %Na (high sodium and potassium), SAR (high sodium), PS (high sulfate and chloride) | <b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b>                                                                 |

| Borehole number | Drinking |                                                                   | Livestock |                    | Irrigation |                                                                                                      | Remediation recommendation                                                                                                                                                                                    |
|-----------------|----------|-------------------------------------------------------------------|-----------|--------------------|------------|------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                                                | WQI       | Elevated parameter | WQI        | Elevated parameter                                                                                   |                                                                                                                                                                                                               |
| 11              | V        | Nitrate, iron, manganese, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | III        | KR (high sodium), SAR (high sodium), PS (high sulfate and chloride)                                  | <b>Drinking:</b><br><b>1)</b> D2 and F6/F7/F8/IX<br><b>2)</b> D1/D2/D3/D4/D5 and F7<br><b>3)</b> D1/D2/D3/D4/D5, F6/F8/IX and F1/F3/CF<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 12              | V        | <i>E. coli</i> , <i>Faecal coliform</i>                           | I         | -                  | IV         | KR (high sodium), %Na (high sodium and potassium), SAR (high sodium), PS (high sulfate and chloride) | <b>Drinking:</b><br><b>2)</b> D1/D2/D3/D4/D5<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                                                                                           |

| Borehole number | Drinking |                                                             | Livestock |                    | Irrigation |                                                                                                      | Remediation recommendation                                                                                                          |
|-----------------|----------|-------------------------------------------------------------|-----------|--------------------|------------|------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter                                          | WQI       | Elevated parameter | WQI        | Elevated parameter                                                                                   |                                                                                                                                     |
| 13              | V        | Nitrate, manganese, <i>E. coli</i> , <i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride)                                                                       | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 14              | I        | -                                                           | I         | -                  | III        | KR (high sodium), SAR (high sodium), PS (high sulfate and chloride)                                  | <b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                                                                 |
| 15              | I        | -                                                           | I         | -                  | II         | -                                                                                                    | -                                                                                                                                   |
| 16              | V        | Nitrate, <i>Faecal coliform</i>                             | I         | -                  | IV         | KR (high sodium), %Na (high sodium and potassium), SAR (high sodium), PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |

| Borehole<br>number | Drinking |                        | Livestock |                    | Irrigation |                                | Remediation recommendation                                                                                                  |
|--------------------|----------|------------------------|-----------|--------------------|------------|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------|
|                    | WQI      | Elevated parameter     | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                             |
| 17                 | V        | <i>Faecal coliform</i> | I         | -                  | III        | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5<br><br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><br><b>2)</b> F6/F7 |

**Table 50:** WQI ratings and water treatment recommendations for drinking, livestock, and irrigation purposes for the Tswaing area.

| Borehole number | Drinking |                        | Livestock |                    | Irrigation |                                | Remediation recommendation                                                                                           |
|-----------------|----------|------------------------|-----------|--------------------|------------|--------------------------------|----------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter     | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                      |
| 1               | II       | Nitrate                | I         | -                  | III        | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1) F6/F7/F8/IX</b><br><br><b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b> |
| 2               | I        | -                      | I         | -                  | II         | PS (high sulfate and chloride) | <b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b>                                                  |
| 3               | V        | <i>Faecal coliform</i> | I         | -                  | I          | -                              | <b>Drinking:</b><br><b>1) D1/D2/D3/D4/D5</b>                                                                         |
| 4               | I        | -                      | I         | -                  | II         | PS (high sulfate and chloride) | <b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b>                                                  |

| Borehole<br>number | Drinking |                                                     | Livestock |                    | Irrigation |                                | Remediation recommendation                                                                                                              |
|--------------------|----------|-----------------------------------------------------|-----------|--------------------|------------|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
|                    | WQI      | Elevated parameter                                  | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                                         |
| 5                  | I        | Nitrate                                             | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                    |
| 6                  | V        | Nitrate, <i>E. coli</i> ,<br><i>Faecal coliform</i> | I         | -                  | III        | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 7                  | I        | Nitrate                                             | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                    |

| Borehole<br>number | Drinking |                                 | Livestock |                    | Irrigation |                                                                     | Remediation recommendation                                                                                                                                            |
|--------------------|----------|---------------------------------|-----------|--------------------|------------|---------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                    | WQI      | Elevated parameter              | WQI       | Elevated parameter | WQI        | Elevated parameter                                                  |                                                                                                                                                                       |
| 8                  | V        | Manganese, EC, <i>E. coli</i>   | V         | EC                 | V          | PI (high calcium and magnesium), PS (high sulfate and chloride), EC | <b>Drinking:</b><br><b>1)</b> F6/F7//IX and D1/D2/D3/D4/D5<br><b>Livestock:</b><br><b>1)</b> F6/F7/IX<br><b>Irrigation:</b><br><b>1)</b> F7<br><b>2)</b> IX and F1/F8 |
| 9                  | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride)                                      | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                                   |

| Borehole<br>number | Drinking |                               | Livestock |                    | Irrigation |                                       | Remediation recommendation                                                                                                                                                  |
|--------------------|----------|-------------------------------|-----------|--------------------|------------|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                    | WQI      | Elevated parameter            | WQI       | Elevated parameter | WQI        | Elevated parameter                    |                                                                                                                                                                             |
| 10                 | V        | Nitrate, manganese,<br>EC     | V         | EC                 | V          | PS (high sulfate and<br>chloride), EC | <b>Drinking:</b><br><b>1) F6/F7/IX</b><br><b>Livestock:</b><br><b>1) F6/F7/IX</b><br><b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b>                    |
| 11                 | V        | Manganese, EC, <i>E. coli</i> | V         | EC                 | V          | PS (high sulfate and<br>chloride), EC | <b>Drinking:</b><br><b>1) F6/F7/IX and D1/D2/D3/D4/D5</b><br><b>Livestock:</b><br><b>1) F6/F7/IX</b><br><b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b> |

| Borehole<br>number | Drinking |                           | Livestock |                    | Irrigation |                                                                              | Remediation recommendation                                                                                                                        |
|--------------------|----------|---------------------------|-----------|--------------------|------------|------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
|                    | WQI      | Elevated parameter        | WQI       | Elevated parameter | WQI        | Elevated parameter                                                           |                                                                                                                                                   |
| 12                 | V        | Nitrate, manganese,<br>EC | V         | EC                 | V          | PI (high calcium and<br>magnesium), PS<br>(high sulfate and<br>chloride), EC | <b>Drinking:</b><br><b>1) F6/F7/IX</b><br><b>Livestock:</b><br><b>1) F6/F7/IX</b><br><b>Irrigation:</b><br><b>1) F7</b><br><b>2) IX and F1/F8</b> |
| 13                 | I        | -                         | I         | -                  | II         | PS (high sulfate and<br>chloride)                                            | <b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b>                                                                               |
| 14                 | II       | Nitrate                   | I         | -                  | III        | PS (high sulfate and<br>chloride)                                            | <b>Drinking:</b><br><b>1) F6/F7/F8/IX</b><br><b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b>                                  |

| Borehole number | Drinking |                                 | Livestock |                    | Irrigation |                                | Remediation recommendation                                                                                                              |
|-----------------|----------|---------------------------------|-----------|--------------------|------------|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter              | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                                         |
| 15              | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |
| 16              | I        | Nitrate                         | I         | -                  | II         | -                              | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX                                                                                               |
| 17              | V        | Nitrate, <i>Faecal coliform</i> | I         | -                  | III        | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |

| Borehole<br>number | Drinking |                               | Livestock |                    | Irrigation |                                                                              | Remediation recommendation                                                                                                                                                                           |
|--------------------|----------|-------------------------------|-----------|--------------------|------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                    | WQI      | Elevated parameter            | WQI       | Elevated parameter | WQI        | Elevated parameter                                                           |                                                                                                                                                                                                      |
| 18                 | II       | Nitrate                       | I         | EC                 | V          | KR (high sodium),<br>SAR (high sodium),<br>PS (high sulfate and<br>chloride) | <b>Drinking:</b><br><br><b>1) F6/F7/F8/IX</b><br><br><b>Livestock:</b><br><br><b>1) F6/F7/IX</b><br><br><b>Irrigation:</b><br><br><b>1) F1/F8 and IX, or</b><br><br><b>2) F6/F7</b>                  |
| 19                 | V        | Manganese, EC, <i>E. coli</i> | V         | EC                 | V          | PS (high sulfate and<br>chloride), EC                                        | <b>Drinking:</b><br><br><b>1) F6/F7//IX and D1/D2/D3/D4/D5</b><br><br><b>Livestock:</b><br><br><b>1) F6/F7/IX</b><br><br><b>Irrigation:</b><br><br><b>1) F1/F8 and IX, or</b><br><br><b>2) F6/F7</b> |

| Borehole number | Drinking |                               | Livestock |                    | Irrigation |                                    | Remediation recommendation                                                                                                                                                           |
|-----------------|----------|-------------------------------|-----------|--------------------|------------|------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | WQI      | Elevated parameter            | WQI       | Elevated parameter | WQI        | Elevated parameter                 |                                                                                                                                                                                      |
| 20              | V        | Manganese, EC, <i>E. coli</i> | V         | EC                 | V          | PS (high sulfate and chloride), EC | <b>Drinking:</b><br><b>1) F6/F7//IX and D1/D2/D3/D4/D5</b><br><br><b>Livestock:</b><br><b>1) F6/F7/IX</b><br><br><b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b> |
| 21              | II       | Nitrate                       | I         | -                  | III        | PS (high sulfate and chloride)     | <b>Drinking:</b><br><b>1) F6/F7/F8/IX</b><br><br><b>Irrigation:</b><br><b>1) F1/F8 and IX, or</b><br><b>2) F6/F7</b>                                                                 |

| Borehole<br>number | Drinking |                                                     | Livestock |                    | Irrigation |                                | Remediation recommendation                                                                                                          |
|--------------------|----------|-----------------------------------------------------|-----------|--------------------|------------|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
|                    | WQI      | Elevated parameter                                  | WQI       | Elevated parameter | WQI        | Elevated parameter             |                                                                                                                                     |
| 22                 | III      | Nitrate                                             | I         | -                  | III        | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7                    |
| 23                 | V        | Nitrate, <i>E. coli</i> ,<br><i>Faecal coliform</i> | I         | -                  | II         | PS (high sulfate and chloride) | <b>Drinking:</b><br><b>1)</b> D1/D2/D3/D4/D5 and F6/F7/F8/IX<br><b>Irrigation:</b><br><b>1)</b> F1/F8 and IX, or<br><b>2)</b> F6/F7 |

## APPENDIX C: ETHICS APPROVAL LETTER OF STUDY



**NWU**  
NORTH-WEST UNIVERSITY  
NORDEAST CAMPUS  
VANDERWATERFONTEIN  
PO BOX 1212  
VANDERWATERFONTEIN 1901

Private Bag X1250, Potchefstroom  
South Africa 2520

**North-West University Engineering Research  
Ethics Committee (NWU-ENG-REC)**

Tel: 018 259-2545  
Email: [ENG-REC@nwu.ac.za](mailto:ENG-REC@nwu.ac.za)

18/08/2021

### ETHICS APPROVAL LETTER OF STUDY

Based on approval by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 18/02/2021, the NWU-ENG-REC hereby approves your study as indicated below. This implies that the NWU-ENG-REC grants its permission that, provided the general and specific conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

**Study title:** Groundwater quality assessment in the Ngaka Modiri Molema District using the Water Quality Index

**Principal Investigator/Study Supervisor/Researcher:** Corneels Schabert

**Student:** Caitlin Margaret van der Merwe (26989972) [caitlinvandermerwe6@gmail.com](mailto:caitlinvandermerwe6@gmail.com)

**Ethics number:** NWU-00109-21-A3

Institution Study Number Year Status  
 Status: S = Submission; R = Re-Submission; P = Provisional Authorisation;  
 A = Authorisation

**Application Type:** Single

**Approval date:** 18/08/2021 **Risk:** Low Risk

**Expiry date:** 18/08/2022

Approval of the study is provided for a year, after which continuation of the study is dependent on receipt and review of annual monitoring report and the concomitant issuing of a letter of continuation.

**General conditions:**

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply:

- The principal investigator/study supervisor/researcher must report in the prescribed format to the NWU-ENG-REC:
  - Annually on the monitoring of the study, whereby a letter of continuation will be provided annually, and upon completion of the study; and
  - without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study.
- The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the principal investigator/study supervisor/researcher must apply for approval of these amendments at the NWU-ENG-REC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited.
- Annually a number of studies may be randomly selected for active monitoring.
- The date of approval indicates the first date that the study may be started.
- In the interest of ethical responsibility, the NWU-ENG-REC reserves the right to:

9.1.5.4.2 Ethics Approval Letter of Approval

1

Figure 63: Ethics approval letter of study.

- request access to any information or data at any time during the course or after completion of the study;
  - to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process;
  - withdraw or postpone approval if:
    - any unethical principles or practices of the study are revealed or suspected;
    - it becomes apparent that any relevant information was withheld from the NWU-ENG-REC or that information has been false or misrepresented;
    - submission of the annual monitoring report, the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or
    - new institutional rules, national legislation or international conventions deem it necessary.
- NWU-ENG-REC can be contacted for further information via [ENG-REC@nwu.ac.za](mailto:ENG-REC@nwu.ac.za) or 018 299 2645

Special conditions of the research approval (if applicable): NA

Special in process conditions of the research for approval (if applicable): NA

The NWU-ENG-REC would like to remain at your service and wishes you well with your study. Please do not hesitate to contact the NWU-ENG-REC for any further enquiries or requests for assistance.

Yours sincerely,

**Hein  
Neomagus**

Digitally signed by  
Hein Neomagus  
Date: 2021.08.16  
13:24:08 +02'00'

Prof H. Neomagus  
Chair NWU-ENG-REC

Current details (SPN7964) \NWU\RecCloud\ENG-REC\Letters\_sent\Date\9.1.5.4.2\_NWU-ENG-REC\_REC\_EAL\_[student surname\_name]

File Reference: 9.1.5.4.2

**Figure 64:** Ethics approval letter of study (Continue).