NAMIBIA UNIVERSITY OF SCIENCE AND TECHNOLOGY

MICROBIAL QUALITY AND PHYSICO-CHEMICAL PROFILING OF WATER USED FOR IRRIGATION IN NAMIBIA UNDER CLIMATE CHANGE

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Thesis/Dissertation submitted in fulfilment of the requirements for the Doctorate degree in Natural Resources Sciences at the Namibia University of Science and Technology

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I, Petrus Tuhafeni Paulus, hereby declare that the work contained in the thesis entitled: Microbial Quality and Physico-Chemical Profiling of Water Used for Irrigation in Namibia Under Climate Change is my own original work and that I have not previously in its entirety or in part submitted it to any university or higher education institution for the award of a qualification.

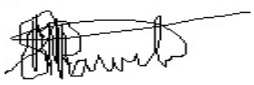


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List of Acronyms

ASR	Ancestral State Reconstruction
ASVs	Amplicon Sequence Variants
CCS	Circular Consensus Sequences
CHIRPS	Climate Hazards Group Infrared Precipitation with Station data
EC	Enzyme Classification
FAO	Food and Agriculture Organisation of the United Nations
FIB	Faecal Indicator Bacteria
GAPs	Good Agricultural Practices
GM	Geometric Mean
GTOMT	Grootfontein-Tsumeb-Otavi Maize Triangle
ICP – OES	Inductively Coupled Plasma Optical Emission Spectroscopy
IWRM	Integrated Water Resources Management
LEfSe	Linear Discriminant Analysis Effect Size
MAWLR	Ministry of Agriculture, Water and Land Reform
MPN	Most Probable Number
MWQP	Microbial Water Quality Profile
NAB	Namibia Agronomic Board
NamWater	Namibia Water Corporation
NASA	National Aeronautics and Space Administration
NDP4	National Development Plan 4
NGS	Next Generation Sequencing
NHSP	National Horticulture Support Programme
NTU	Nephelometric Turbidity Unity
NUST	Namibia University of Science and Technology
ORIP	Orange River Irrigation Project
OTUs	Operational Taxonomic Units
PCR	Polymerase Chain Reaction
PI	Permeability Index
PS	Potential Salinity
QIIME	Quantitative Insights Into Microbial Ecology

qPCR	Quantitative Polymerase Chain Reaction
RDA	Redundancy Analysis
RSC	Residual Sodium Carbonate
SADC	Southern African Development Community
SAR	Sodium Adsorption Ratio
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
SDGs	Sustainable Development Goals
SGSP	SASSCAL Graduate Study Programme
SMRT	Single Molecule Real-Time
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SS	Suspended Solids
STV	Statistical Threshold Value
TDS	Total Dissolved Solids
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USSL	United States' Salinity Laboratory
WHO	World Health Organisation
WQIs	Water Quality Indices

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Dedication

I am dedicating this thesis to the PHETE family, comprising of myself, Petrus (Father), Hilia (Wife) and children (Enoch, Tuhafeni-Junior and Elijah).

Abstract

Surface and groundwater sources are vital to sustainable livelihood. They constitute a key component of human life, and in achieving the Sustainable Development Goals outlined by the United Nations. However, with the rise in industrialisation, population growth and an increase in anthropogenic activities, the quality of the water sources is of great concern when considering its suitability for irrigated agriculture. This study was therefore, aimed at profiling the microbial and physico-chemical characteristics of the water used for irrigation of horticultural crops in alignment with water and food security under climate change in Namibia.

Surface and groundwater, and sediment samples were collected from four irrigation schemes and farms in the Grootfontein-Otavi-Tsumeb area. Physico-chemical analysis was conducted at the Namibia University of Science and Technology and the Namibia Water Corporation laboratories using Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES). DNA extraction and sequencing were performed at Inqaba Biotech. To assess the impact of climate change on water availability and its impact on food security, historical data on major staple food crops' production was obtained from the Namibian Agronomic Board from 2010 to 2024 and, monthly climatic parameter data of precipitation, climatic temperature, relative humidity and evapotranspiration were obtained from CHIRPS' gridded data, and from NASA Climatology Resource for Agroclimatology for the period of 1972-01-01 to 2023-12-01.

Results indicated that the abundance of ions in analysed water samples was in the following order: $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and alkalinity $> SO_4^{2-} > Cl^- > NO_3^- > F^- > NO_2^-$. The water quality indices showed that all the water samples ranged from being permissible to excellent for Na%, while 48% of the samples were classified as water that could be used safely for irrigation according to the Residual Sodium Carbonate index. The index-based assessment of the irrigation water quality is appropriate in decision-making processes, when it comes to identifying surface and ground water sources that are suitable for irrigation schemes and, in establishing preventive measures against crop damage for enhanced productivity in alignment with SDGs 2, 3, 6, 12, 14, and 15. Furthermore, the profile of the microbial community composition of the water indicated that *Pseudomonadota* was the most prevalent phylum, dominating 54% of samples, particularly in groundwater sources, where it constituted 93% of microbial communities in Grootfontein. The presence of faecal indicator organisms in the irrigation water, confirmed by the detection of *Escherichia coli* in Shadikongoro and Ndonga Linena, underscores the necessity of understanding microbial community structure to enhance water management strategies for producing safe horticultural products, thereby protecting human, plant, and environmental health, and advancing sustainable development goals. Lastly, trend analysis of the precipitation versus the production of major

crops showed in 2019 when the precipitation was 469mm, white maize, wheat and pearl millet productions were 28887, 4466 and 278 tons respectively, while in 2020 when the precipitation rose to 976mm, the crop production was 66642, 11498 and 4139 tons respectively for white maize, wheat and pearl millet. Therefore, climate change is indeed affecting food production and security.

Keywords: Integrated water resources management, Sustainable Development Goals, water quality indices, microbial diversity, sequencing, climate change.

Chapter 1: General Introduction

1.1 Background

Namibia is the most arid country in sub-Saharan Africa (**Figure 1-1**). It is located between 17°S and 29°S latitudinally, and longitudinally between 11 °E and 26 °E. The area that is covered by land is about 825,418 km^2, and the country has a 1,500 km long coastline that stretches along the South Atlantic Ocean. Namibia shares borders with four countries, namely, Angola to the north, Botswana to the east, South Africa to the south, and Zambia to the northeast. Another key aspect of Namibia is that it is predominantly arid with deserts, the Kalahari and Namib, covering a very large portion of the country's land to the east and west, respectively.

The distribution of the country in terms of aridity is that it reduces towards the central plateau regions, and the great escarpment located between the central plateau and the Namib Desert. The climatic conditions are characterised by persistent droughts, unpredictable and variable rainfall patterns, scarcity of water, and high temperature variability.

Economically, Namibia is ranked as an upper-middle-income country; this is mainly due to the country's natural mineral wealth and its relatively small population. Although Namibia has achieved in reducing its poverty rate, the battle against unemployment is still raging as job creation continues to stagnate, with socio-economic inequalities at the extreme due to the country's past apartheid system.

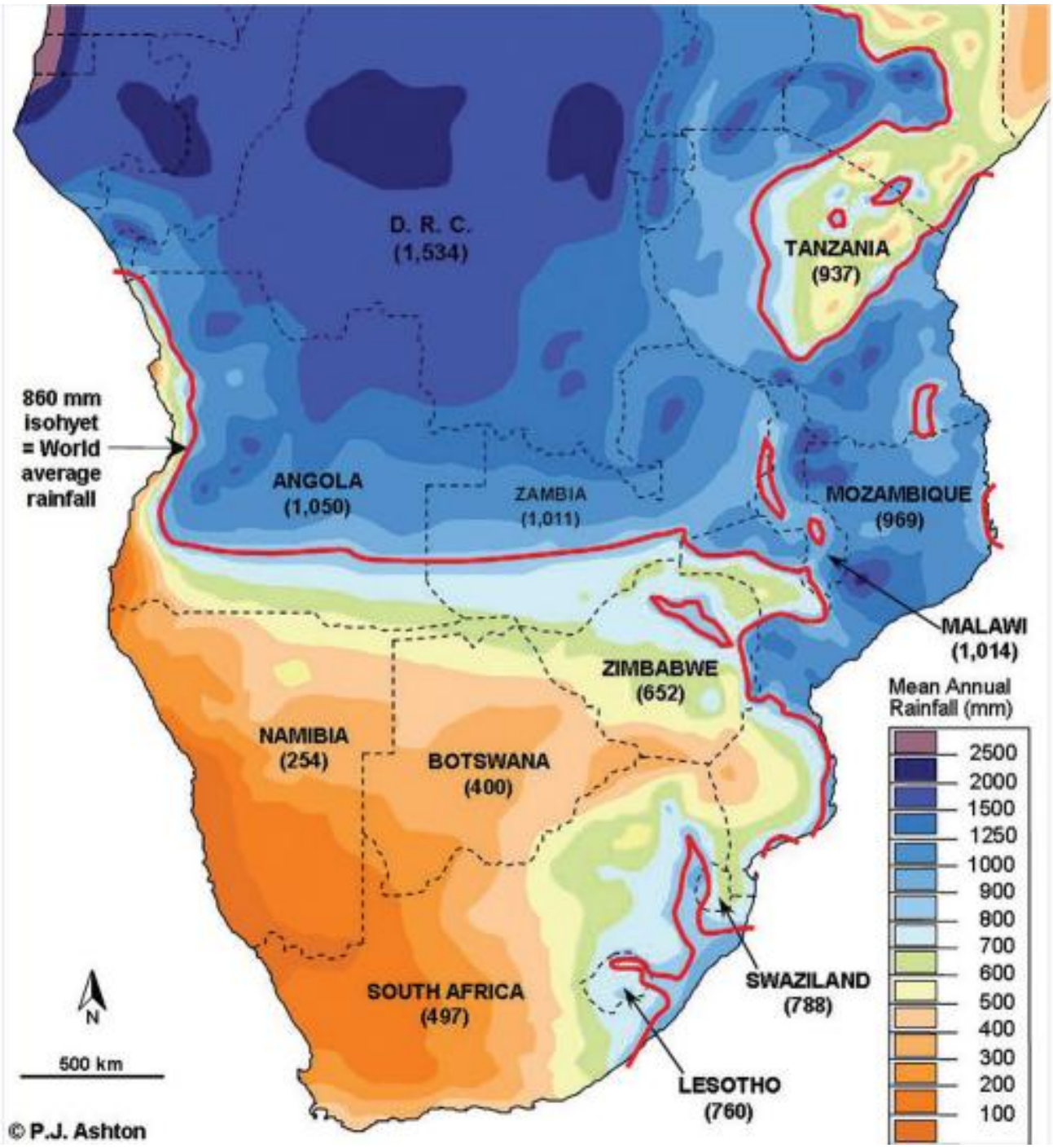


Figure 1-1. SADC Region Rainfall Variability (Sourced: Global Water Partnership Southern Africa, 2021)

The population of Namibia is nearly 2.54 million (2020), with a growth rate of about 1.8% (2020). The country is projected to grow to 3.01 million and 3.98 million by 2030 and 2050, respectively. The population distribution shows that 50% live in urban areas, particularly Windhoek, the capital city and economic centre. The projection indicates that the population is expected to increase to 61% by 2030 and 72% by 2050, respectively (The World Bank Group, 2021).

Water is the most abundant natural resource that supports all forms of life, covering about 70% of the earth. However, the demand for freshwater is still very high in many parts of the world (World Economic Forum, 2018). As the earth's population continues to increase, so does the human need for freshwater (Rios, 2019). According to the United Nations' report (2021), on water development, the global demand for freshwater over the past 100 years has increased by a factor of six and is predicted to continue rising at a rate of 1% per annum (United Nations, 2021). The increased demand for fresh water is attributed to population growth, among other factors. The report establishes that 69% of the global water withdrawals are due to agricultural activities, mainly for irrigation purposes in crop production, and that figure can go up to 95% in most developing countries.

It has been reported by various scholars that the quality of water has deteriorated in nearly all major rivers in Africa, Asia, and Latin America due to land-water interactions (United Nations, 2021; Qin et al., 2021; Chen et al., 2022). The United Nations (2021) reported that major water contaminants include microbes such as bacteria, viruses, parasites, and/or physicochemical, such as dissolved solids, inorganic, and organic matter. Contaminated surface water can be a major source of water-borne and food-borne pathogens. This alarming situation calls for concern about the effect this would have on human health in cases where untreated and contaminated water is used for horticultural crop irrigation.

In Namibia, agriculture is one of the key drivers of sustainable development and sustenance of the livelihoods of many communities, especially those in the rural areas. However, Namibia is an arid and semi-arid country with scarce and unpredictable rainfall, averaging about 250 mm per year (Shalumbu & Munyayi, 2015; Isala et al., 2016). The ephemeral rivers are generally dry during most of the period of the year. They offer a very limited surface water source, only during the rainy season when the run-off is harnessed into dams. The perennial surface water that is available is under threat of pollution due to human anthropogenic and industrial activities. Contaminated surface water has a significant effect because farmers depend on it for crop irrigation, primarily because of its availability and cost-effectiveness (Roy et al., 2015). When contaminated water is used for irrigation, it causes health problems to both the producers and consumers and results in environmental pollution. This scales down to the contamination of the soil and reduction in crop yields, which is a threat to food security and is placing immense pressure on policy and decision makers whose main interest is to develop sustainable strategies for resource development and deployment.

In Namibia, water for irrigation is mainly from riparian sources, namely the Zambezi, Kunene, Kavango, and Orange rivers, and from dams and boreholes. The rivers are fed by streams that come from different areas. The water is polluted by mines, animal production systems, industrial companies, hospitals, and settlements that lack adequate sanitation facilities (Lewis and Claasen, 2018). Hence, it is essential to come up with regional approaches that will help to control and mitigate the effects of water pollution.

Table 1-1. Sources of Irrigation Water for the Agricultural Schemes in Namibia

#	Name of Agricultural Scheme	Source of Irrigation Water
1	Etunda Green Scheme Irrigation Project	Kunene River
2	Hardap Green Scheme Irrigation Project	Hardap Dam
3	Kalimbeza Green Scheme Irrigation Project	Zambezi River
4	Mashare Green Scheme Irrigation Project	Kavango River
5	Musese Green Scheme Irrigation Project	Kavango River
6	Sikondo Irrigation Green Scheme Project	Kavango River
7	Shitemo Green Scheme Irrigation Project	Kavango River
8	Shadikongoro Green Scheme Irrigation Project	Kavango River
9	Ndonga Linena Green Scheme Irrigation Project	Kavango River
10	Uvhungu-Vhungu Green Scheme Irrigation Project	Kavango River
11	Orange River Green Scheme Irrigation Project	Orange River

The practice of agriculture in Namibia ranges from subsistence to commercial farming. Subsistence farmers are generally individuals and families who mainly depend on rainfall for irrigation, and to some extent, source their irrigation water from the rivers. They are mainly seasonal farmers. Commercial farmers source their water from rivers, dams, and boreholes, and these are all-seasons farmers. They play a significant role in ensuring food security and sustainable development.

Moreover, climate change presents a real challenge to Namibia. As climate change intensifies, it is anticipated that renewable surface water will decline, and the groundwater resources will also reduce significantly, subsequently impacting water quality (Hirwa et al., 2019; Bi et al., 2018; Musiyarira et al., 2017). In addition, land use evolution, deforestation, and urbanisation are contributing to water quality degradation. Both climate and anthropogenic factors result in

significant changes in the variables and processes that affect water quality in terms of its physical, chemical, and biological parameters (Akhtar et al., 2021).

Despite Namibia being arid and semi-arid, it has a strong reliance on agriculture, with about 70% of its population depending on it for food security (Isala et al., 2016). Namibia produces various crops, including cereals, fruits, and horticultural products. The horticulture covers fresh agricultural produce such as tomatoes, potatoes, carrots, cabbage, butternuts, beans and groundnuts, dates, grapes, melons, citrus, and others under irrigation. Cereal crops include maize, pearl millet (*Mahangu*), wheat, and sunflower (Gross, 2022).

South Africa, the immediate neighbour to Namibia, and a great exporter of fresh produce to Namibia, has a growing concern about the safety status of its agricultural produce (Ntuli & Uyttendaele, 2017). A substantial portion of this produce is eaten without being cooked or with minimal processing, and the number of foodborne outbreaks associated with these products has also been on the rise (Ntuli & Uyttendaele, 2017) due to microbial contaminations (Balali et al., 2020). To protect people from water-borne diseases, the employment of Integrated Water Resources Management approaches is significant to combat issues affecting water and food security, and protection from water-borne diseases that generally cross political boundaries. The significance of viability in risk determination for any pathogenic or indicator organism is an indispensable aspect of detection, with the understanding that the nonviable organisms do not signify a health hazard (Trinh and Lee, 2022).

The Ministry of Agriculture, Water and Land Reform, through its Department of Water Affairs, is mandated to monitor and protect the water quality of the nation's water sources. However, the physico-chemical and microbial parameters for quality of the water are not monitored against suitability for crop irrigation, and prevention of food-borne diseases. The advancement in sequencing technologies and computational biology has allowed analysis of microbial population compositions in water sources to provide a robust scientific understanding of pathogens that may be in the water, which may affect both health and food security.

Furthermore, exposure to microorganism and their related roles in the water used for irrigation will offer the needed understanding that is essential when framing new approaches for managing diseases and outbreaks and averting catastrophic health and economic problems. To this, the high-throughput sequencing technique comes in handy to enable the identification of complex microbial communities independently of bacterial culture, as the case had been in the past. Analysing the prokaryotic 16S ribosomal RNA with nine variable regions interspaced between conserved regions, the bacterial microbiota can be identified (Klair et al., 2022).

This study seeks to fill the knowledge gap by providing a scientific understanding of the link between water quality and crop health and safety . It is necessary to understand, in the local context, the effects that climate change has on water-borne pathogens with a definite focus on factors such as variations in the amount and intensity of precipitation, temperatures, humidity, and related evapotranspiration rates. All these climatic parameters influence the physico-chemical and microbial quality of the water source. Hence, the main purpose of this research was to assess the microbial composition and contamination levels in irrigation water and investigate their influence on the microbiological safety of produce irrigated with that water. The outputs of this study will aid in protecting the health of consumers by allowing the implementation of essential measures that are required to produce safe food, and thereby preventing epidemics of diseases, and ensuring dependable food security. This was the first study to use genomics to identify microbial communities in water sources used for agriculture in Namibia.

1.2 Problem Statement

According to the Southern African Development Community (SADC)'s Regional Water Strategic Action Plan on Integrated Water Resource Development and Management Phase IV of 2016, not more than 40% of the people in Southern Africa have access to safe water to meet their essential suitable hygiene demands (Southern Africa Development Community, 2016). Furthermore, the SADC regional water strategy further stresses that health and socio-economic implications are massive, with elevated disease burden emanating from water-borne diseases such as cholera, resulting in loss of life, children kept out of school, and women deprived of time for productive pursuits due to daily drudgery of fetching water and caring for sick family members (Southern Africa Development Community, 2006). The Regional Water Strategy was developed as a long-standing instrument for planning in Southern African countries (Southern Africa Development Community, 2016). The Southern African region has already been experiencing an upsurge in water and food-related diseases (Mpandeli et al., 2018).

The Namibian government, through the Ministry of Agriculture, Water and Land Reform (MAWLR), has come out with different initiatives like the National Horticulture Support Programme (NHSP), the Revised National Food and Nutrition Security Policy (2021), and the Namibia Agricultural Policy (2015) to promote rural communities' vegetable gardens to be self-sustainable. These initiatives will result in increased cultivation of horticultural crops and demand for irrigation water. In Namibia, rainfall is erratic, inconsistent, and unpredictable;

therefore, the current demand for clean water for irrigation far exceeds what is available. In many parts of the country, river water is used for irrigation without any purification, and this increases the potential risk of transferring water-borne pathogens onto crops, especially those which undergo minimal postharvest processing, as has been reported in other countries (Bell et al., 2021).

Previous studies in other countries have found faecal contamination indicator microorganisms like *Escherichia coli* and other significant waterborne or foodborne human pathogens in agricultural environments (Diodati et al., 2015). In Namibia, these pathogens are potentially present in surface irrigation waters but often go undetected, as there is no legislative pressure to test for them.

It was envisaged that this study will provide information and data that would inform farmers of the potential hazards associated with the use of contaminated irrigation water. The information on the physico-chemical and microbial quality of irrigation water in Namibia will provide a scientific understanding of the relationship between water sources and water-borne diseases affecting crops to promote the safe and appropriate use of surface irrigation water as well as enable the government, regional councils to develop and implement intervention strategies, regulations and guidelines for the production of safe food, preventing disease epidemics, and ensuring food security.

1.3 Research Questions

a) What are the physico-chemical properties of the water sources used to irrigate horticultural crops in Namibia?
b) What are the bacterial community compositions of irrigation water and the potential food safety risks associated with the water used to cultivate fresh produce in Namibia?
c) What are the impacts of climate change on the availability of water and food security?

1.4 Research Objectives

This study was designed to profile the microbial quality and physico-chemical characteristics of the water used for irrigation of horticultural crops in alignment with water availability and food security in Namibia under climate change. Specific objectives were set up to guide the study in ensuring that the aim of the study was achieved.

Specific Objectives

a) To evaluate the physico-chemical profiles of the water used for irrigation of horticultural crops in comparison with the irrigation water quality indices.

b) To profile the bacterial community composition and potential food safety risks in water used to cultivate fresh produce in Namibia.

c) To assess the impact of climate change on water availability and food security.

1.5 Significance of the Study

The project, being the first of its kind in Namibia, contributed by providing important information on the microbial water profile of the water used for irrigation. Additionally, it will produce a better comprehension of the dangers connected with different water systems, with the objective of assessing the microbial composition of irrigation water to inform implementation of important strategies for safe food production, preventing outbreaks of diseases, and ensuring reliable food security. Moreover, the findings of this project shall be accessible to the university and therefore, the academic fraternity will benefit through research, teaching, and learning by making reference to this project. The knowledge gap on the microbial quality and the physico-chemical profile of irrigation water used in Namibia will be narrowed through the findings of this project.

1.6 Delimitations of the Study

This study did not experience significant limitations in its execution and achievement of the specific objectives. However, the scope of the study was only limited to the 16S rRNA gene sequencing, and thus could not cater for the microbial composition of viruses and fungi. Again, the microbial quality of the vegetables was excluded in this study. Raw and historical data were utilised in the study. This research was funded through the SASSCAL's SGSP-IWRM Programme.

1.7 Thesis Structure

Chapter One: **General Introduction**

This chapter will provide the background of the research, the main research aim, specific objectives & research questions, limitations, problem statement, main contribution of this research, and lastly, the thesis structure.

Chapter Two: **Literature review**

An elaborate and extensive review will be provided on the matters that speak to the research. Past studies, the relevance of this research, identified problems, and the knowledge gap will be outlined. This chapter will also provide details on appropriate methods and data analysis tools that are key to achieving the research objectives for this research.

Chapter Three: **Methodology**

It will outline the study area, sampling, and detailed research methods that will be used to achieve each specific objective. The research procedures will be fundamental to answer each research question will also be detailed. This chapter will also provide the methods and discuss the tools that will be used to analyse the data.

Chapter Four: **Results and Data Analysis**

This chapter will firstly outline the findings of the research, beginning with an appropriate presentation of the raw data (the complete raw data will be annexed). The results for each of the four (4) specific objectives will be provided and analysed accordingly.

Chapter Five: **Discussion**

The analysed results of each specific objective will be discussed to make application of the research findings. This will be compared to the findings and recommendations of similar studies.

Chapter Six: **Conclusions and Recommendations**

This chapter will give the conclusion of the research, and offer a guide towards future work will be presented, and recommendations will also be outlined.

Chapter 2: Literature Review

2.1 Introduction

Water is a very important resource in agriculture. The water used to produce fresh produce commodities has to be safe to prevent water-borne diseases. There is however a growing concern regarding the quality of water used for irrigation due to possibilities of contamination with agricultural runoffs, rainwater runoff, polluted storm water runoffs and poor wastewater management as these are potential sources of pathogens that could result into economic crop losses and health risks for both human and animals (Redekar et al., 2019; Klair et al., 2023). Microbial pathogens are known to live in water for prolonged periods of time (Saxena et al., 2015). It is crucial to identify microbial communities in water used in irrigating crops to formulate suitable protective plans for crop farmers and decision makers who have the mandate of both ensuring food security and health protection.

Four major foodborne pathogens of serious concern including the Shiga toxin-producing *Escherichia coli*, *Salmonella*, *Campylobacter,* and *Listeria monocytogenes,* are water-borne. These pathogens have been connected to disease outbreaks in fresh produce, with some devastating consequences, and in a few cases, the contamination was traced to the water used for crop production or post-harvest activities (Bell et al., 2021). The foremost sources of water pollution by the indicator organisms like *E. coli* and *Salmonella enterica* are related to wildlife, livestock, and humans. Particularly, Shiga toxin–producing *E. coli* is accountable for numerous disease occurrences related to contaminated foods. One prominent Shiga toxin–producing *E. coli* is the 2011 Germany *E. coli* O104:H4 outbreak with fenugreek sprouts (Bell et al., 2021). Lately, there was an outbreak of *E. coli* O157:H7 in 2018 that affected many states in the United States of America (Bottichio et al., 2019). It was reported to have been linked to an agricultural produce, the romaine lettuce.

Moreover, besides the problem of bacteria that cause diseases, parasites, such as *Cryptosporidium* spp., *Giardia*, and *Cyclospora* spp., have also been linked with outbreaks in fresh produce (Marques et al., 2022). *Giardia* is a microscopic parasite that can be transmitted in numerous ways; however, water is the main means of spreading. For instance, a noteworthy correlation was found between the densities of *Cryptosporidium* and *Giardia* and parameters such as total and fecal coliform levels and turbidity by Banach & Van Der Fels-Klerx (2020).

Again, alongside the danger posed by pathogenic bacteria and parasites, viruses, such as norovirus and hepatitis A, have also been linked to fresh produce outbreaks. The projected health dangers of viral infection in the soft-fruit supply chains and in lettuce are largely minimal.

The influence that virus contamination has on the water used for irrigation or rinsing is less than that of hand contact by the cultivator of the produce (Banach & Van Der Fels-Klerx, 2020).
Furthermore, the water used for irrigation, whether it is sourced from surface water, pumped wells, such as boreholes and springs, or diverted from streams, generally contains appreciable amounts of chemical substances that are dissolved, which may reduce the crop yield and deteriorate the soil fertility. Of concern are the dissolved salts, which have been known for centuries to be problematic, and the presence of substances derived from their natural environment or from the waste products that come from anthropogenic activities such as domestic and industrial effluents. These harmful substances may differ in a wide range but mainly consist of dirt and suspended solids (SS), resulting in the emitters' blockages in micro-irrigation systems and bacteria populations and coliforms that are detrimental to humans and animals.

In Namibia, some of the green schemes that produce most of the local agricultural crops source their irrigation water from riparian rivers. The level of water treatment on the water used is another critical factor in the safety of the water. It is important to point out that water-borne pathogens do not know political boundaries. Hence, the water users and decision-makers should have a sound and comprehensive understanding of the water systems and water-borne pathogens in crops.

2.2 Water Quality Monitoring in Namibia

The Namibian Government has entrusted the overall mandate for monitoring the quality of both surface and groundwater to the Department of Water Affairs in the Ministry of Agriculture, Water and Land Reform. The concept of water quality in the Namibian context refers to the physical, chemical, and biological characteristics of the water (Water Resource Management Act, 2013). Although the government is the custodian of the nation's natural resources, various water users, such as bulk water suppliers, municipalities, and town councils, have the obligation to ensure that the national water quality standards are met.
After independence, it became necessary for the government to draft new policies to manage equitable access to and sustainable use of water resources in Namibia (Remmert, 2016). Over the years, several Acts and policies have been developed, which form the backbone of the national water management framework:

- The Water Act No. 54 of 1956 (pre-independence)

- The Namibia Water Corporation Act No. 12 of 1997
- The National Water Policy White Paper 2000
- The Water Resource Management Act No. 24 of 2004
- The Water Supply and Sanitation Policy 2008
- The Integrated Water Resource Management Plan 2010
- The Water Resources Management Act No. 11 of 2013

The Water Resources Management Act No. 11 of 2013 was passed by parliament and signed by the president on 2 December 2013, but it has not yet come into force. This is primarily due to the need to develop the necessary regulations that need to accompany the Act.

Furthermore, the Namibia Agriculture Policy (2015) does not categorically point out the importance of water quality monitoring on irrigation water sources. At the heart of this policy was the motivation to provide a clear framework for all the stakeholders involved in the agriculture sector of Namibia to have an enabling environment that will help them offer meaningful contributions towards attaining sustainable development and growth.

2.3 Irrigation water and food-borne pathogens

The water used for irrigation is one of the main cause of contamination with pathogenic microorganisms of fresh produce (Truchado et al., 2016). Diseases that come because of water-borne pathogens are a great burden globally, with an estimated annual mortality rate of 2.2 million and advanced incidences of infections daily, such as diarrhoea, gastrointestinal diseases, and systemic illnesses (Ramírez-Castillo et al., 2015). Of these deaths, about 1.4 million are children. It is estimated that water-borne diseases have an economic cost of about 1 billion dollars per annum only in the United States, and that of the world being nearly 12 billion per year (Ramírez-Castillo et al., 2015).

The water-borne diseases occur mainly by the means of ingestion, airborne, or contact with contaminated water by several infectious agents such as bacteria, protozoans, and helminths. Access to clean water remains a serious issue in many parts of the world, particularly in developing countries. About 780 million people do not have access to a clean water source, and a further estimate of about 2.5 billion people do not have access to better sanitation worldwide. Hence, it is projected that 3.2% of deaths worldwide are ascribed to hazardous water originating from poor hygiene and sanitation. During the tenure of the Millennium Development Goals (MDGs), it was the United Nations' goal number eight (8) to improve water quality, and its target back then was to decrease the number of people without access to safe water by 50% in 2015.

The mission to improve the quality of water was important as that would reduce the global disease burden by approximately 4%. Since then, the United Nations has come up with Sustainable Development Goals (SDGs) with a noble purpose of improving the quality of water by reducing pollution as per the expectation of Goal 6 on “Clean Water and Sanitation” (United Nations, 2022).

2.4 Composition of Microbial Communities

Surface water ecosystems, such as rivers, are vital sources of water for irrigation in many countries, including Namibia. One of the key concerns is the effect that anthropogenic activities have on the microbial quality of the water. Small-scale farmers and, to some extent, commercial farmers in developing countries generally use the water for irrigation without knowledge of the microorganisms that inhabit the water. Some of these microorganisms have health effects on humans. Over the years, the techniques used to identify the different pollutants (whether biological and chemical) in water have been sluggish, painstaking, and at times demanding proficiency (Wani et al., 2021).

Hence, there has been a need to determine the quality of the water using more delicate and dependable metagenomic-based approaches (Wani et al., 2021). The application of metagenomics will help explore the diversity of organisms as a microbial community by analysing the organism-specific DNA in environmental samples (Wani et al., 2021). This will mitigate the limitation of the traditional methods that are mainly culture-based and were used to describe the diversity of microorganisms, but failed to operate as a robust marker because of having limited taxonomic and phylogenetic implications. Sequencing techniques will help to characterise total microbial composition in the water (Shomar et al., 2020). The flowchart of the experimental and computational methods that are used to recover genomics information, which can further be examined with different bioinformatic tools, is shown in Error! Reference source not found.**-1** below.

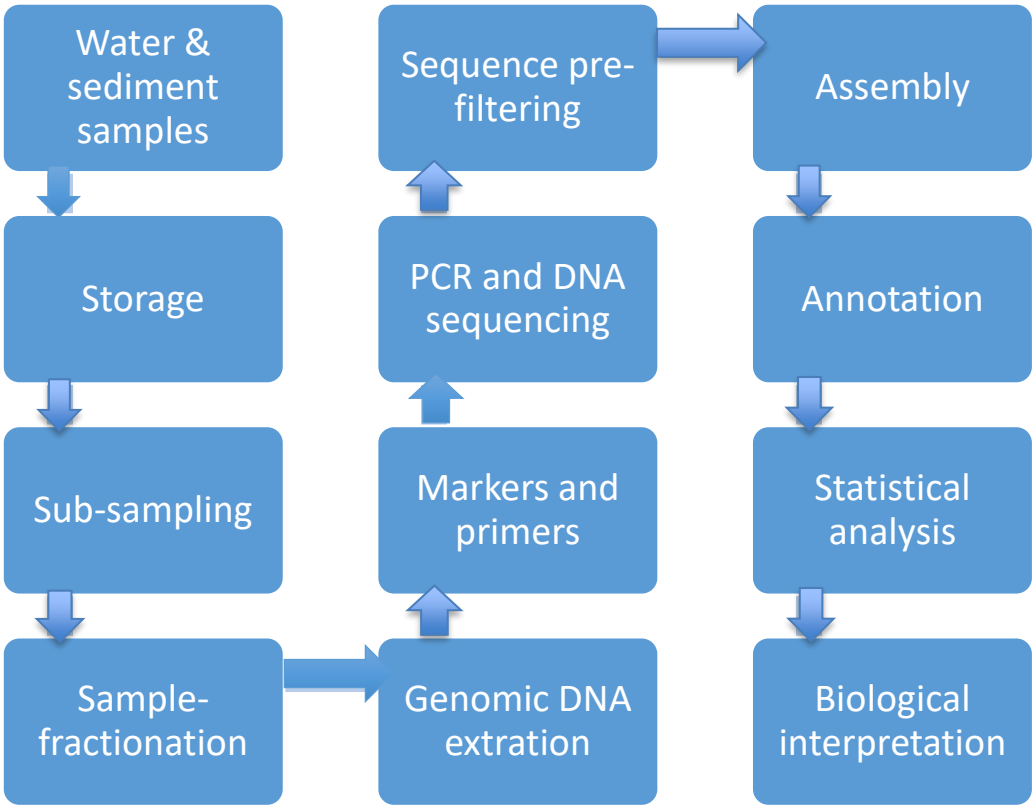


Figure 2-1. Flowchart of experimental and computational methods

Current innovations and advances in high-throughput sequencing methods have made identifying complete microbial communities present in environmental samples feasible, including those in water and fresh produce (Qurbani and Hamzah, 2020. High-throughput sequencing refers to methods that sequence deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) at an unprecedented speed, with greater coverage (amount sequenced), and at a lower cost than previously possible. Furthermore, called next-generation sequencing, high-throughput sequencing is being used for the first time to evaluate the microbial water quality of water used for irrigation in Namibia, to provide fascinating insights it the microbial profile of the water used for irrigation in this country.

Water is commonly used for more than one purpose, such as drinking (i.e., potable use), irrigation, and industry. To detect known species of interest, such as pathogens, researchers and utilities often use polymerase chain reaction (PCR) (Zhu et al., 2020). In this method, microorganisms are collected from an environment (e.g., via filtration of water), the bacteria are broken open, and their DNA is extracted. The segments of DNA matching a specific sequence of interest are copied repeatedly using an enzyme called DNA polymerase. This amplification process allows researchers to detect DNA sequences of interest in a sample, even if it is at very low prevalence. PCR used in this manner requires specific, specially optimised probes and thus

requires a priori knowledge of the DNA sequence of interest. This method can be used to detect anything for which the DNA sequence is known, including many bacterial, viral, or fungal pathogens, as well as antibiotic resistance genes (ARGs).

A more advanced method, called quantitative PCR (qPCR), uses calibration to a known standard to determine the exact number of copies of DNA within the original sample. This number corresponds to the number of organisms in the sample. PCR and qPCR have the advantages of detecting and quantifying specific microorganisms, respectively, regardless of whether the organisms can be grown in the laboratory. However, for many targets, a separate reaction must be performed for each species of interest, and these methods can only be used where DNA sequences are already known (i.e., requires *a priori* knowledge).

In recent years, high-throughput DNA sequencing technologies (e.g., Illumina, Thermo Fisher, PacBio, and Oxford Nanopore) have been developed that allow sequencing all the DNA present in a sample. Through computational methods (bioinformatics), the large volume of data generated by sequencing can be used to identify and characterise all microbial species within a community. This process is independent of whether microorganisms can be cultured in the laboratory. However, sequencing alone does not determine the viability of the organisms, only that their DNA is present (in other words, those organisms could be alive or dead). The most employed sequencing approach used to identify and analyse microbial communities is 16S ribosomal RNA (rRNA) gene amplicon sequencing (Church et al., 2020).

This method usually focuses on bacteria and uses a “fingerprint” region of DNA that is unique between different bacteria, but similar enough across all bacteria to be targeted by PCR. To perform amplicon sequencing, samples are collected, and DNA is extracted. Using semi-specific probes targeted to the fingerprint region of interest, the DNA is amplified using PCR. The amplified DNA fragments, known as amplicons, are then sequenced using high-throughput sequencing. Amplicon sequencing allows identification of bacteria that are present in very low numbers, as well as those that make up most of the microbial community. The evaluation of such microbial community composition is enabled by a less costly and yet comprehensive application of the 16S rRNA gene sequencing (Church et al., 2020; Ercolini, 2013). The 16S ribosomal RNA, also known as 16S rRNA, is part of the 30S subunit (Giuliano and Engl, 2021; Byrne et al., 2018; Case et al., 2007). This 30S subunit is the small subunit of the 70S ribosome, which occurs in prokaryotes. Ribosomes are macromolecular complexes that facilitate protein synthesis. The 16S rRNA has a unique role, as it is crucial for initiating translation by binding to the Shine-Dalgarno sequence. This sequence is generally located upstream of the start codon and complementary to a segment in the 16S rRNA. The genes coding for this crucial component

of the ribosome are referred to as 16S rRNA genes. The 16S rRNA gene shows slow rates of evolution. These slow evolutionary rates make them valuable for phylogenetic reconstructions. Thus, the 16S rRNA gene can give valuable insights into phylogenetics, the evolution of life, and the investigation of the relationships between different organisms. The extraordinary accuracy and length of PacBio HiFi reads generated using circular consensus sequencing (CCS) mode allow microbial taxa detection at high resolution.

The 16S rRNA gene spans about 1500bp and is structured in highly conserved regions that are interspersed with nine (9) variable regions (V-regions), V1 to V9. (Abellan-Schneyder, et al., 2021). These conserved regions could be utilised to bind primers of interest and thereby enable the capture of a greater number of different bacterial taxa. This would sometimes bring along archaea, while the variable regions allow the selection of the taxa within microbial environments. Sequencing technologies such as the Illumina MiSeq offer the opportunity to amplify up to 600 bp with high accuracy. However, this length only allows the assessment of one to three adjacent variable regions of the 16S rRNA by using universal primers for the conserved regions. In such applications, subsequent to the Polymerase Chain Reaction (PCR), sequencing adapters would be added to the amplicons, and after the clean-up process, the amplicon libraries would be sequenced. The resultant reads are then analysed for similarities and differences among the samples with varying microbial community compositions, for instance, the alpha- and beta-diversity. However, in contrast to the former limited technology of sequencing, the use of more advanced sequencing techniques, such as Oxford Nanopore MinIon and PacBio Revio System, enables the full-length sequencing of the 16S rRNA gene. This technology offers the valuable advantage of providing long read length, which can be up to 10,000 bp, and sequencing that is carried out on a single-molecule level in a brief period of time. These long reads make it possible to have an improved identification of bacterial taxa.

For instance, the PacBio sequencing platform and circular consensus sequencing (CCS) enable the full-length sequencing of the 16S gene and not only of sub-regions. The CCS mode allows the generation of so-called high-fidelity reads, short HiFi. During this process, single-molecule real-time (SMRT) libraries are prepared using double-stranded high-quality DNA and hairpin adapters on both sides of the double-stranded DNA. The resulting circularized DNA is sequenced in repeated passes. The adapters of the repeated passes are trimmed, and the resulting subreads are merged into a consensus read. Such consensus reads of a sufficient quality are then called HiFi reads. The sequencing errors that naturally and randomly occur are rapidly diminished with an increasing number of passes, leading to a high read accuracy for long reads. The circular consensus sequencing mode generates long HiFi reads with a high read accuracy.

Thus, Full-Length 16S Sequencing can, amongst others, enhance phylogenetic studies and the detection of microbial biomarkers. The applications of full-length 16S sequencing are diverse and include characterisation of different microbial communities (Bertolo et al., 2024), microbial biomarker detection (Lei et al., 2025), and disease monitoring (Campodónico et al., 2025). The accurate characterisation and identification of microbial communities would potentially contribute to the optimisation of drug efficiency, the prediction of drug resistance mechanisms, and even the discovery of drug targets.

Again, profiling phylogenetic marker gene 16S rRNA is an important tool for studies of microbial communities, but it, however, does not provide direct evidence of a community's functional characteristics. The use of bioinformatics tools such as the Phylogenetic Investigation of Communities by Reconstruction of Unobserved States (PICRUSt2) has proved promising for the analysis of metagenomic data for functional profiling of various microbial communities (Ijoma et al., 2021). PICRUSt2, a computational approach that reliably predicts the functional properties of microbial communities based on sequences of the marker gene, is vital as it makes predictions based on the sequence data of 16S rRNA gene sequence, which are used to predict the KEGG Ortholog (KO), Enzyme Classification (EC) numbering, and MetaCyc pathways (Peng et al., 2025). The predictions of the functional composition of a metagenome are made using marker gene data and a database of reference genomes (Langille et al., 2013). The operation of PICRUSt2 is significant in that it directly reads the representative sequences of the ASVs, which are output from QIIME2, and additionally predicts the functional properties of the microbial communities based on the abundance composition of the species. It requires a reference phylogeny with tips corresponding to taxa with reference genomes, as well as taxa lacking sequenced genomes. A modified ancestral state reconstruction (ASR) method is then used to infer counts of functional categories for taxa without reference genomes. The predictions are written to pre-calculated files, which can be cross-referenced with other datasets to quickly generate predictions of functional potential for a community (Douglas et al., 2018). The reliability of PICRUSt2 is attested by its numerous applications in metagenomic studies. Manter et al. (2023) utilised PICRUSt2 to make predictions of enzyme functions in the soil, where the functional characteristics of the microbial community were revealed (Manter et al., 2023). Furthermore, Peng et al. (2025) applied the PICRUSt2 technology to help predict the enzyme functions of the microorganism in the rock tea (Rougui) to reveal the pathways of flavour transformation substances involved by microorganisms, at an enzymatic point of consideration. The microbial functions in the tea varieties were predicted by the PICRUSt2 software. Importantly, PICRUSt2 enables the prediction of the functional properties of unculturable microorganisms. The main limitation of

PICRUSt2 is that it only detects the 16S gene sequence of bacterial and archaeal genomes, and therefore, it can only be utilised to analyse the systems dominated by bacteria and archaea (Yin and Wang, 2021), which makes it appropriate for this study. The differences in the functional enzymes between the different production areas were analysed too. To date, no studies have been undertaken on the water used for irrigation at the agricultural green schemes and farms for the production of fresh produce in Namibia, to predict the functional profiles of the microbial communities that inhabit these water sources. In this study, PICRUSt 2 was adopted to analyse the microbial communities in water and sediments to provide the prediction of the functional characteristics of these microbial communities.

2.5 Environmental Impacts of Climate Change

The reality of the existence and impacts of climate change has gone out of the box of doubts and speculations into a phenomenon of daily experiences. Climate change is affecting many things, as shown in **Figure 2-2**. Southern Africa has witnessed an increase in the occurrences and degree of impact of very high weather events associated with climate change, which has resulted in, among others, water and food insecurity (Mpandeli et al., 2018). In Southern Africa, the annual rainfall is project rainfall is projected to reduce by 20%. This reduction will increase the socio-economic changes that the region is facing and further aggravate the region's resource scarcity and vulnerabilities. In addition, the impact of climate change will be felt both directly and indirectly on nutrition, human well-being, and health. Other areas of significant concern that can also be attributed to climate change are the decline in agricultural production, lack of access to clean water, sanitation, and clean and sustainable energy (Mpandeli et al., 2018).

The Southern African region has already been facing an increase of vector, water-and food - borne diseases (Mpandeli et al., 2018).

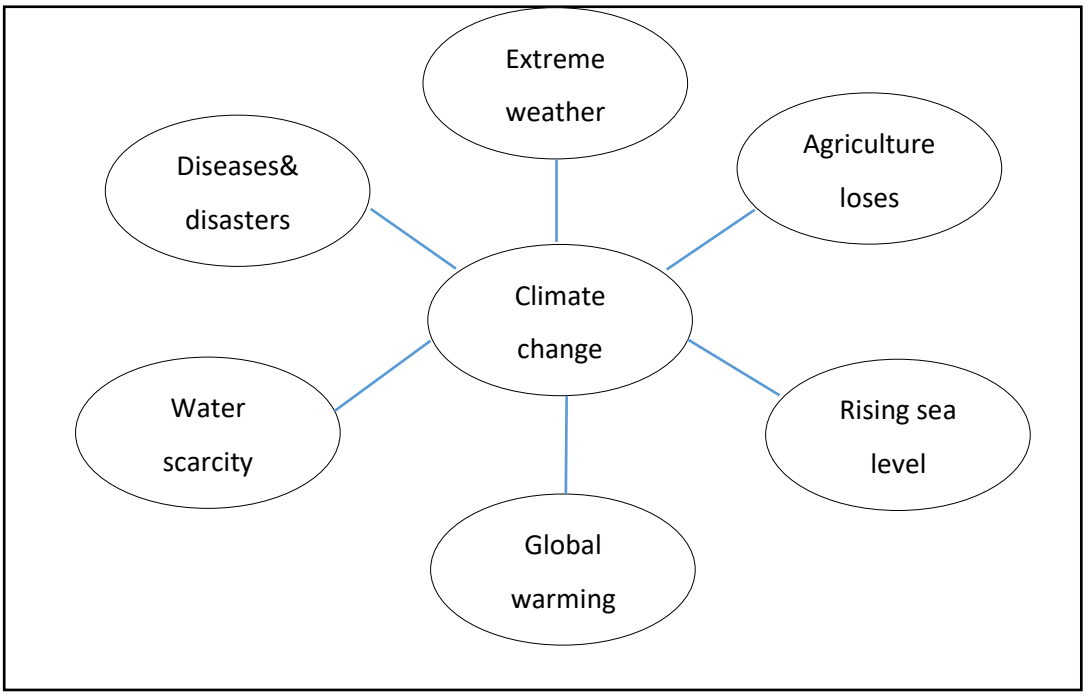


Figure 2-2. The Environmental Effects of Climate Change

2.6 Effects of Climate Change on Water Quality and Quantity

Climate change has influenced ecological, hydrological, and biological systems, of which the latter includes variations in microbial composition in water (**Figures 2.2** and **2.3**). The change in climatic conditions over the years has brought about significant changes in weather and precipitation patterns, as well as temperature fluctuations (Timmusk et al., 2020). The main and frontline manifestation, and susceptibility to surface water and groundwater, are the natural regional climate fluctuations and weather changes. Evapotranspiration, humidity, and the amount of rainfall received constitute the parameters of interest in terms of the most important factors of climate. Furthermore, another factor of concern is that of cyclical changes in temperature. Temperature influences a lot of environmental processes. At the heart of climate change is temperature. Gases are known to be highly soluble and viscous in water. When the temperature is low, the air binding capacity of filters is affected, and that will in turn decrease the pressure of the filter beds to enhance the release of gases and thus hinder the movement. When there is high rainfall, the water of the river gets diluted suddenly due to the addition of rainwater. That would have a serious effect on the quality of the water, and therefore, heavy precipitation constitutes a direct and indirect impact on the quality of surface water. Again, high atmospheric moisture and rainfall are prime considerations for many aquifers as they contribute

to groundwater infiltration and surface water runoffs. The rainfall patterns are not consistent, and evapotranspiration is somehow high due to high temperatures, resulting in a decline in aquifer recharge and high solute concentrations of the groundwater (Akhtar et al., 2021).

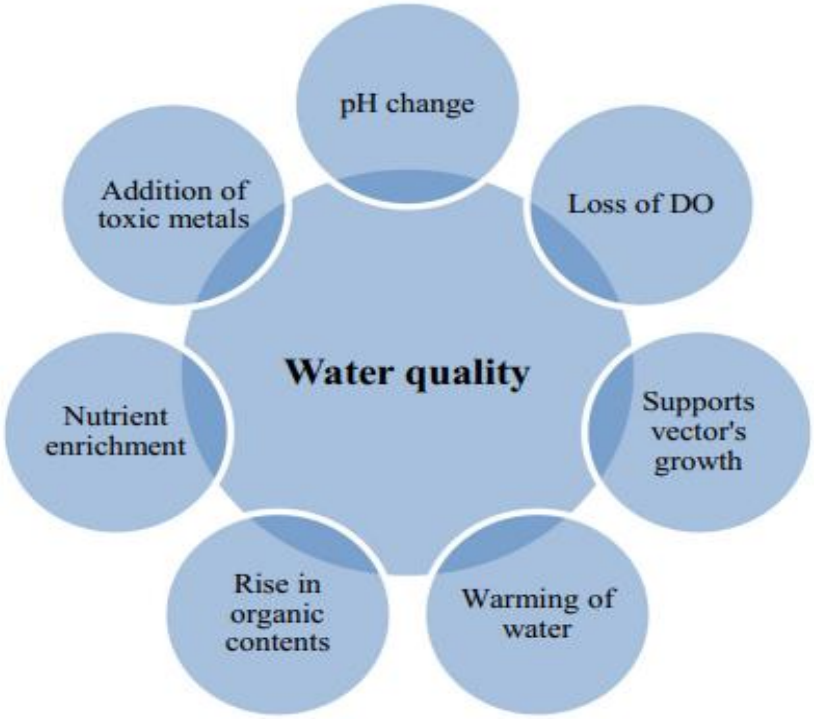


Figure 2-3. Water Quality Impacts of Climate Change

The water resources in the Southern Africa region are witnessing the serious impacts of climate change. The regions have been experiencing severe spatial and temporal changes in climate and water resources, mainly observed in the most arid nations such as Namibia (Mpandeli et al.,2018). These observations are shown in **Figure 2-4**, in which it was observed in the period forty-seven (47) years (1960 to 2007), the rainfall has been declining in Southern Africa. Mpandeli et al. (2018) noted that about 50% SADC's surface area has become dry, and that the precipitation is less than 650 mm.

Furthermore, climate change is increasing the problems associated with infectious diseases. Some infections are sensitive to climate, such as malaria, a well-known vector-borne disease. The spread of this disease is predicted to rise due to increased climatic adaptations for the mosquito vector in the developing countries. Even though the advent of hygiene practices such as water, sanitation, and hygiene (known as WASH) has resulted in the decline of water-borne pathogens causing diseases such as diarrhoea as far back as the 1990s, the burden of infections and diseases due to water-borne pathogens globally remains because of climate change. For

instance, several water-borne outbreaks were noted to have been caused by disease-causing microorganisms in water, such as bacteria, parasites, protozoans, and viruses. An example of a climate-dependent microorganism is *Salmonella*. This microorganism responds to changes in climatic conditions; it grows in slight temperature envelopes and has a strong seasonality. A rise in *Salmonella* occurrences has been noted to be associated with the increase in ambient temperature. This clearly shows that climate has a direct effect on the reproduction rates of this pathogen (Semenza et al., 2022).

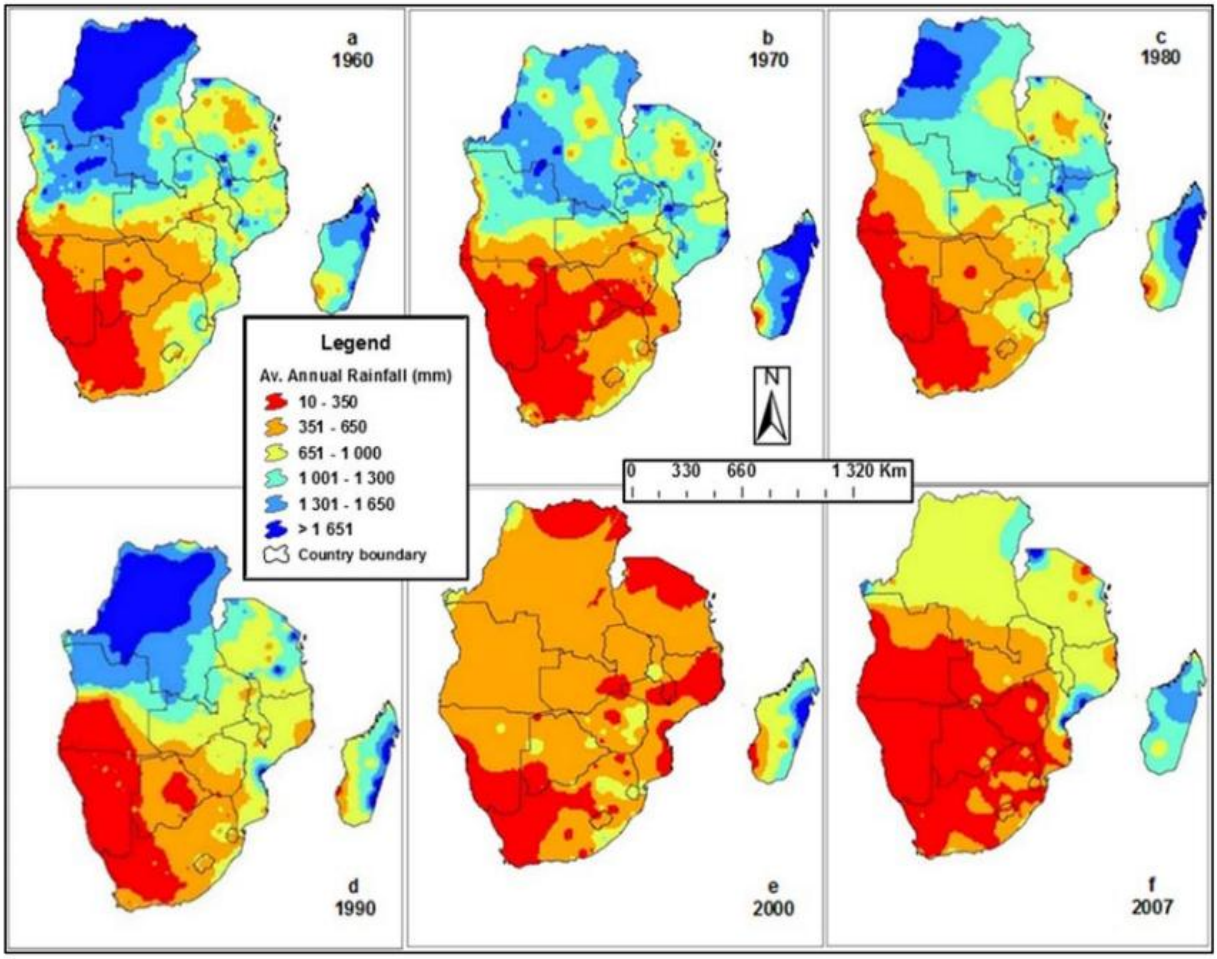


Figure 2-4. SADC Spatio-temporal changes (Source: Mpandeli et al., 2018)

2.7 Microbial water quality analysis

As far as public and environmental health protection is concerned, the water used for irrigation should be of safe microbial quality, and this means that it should be free from pathogenic microorganisms (Rompre et al., 2002). The general microbial water quality of surface water is assessed by analysing the population of indicator organisms. Generally, three different

microorganisms are enumerated by the most probable number method (MPN/100 ml) as indicator organisms, namely total coliforms (TC), generic *E. coli,* and enterococci. The populations of for total coliform (TC) and *E. coli* are examined through the activity of β-galactosidase and β-glucuronidase, respectively, whereas that of enterococci is examined by the activity of β-glucosidase.

The traditional enumeration for indicator organisms is born out of the understanding that the act of monitoring every pathogenic microorganism that may be potentially present in the water, such as protozoans, fungi, bacteria, and viruses, is not practically realistic, considering the cost of the resources needed for this endeavour (Teixeira et al., 2020). The use of faecal indicator bacteria (FIB) such as *Escherichia coli* and *Enterococcus* spp, among others, has become handy as an alternative to assess the microbiological quality of the water. Faecal indicator bacteria generally serve as surrogates for enteric pathogens, particularly for the monitoring of faecal contamination in environmental waters, based on the understanding that the existence of faecal indicator bacteria is concomitant with the presence of pathogens (Teixeira et al., 2020).

2.8 Water Quality and Water Scarcity

One of the main factors contributing to the problem of water scarcity, which has often been overlooked, is the water quality deterioration (Drechsel et al., 2023). This is particularly of concern in many of the countries that are termed as low and middle-income countries. In these nations, the treatment of water and application of control measures against pollution of significant water sources are not parallel nor aligned to urbanisation and population growth. Consequently, and unfortunately, about 30 million hectares of agricultural land, which is home to about 800 million inhabitants, is irrigated with unsafe water. The use of unsafe water for irrigation has health implications to the consumers of agricultural products and produce. Specifically, salinity has been identified as a constituent of note that is affecting water quality. Globally, 20% of the cultivated land area and an estimated 33% of irrigated land are affected by salinity (Drechsel et al., 2023).

The Food and Agriculture Organisation of the United Nations and the International Water Management Institute have noted that in the past 30 years, water quality challenges have significantly grown. The 2030 Agenda for Sustainable Development recognises the importance of water quality to a more sustainable future amidst the impacts and challenges posed by climate change. Growing nations, towns, and cities due to urbanisation have an increasing

demand for water and produce more wastewater in return. Key sectors such as agriculture and households face competition for the scarce water resources. The achievement of sustainable development in terms of food and water security would require sustainable production and consumption patterns by incorporating water valuation into integrated water resources management and transforming food systems. Global statistics point that about 330 km^3 of urban wastewater, 660 km^3 of industrial wastewater (including that from cooling towers), and about 1260 km^3 of agricultural drainage effluent are annually discharged untreated into the environment. This, in turn, affects about 29 hectares of irrigated farmland (Drechsel et al., 2023).

2.9 Methodology for analysing Water Samples

DNA extraction from any sample is generally performed using an appropriate kit accompanied by the manufacturer's protocol to achieve the desired results. The kits that are used for DNA extraction from water samples do not all operate the same, nor do they meet all the requirements for sequencing. The PowerWater DNA isolation kit by Qiagen is of great preference because it incorporates reagents that are very important for the removal of inhibitors that may interfere with downstream PCR and DNA sequencing reactions (Hamner, et al., 2019). Furthermore, the use of an appropriate filter is vital in the methodology, depending on the turbidity of the water. It is recommended that for highly turbid water, 0.45 µm filters be used to collect the particulates. This is essential to reduce the possibility of clogging and hence allow a greater amount of water that would be filtered than would be possible with the most restrictive 0.22µm filters. The problem, however, with the 0.45µm filters is that this may reduce the variety of microorganisms that would be detected, since during the initial step of filtering, smaller microorganisms would be lost through the larger 0.45µm pores, whereas if clogging was allowed, many small cells would have been captured (Hamner et al., 2019). Therefore, under normal circumstances, the use of 0.22µm filters is strongly recommended to ensure maximum capturing of the microorganisms.

2.10 Microbial Water Quality Profiles

The World Health Organisation (WHO) (2015) reported that foodborne diseases cause about 600 million sicknesses per annum, resulting in 420,000 deaths globally. In the United States of America, the foodborne diseases were reported by WHO (2015) to cause 48 million illnesses, with 128,000 hospitalisations and an annual death toll of 3000. At the heart of all these maladies,

produce such vegetables, herbs, vegetable row crops, and fruits caused about 28% of the foodborne illnesses in the United States from 2009 to 2015, constituting the highest cause of foodborne illnesses.

Foodborne diseases cause approximately 600 million illnesses per year, leading to 420,000 deaths worldwide (World Health Organisation, 2015; Scallan et al., 2011). Within the United States, foodborne diseases cause 48 million illnesses, 128,000 hospitalisations, and 3000 deaths annually (World Health Organisation, 2015; Scallan et al., 2011). Produce (including seeded vegetables, herbs, vegetable row crops, and fruits) caused the most foodborne illnesses (28%), followed by chicken (12%) and pork (10%) in the U.S. from 2009 to 2015 (Gerdes et al., 2022). The United States Congress of 2011 passed the Food Safety Modernisation Act (FSMA) with the aim of improving food safety in the United States by means of identifying the sources of possible contamination that may occur in the food chain and in the farm environment. A key source of contamination on the farm is water, which is used for several purposes such as irrigation, cooling, and pesticide application. The FSMA addressed the necessity to assess irrigation water sources through the Produce Safety Rule (PSR) agricultural water standards. The farmers falling under the Produce Safety Rule are required to generate a Microbial Water Quality Profile (MWQP) by calculating the Geometric Mean (GM), which is typically a type of average, and Statistical Threshold Value (STV) (a measure of variation) of the generic *Escherichia coli*, which is a widely used indicator of faecal contamination. On this account, any water source that will be used for irrigation and in one way or the other comes into contact with the fresh produce that is generally consumed raw has to meet the standard of the Geometric Mean and Statistical Threshold value for *Escherichia coli* (Gerdes et al., 2022).

The MWQP is constructed by first calculating the GM by summing the log-transformed *E. coli* counts from each water source (measured in CFU/100 ml), then dividing by the number of samples for that site (Gerdes et al., 2022). Thereafter, convert the log-transformed GM to the regular scale by taking the antilog to calculate the GM. Next, the STV is calculated using the formula:

*log(STV) = (log-transformed GM) +1.282*std (log values)*

The GM and STV are calculated for each site using all samples, considering that the PSR requires that an MWQP must be constructed using at least 20 data points (Gerdes et al., 2022).

2.11 Grootfontein-Tsumeb-Otavi Maize Triangle

The maize triangle of Namibia is made up of three neighbouring municipalities, namely Grootfontein, Otavi, and Tsumeb. Their geographical locations set these municipalities in a triangle. However, the gist of the name comes from the maize production that had been predominant in these municipalities, and formerly, this maize triangle was the breadbasket of Namibia before the advent of the agricultural schemes that are spread across the country.

The Grootfontein-Tsumeb-Otavi Maize Triangle (GTOMT) is opportune to sit on the karst aquifers, which supply it with irrigation water. The presence of the karst aquifers is regarded as an area with high water potential (Ihemba and Esterhuyse, 2020). The karst has carbonate rocks that hold large quantities of groundwater resources. The large groundwater supply capacity of the karst aquifers can be attributed to the high precipitation in this area, about 500mm, associated with the good groundwater storage capacity of the karst aquifers.

Furthermore, the thin soil cover and high porosity and permeability of the dolomite and limestone that characterise the karst aquifers enable rapid infiltration of rainfall and its storage as groundwater. This abundant water places the commonly known Maize Triangle (GTOMT) at a vantage point marked with agricultural and horticultural activities such as irrigation and livestock farming. The Karst aquifers are characterised further to have the presence of the sediments of the Nosib Group and the visible impervious basement rocks along the E-W trending Nosib Anticline, formed by a hydraulic barrier in the N-S direction that separates the Karst aquifers into a northern portion, which are called the Tsumeb Aquifers, and the southern portion, called the Grootfontein-Otavi Aquifers. The aquifers are collectively segmented into eight sub-regions, indicated in **Figure 2-5** and in terms of sustainable yield with respect to

quantities for safe use, each sub-region has a recommended environmentally safe yield (Ihemba and Esterhuyse, 2020).

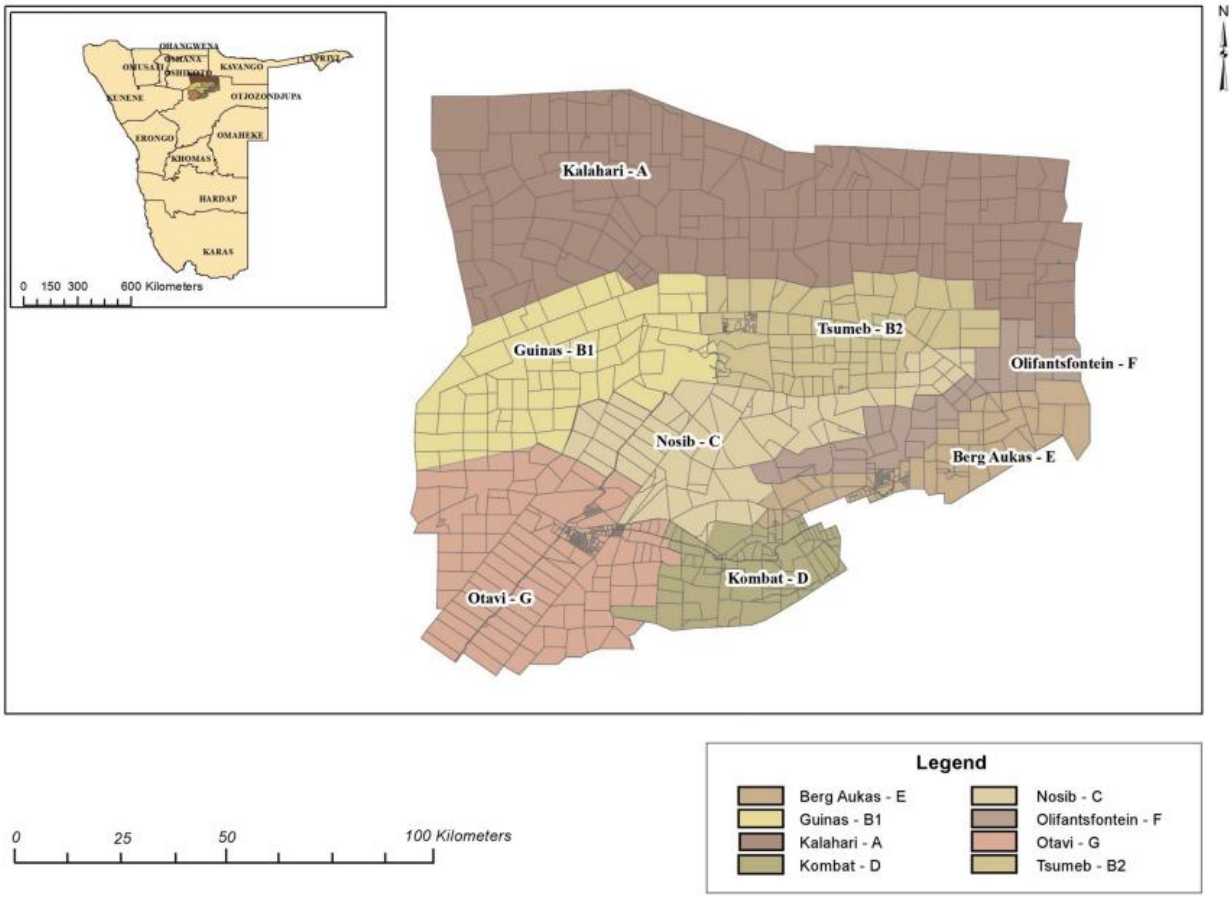


Figure 2-5. Grootfontein-Tsumeb-Otavi Karst Aquifers (*Ihemba and Esterhuyse, 2020*)

2.12 Agricultural Schemes in Namibia

Agricultural schemes in Namibia fall under the Green Scheme Irrigation programme. The Green Scheme is an initiative of the Government of the Republic of Namibia to increase food production through irrigation production (Shapi, 2017). The project of the Green Schemes was born to enhance irrigation possibilities along the well-known maize triangle area Grootfontein-Tsumeb and Otavi (in the Otjozondjupa and Oshikoto regions), and the North Central and Northeastern regions that have the advantage of riparian rivers of the Kunene, Kavango, and Zambezi. Furthermore, the Green Scheme Project includes agricultural activities that make use of the Orange River, far in the south of Namibia, and in Hardap.

The Green Scheme has socio-economic impetus that aims at advancing the resources of the government and supportive stakeholders in pursuit of increasing agricultural productivity and social development as envisaged by key economic drivers of Namibia, namely the National

Development Plan 4 (NDP4), Harambee Prosperity Plan (which is a Presidential initiative geared towards poverty eradication), and the Vision 2030 strategy.

Currently, there are eleven (11) Green Schemes across Namibia (table 1), which excludes the irrigation farmers of the Karst areas of Grootfontein-Tsumeb and Otavi. The Green Schemes vary in scope, focus, and area size. The sizes of their area range from 150 hectares to 1263 hectares at the Mashare Irrigation Green Scheme and Etunda Irrigation Green Scheme, respectively. All these schemes occupy a cumulative area of about 7641.6 hectares, of which 4282.6 hectares (56%) is under production. The farms produce a variety of crops such as cereals, vegetables, and fruits.

Table 2-1. Various Green Schemes and their size in hectares

Green Schemes	Area Production (ha)	Area under Commercial farming (ha)	Area under Medium farmers (ha)	Area under small farmers (ha)	Orchard area	Area not under production (ha)	Total area (ha)
Etunda	963	483	120	300	60	300	1263
Hardap	154.6	60	94.6				154.6
Kalimbeza	150	141		9		79	229
Mashare	150	150					150
Musese	450	450				550	1000
Ndonga Linena	580	421		160		419	1000
Orange River	195	125		70		405	600
Shadikongoro	390	300		90		200	590
Sikondo	590	320	270			240	830
Shitemo	420	420				580	1000
Vhungu-vhungu	240	180		60		585	825
SUM	**4282.6**	**3050**	**484.6**	**689**	**60**	**3358**	**7641.6**

Source: (Shapi, 2017)

2.12.1 Etunda Green Scheme Irrigation Project

The Etunda project is so far the largest farm of the Green Scheme Irrigation Projects in terms of size of land and volume of production. The project is situated 45km west of Outapi in northern Namibia, 17°28’40” S and 14°32’10” E, and while the total farmland earmarked for production is 1200 hectares, currently only 900 hectares are under production. Etunda is divided into two (2) segments of 450 hectares each for small-scale and commercial farming. Sixty-seven (67) small-scale farmers occupying three (3) hectares each and ten (10) medium-scale farmers, totaling seventy-seven (77) small and medium-scale producers that utilize the project (AGRIBUSDEV, 2015).

2.12.2 Hardap Green Scheme Irrigation Project

The Hardap Green Scheme Irrigation Project is situated 10km before Mariental in southern Namibia, along the B1 highway, 24°33’0” S and 17°55’59” E. The project covers an area of about 96.5 hectares, of which 73 hectares are under production. Fourteen (14) medium-scale farmers are registered with the Hardap project, and each farmer has six (6) hectares assigned for production. Commercial production covers 12.5 hectares of the project (AGRIBUSDEV, 2015).

2.12.3 Kalimbeza Green Scheme Irrigation Project

The Kalimbeza Green Scheme Irrigation Project is situated 56km north-east of Katima Mulilo in the Zambezi Region, 17°32'38.472" S and 24°31'26.688" E. The total farmland is 229 hectares, of which only 144 hectares are irrigated. Five (5) small-scale farmers occupying three (3) hectares each were placed on the project, while 114 hectares are used for commercial farming. The Kalimbeza project produces three (3) varieties of rice, and a smaller section of the farm is used for scientific trials of rice crops with the intention to expand to larger-scale production based upon growth and performance (AGRIBUSDEV, 2015).

2.12.4 Mashare Green Scheme Irrigation Project

The Mashare Green Scheme Irrigation Project is situated 50km east of Rundu in Kavango West, 17°53'46.284" and 20°11'10.643". The project covers an area of about 130 hectares, of which 127 hectares are irrigated and are under production. The project has been earmarked to expand with an additional 300 hectares. At present, there is no provision made for small or medium-scale farmers on the project because the entire farm is confined to commercial production. There have been plans to accommodate medium-scale farmers in the future, once the additional 300 hectares are available and completed (AGRIBUSDEV, 2015).

2.12.5 Musese Green Scheme Irrigation Project

The Musese Green Scheme Irrigation Project is located 85km west of Rundu in Kavango West, at about 17°50'10.068" S and 19°0'28.079" E. The total farmland has an area of about 1000 hectares, of which only 450 hectares are utilised for commercial production (AGRIBUSDEV, 2015).

2.12.6 Ndonga Linena Green Scheme Irrigation Project

The Ndonga Linena Green Scheme Irrigation Project is located 75km east of Rundu in Kavango West, 17°55'31.908" S and 20°28'41.232" E. The farm occupies a total land area of 1000 hectares, of which 506 hectares are under commercial and small-scale production. A total of 332 hectares are utilised by commercial farming, and 174 hectares are under small-scale farming. Twenty-nine (29) small-scale farmers are part of the project, each occupying 6 hectares (AGRIBUSDEV, 2015).

2.12.7 Shadikongoro Green Scheme Irrigation Project

The Shadikongoro Green Scheme Irrigation Project is located about 180km east of Rundu in Kavango East, 18°1'27.084" S and 21°23'19.823" E. The farmland covers an area of 590 hectares, of which 300 hectares are used for commercial farming and 90 hectares are occupied by small-scale farmers. Fourteen (14) small-scale farmers are part of the project, of which 12 have 6 hectares each and 2 have 9 hectares each (AGRIBUSDEV, 2015).

2.12.8 Shitemo Green Scheme Irrigation Project

The Shitemo Green Scheme Irrigation Project is located about 80km east of Rundu in Kavango East region, 17°59'19.392" S and 20°31'38.928" E. The farmland covers an area of about 1000 hectares, of which only 420 hectares are fitted with irrigation infrastructure. The farm is utilised for commercial farming by AGRI-PRO Namibia (Pty) Ltd, (AGRIBUSDEV, 2015).

2.12.9 Sikondo Green Scheme Irrigation Project

The Sikondo Green Scheme Irrigation Project is located about 10 km west of Rundu in the Kavango West region, 17°53'12.48" S and 19°39'25.919" E. The farmland covers a total area of about 850 hectares, of which 580 hectares are used for commercial farming, and 270 hectares are used for medium-scale farming. Nine (9) medium-scale farmers occupy 30 hectares each (AGRIBUSDEV, 2015). There are 11 pivots for commercial farming, and 9 pivots for medium-scale farming. The sizes of the pivots vary, with each covering approximately 20 to 30ha. During winter, the project grows mainly wheat, with an average production of about 70 tons. While in summer, maize, tomatoes, potatoes, butternuts, and green peppers are grown. The annual irrigation water usage is approximately 287,532 m^3.

2.12.10 Orange River Green Scheme Irrigation Project

The Orange River Green Scheme Irrigation Project, which is also known as the Orange River Irrigation Project (ORIP), is located on the extreme southern border of Namibia in Noordoewer in the //Karas Region. It was significantly established by the government of Namibia as an agricultural development initiative, taking advantage of the Orange River's water resources to supply irrigation water for various crops such as dates, vegetables, and table grapes. The farm covers a total land area of 600 hectares, of which 232 hectares are under production. The farm is divided into commercial and small-scale farming areas, of which the largest section of 152 hectares is under commercial production. Small-scale farming covers 80 hectares. The Orange River is the primary source of water for irrigation (AGRIBUSDEV, 2015).

2.12.11 Uvhungu-vhungu Green Scheme Irrigation Project

The Uvhungu-vhungu Green Scheme Irrigation Project is located about 10km east of Rundu in Kavango East region, 17°53'30.3'' S and 19°49'39.431" E. The farmland has a total area of 825 hectares, of which only 380 hectares are under full production. Commercial farming occupies an area of about 320 hectares, whereas 60 hectares are occupied by ten (10) small-scale farmers (AGRIBUSDEV, 2015).

2.13 Exploring Microbial Diversity and Its Applications Using 16S rRNA Sequencing

The 16S rRNA is a ribosomal region used to identify and classify bacteria based on the amplicon. This method takes advantage of the highly conserved 16S ribosomal RNA (rRNA) gene that is found in all prokaryotes, which contain variable regions that distinguish between the species. The technique of identifying bacteria through the 16S rRNA was initiated by Carl Woese and George E Fox in 1977 (Zhulin, 2016).

Traditionally, the culture-based methods for species identification in bulk samples are labour-intensive and time-consuming, and often detect a relatively small portion of the microbial species. However, the adoption of the 16S rRNA as a marker for the identification of organisms in combination with the advances of Next Generation Sequencing (NGS) techniques has enabled the rapid and efficient analysis of numerous samples. This approach has led to the identification of many sequences from previously species that could not be cultured.

2.13.1 16S rRNA Gene Sequence

In description, the 16S rRNA gene sequence is the most widely used genetic marker for investigating bacterial taxonomy and phylogeny (Case et al., 2007). Ribosomes are essential cellular structures involved in protein synthesis, consisting of two subunits composed of proteins and ribosomal RNA (rRNA). The rRNA plays a significant role in translating the information encoded in messenger RNA (mRNA) into proteins.

In prokaryotes, ribosomes are made up of a 30S subunit and a 50S subunit, which together form a complete 70S ribosome. The word "S" stands for the "Svedberg" unit, a measure of the sedimentation rate. The 30S subunit specifically contains 16S rRNA and 21 proteins. The 16S rRNA gene, approximately 1500 base pairs in length, features variable regions interspersed between conserved regions. The conserved regions are crucial for the universal amplification of

the gene, while the variable regions are instrumental in distinguishing specific microorganisms. These variables are particularly valuable for the identification and classification of bacteria. Furthermore, the conserved regions of the 16S rRNA gene exhibit similarity across various bacterial species, making them the ideal targets for universal primers that can amplify the gene from a wide range of bacteria.

The variable regions of the 16S rRNA show sequence diversity among different species, allowing the differentiation and identification of bacteria within diverse microbial environments. The aforementioned regions are thus utilised for the phylogenetic classification of the distinct microbial populations. The 16S rRNA gene contains nine hypervariable regions, which are known as V1 through V9.

2.13.2 The Principle of the 16S rRNA Gene Sequencing

The 16S rRNA employs the principles of targeting a specific region of the genome for amplicon sequencing. Hence, utilising the genetic information encoded in the 16S rRNA gene to identify and classify microorganisms in the domains of archaea and bacteria. The 16S rRNA gene serves as a reliable marker for the identification of these microbes, as it is universally present and highly conserved in these domains. The process of 16S rRNA gene sequencing includes several important steps, namely, DNA extraction, PCR amplification of the 16S rRNA gene, Sequencing, and Bioinformatics analysis (Case et al., 2007; Janda and Abbott, 2007; D'Amore et al., 2016; Rizal et al., 2020; Pichler et al., 2018; Sanschagrin and Yergeau, 2014).

(a) Sample collection

The initial step is that of the collection of a microbial sample from the environment of interest, which can include sources such as water, soil, or biological samples like the human gut microbiome. Different approaches are utilised for collecting different types of samples, and it is critical to note that the collection, handling, and processing of the samples be conducted in manners that minimises the risk of contamination. A pretreatment method may need to be employed to remove contaminants before the isolation of DNA. These may include the use of heat, enzymes, or physical techniques.

(b) DNA extraction

After sample collection, the DNA is extracted using various extraction methods that include several chemical and physical approaches to isolate the DNA from the samples. During this process, physical distortion methods such as sonication, chemical lysis with detergents and enzymes, and purification steps are used to ensure that the DNA is free from impurities and for further analysis.

(c) PCR and Library Construction

This step prepares the DNA for sequencing. The first part of this step involves amplifying the 16S rRNA gene using the polymerase chain reaction (PCR). This step is essential to optimise the PCR conditions and select appropriate primers to avoid non-specific amplification and achieve accurate results. Subsequent amplification, the DNA is processed to create a library for sequencing. This process will involve the fragmentation of the amplified DNA into shorter segments and thereby attaching the adaptors to these fragments. The library is then purified to remove any excess adaptors and primers, ensuring that the DNA fragments are of uniform size for efficient sequencing.

(d) Sequencing

The prepared library is then subject to high-throughput sequencing platforms such as Illumina, Ion Torrent, Oxford Nanopore, or PacBio. During this step, the DNA libraries are amplified and sequenced to generate short DNA sequences in millions simultaneously. The resultant raw sequencing data is undertaken through the process of quality control and then bioinformatics analyses to classify and identify the microbial communities present in the sample(s) under consideration.

(e) Data Analysis

The last step after DNA sequencing is that of data analysis. The sequencing data is processed using various bioinformatics tools to interpret the results. This process includes several steps, such as trimming the reads to ensure quality removal of sequences that do not belong to the targeted domain and then clustering the reads into Operational Taxonomic Units (OTUs), and, lastly, through alignment with a reference database, the taxonomic identities are assigned to the Operational Taxonomic Units.

Tools such as QIIME, MOTHUR, and USEARCH-UPSARSE have been commonly utilised for the task of data analysis, with valuable tutorials and interfaces that are user-friendly (Prodan et a., 2020). The resultant sequences are matched to databases and are applied to appropriate statistical approaches, thereby uncovering the patterns and relationships between different samples.

(f) The Advantages of the 16S rRNA Gene Sequencing

The 16S rRNA gene is conserved across the bacteria and archaea domains, and still contains adequate sequence variations to differentiate between species. This property makes it an excellent and effective means for identifying and comparing microbial communities from samples of interest. Furthermore, in contrast to the traditional culture-based methods, the 16S

rRNA gene sequencing approach offers a direct investigation of the microbial communities from a variety of samples, which includes those with innumerable microorganisms. In addition, the use of high-throughput sequencing technologies facilitates the simultaneous sequencing of thousands of 16S rRNA gene fragments and thereby enables the large-scale analysis of microbial communities. Lastly, though not exhaustive, unlike the traditional laboratory culture techniques that depend on phenotypic characteristics and biochemical reactions, which may be subjective and susceptible (prone) to contamination, the 16S rRNA gene sequencing protocols inculcate aspects of serious quality control measures and validation of the bioinformatic pipelines to ensure that the results are accurate and reliable.

(g) Limitations of the 16S rRNA Gene Sequencing

It is, however, significant to point out that the 16S rRNA gene can be utilised to distinguish bacteria up to certain taxonomic levels. The bacterial species that are closely related often exhibit high sequence similarity in the 16S rRNA genes and thus make it challenging to differentiate them with precision, and therefore, the method often falls short in accurately resolving microbial differences at the species taxa. Moreover, the high sequence similarity in the 16S rRNA gene does not always produce precise and specific identification. It is also considered that processing and analysing the complex sequence data that is generated by the 16S rRNA gene sequencing analysis method would require specialised bioinformatics tools and expertise. Furthermore, the 16S rRNA gene sequencing generally offers lower taxonomical resolution in comparison to the shotgun sequencing method. Lastly, since the 16S RNA gene sequencing targets only a single gene, it has limitations in identifying the functional roles of the microbial communities (Rizal et al., 2020.

2.14 Conceptual Framework

The conceptual framework that links the agricultural schemes to the water sources with the eventual impacts is shown in Figure **2-6** below.

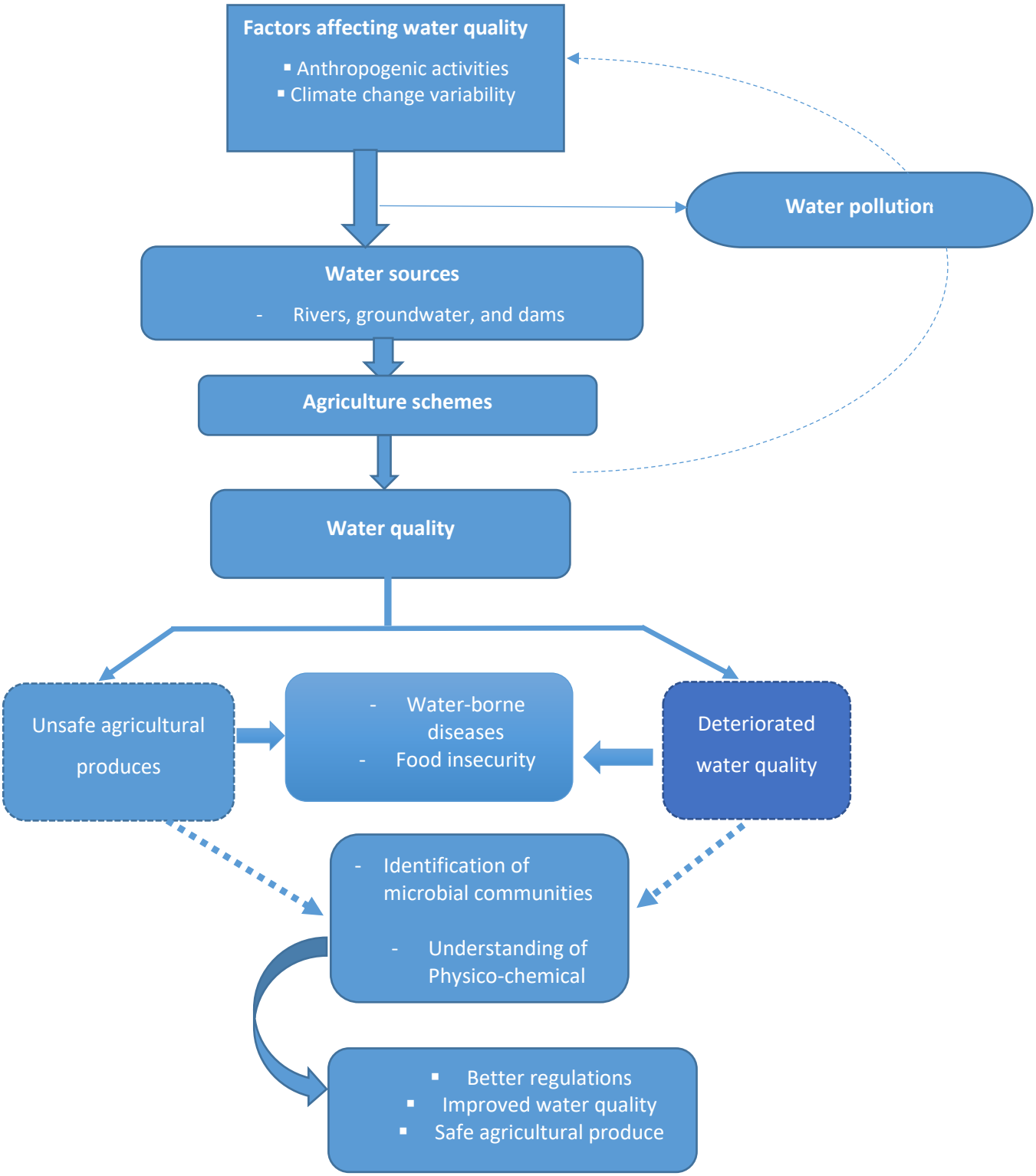


Figure 2-6. Conceptual Framework

Chapter 3: Methodology

3.1 Study Area

The general and specific study area (**Error! Reference source not found.** and **Figure 3-2**) consists of four of the eleven irrigation schemes in Namibia, and the Otavi-Tsumeb-Grootfontein (maize triangle).

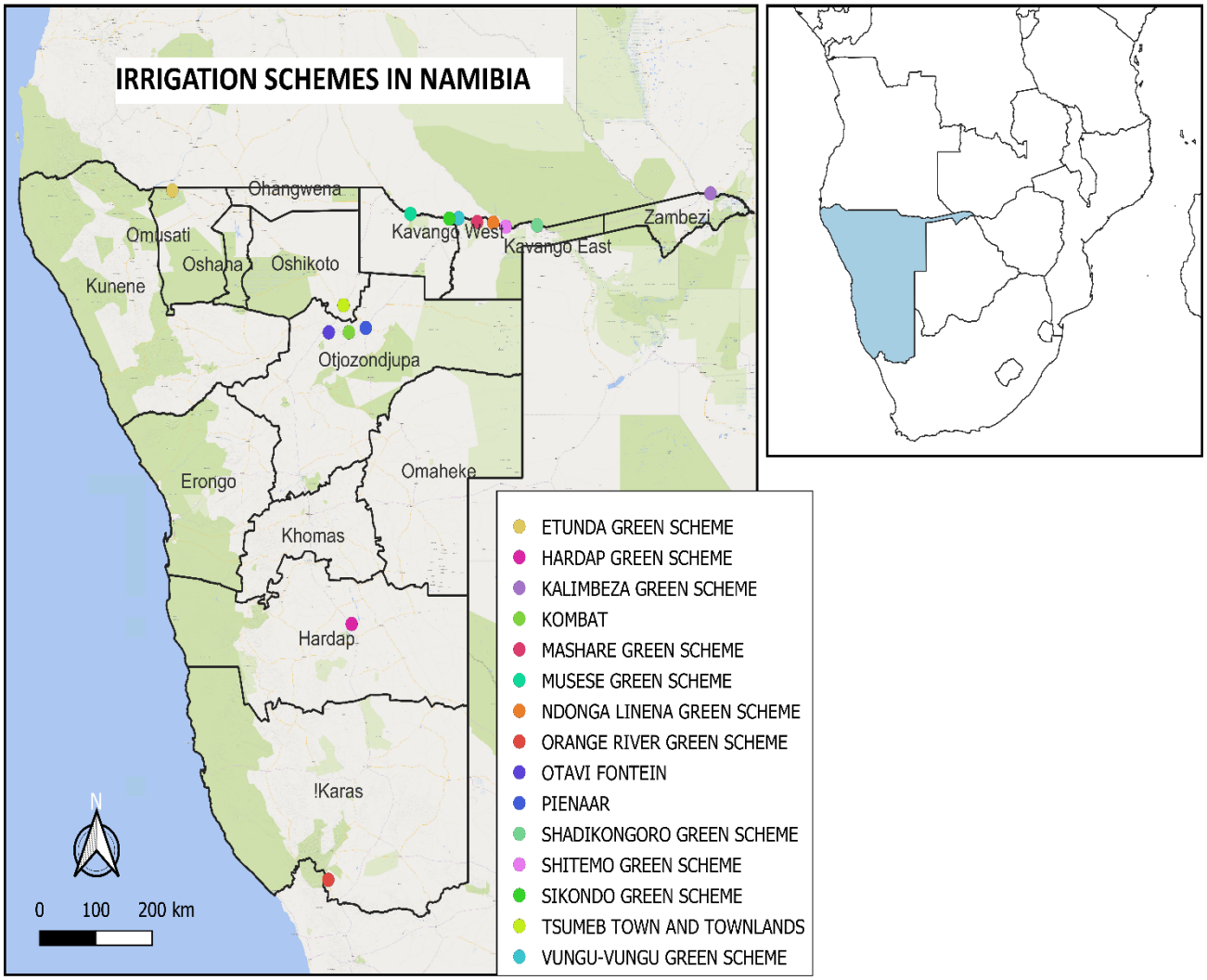


Figure 3-1. Map of the study area and selected study points

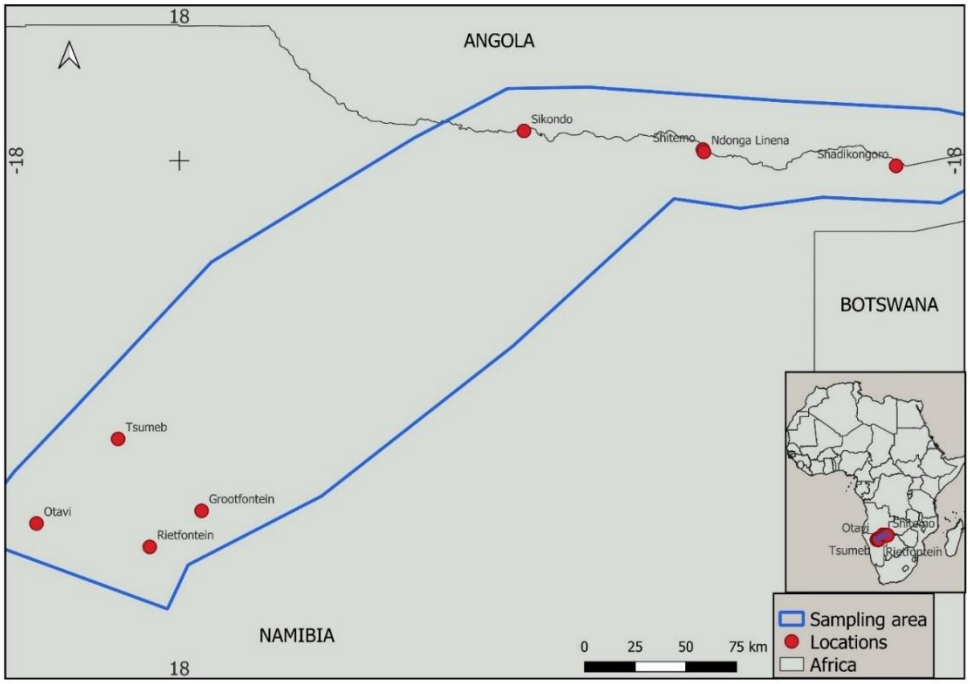


Figure 3-2. The map of the sampling locations

3.2 Sampling

Namibia has 11 green schemes that are pivotal to sustainable development and food security. The water supply to the green schemes is sourced from rivers and dams. From the 11 Green Schemes in Namibia, water and sediment samples were purposefully taken from the Shadikongoro, Sikondo, Ndonga Linena, and Shitemo irrigation green scheme projects. The fifth to seventh points were the Otavi, Tsumeb, and Grootfontein (known as “The Maize Triangle” of Namibia), which gave a total of seven (7) main sampling locations.

This was a quantitative research project that involved extensive sampling, laboratory (experimentation), and data analyses. Samples were collected during the dry season and the wet season.

3.3 Methods as determined for the specific objectives

3.3.1 Evaluation of the physicochemical characteristics of the water used for irrigation of horticultural crops with the application of irrigation water quality indices

Sampling and Analyses

Irrigation water samples were collected during the dry season (September 2023). Thirty (30) water samples were collected from surface and groundwater sources used for irrigation during the dry season, and thirty-two (32) during the wet season. Each of the seven locations had sampling points. The water samples were collected in clean and pre-cleaned plastic bottles. The sampling bottles were initially rinsed with water to be sampled several times, and tightly closed to prevent contamination. The samples were clearly labelled. The parameters that were measured *in-situ* using a multiparameter include: pH, temperature, total dissolved solids (TDS), and electrical conductivity (EC). The collected water samples were analysed for chemical parameters using appropriate equipment and techniques. The anions were analysed at a commercial laboratory, while the cations were analysed at the Namibia University of Science and Technology (NUST) using the ICP-OES.

Application of Water Quality Indices (WQIs)

The suitability of the surface and groundwater for irrigation was determined following the referenced Water Quality Indices, namely the sodium adsorption ratio (SAR), sodium percentage (Na%), potential salinity (PS), permeability index (PI), Kelly's index (KI) also known as the Kelly's ratio, the magnesium adsorption ratio (MAR) and the residual sodium carbonate (RSC) values, with respect to the measured water quality parameters. These water quality indices, among others, do offer a much more comprehensive understanding of the quality of the surface and groundwater for irrigation purposes. This would actually provide a rating that reflects the collective influence of the various water quality parameters.

(a) The Sodium Adsorption Ratio (SAR)

It is understood that water used for agricultural purposes with a high concentration of sodium influences the growth of crops (Alogayell et al., 2023; Shuai et al., 2021) and thus on yield. When the sodium concentrations in the soil increase as a result of raising salt levels in the irrigation water, it affects the soil permeability, causing infiltration problems. Furthermore, the soil may probably spread out and cause cultivation challenges. Therefore, the assessment of the sodium hazard is relevant in the pursuit of achieving food security by minimizing the loss and maximizing

the gains. The Sodium Adsorption Ratio (SAR) is one of the key indicators used to assess the sodium hazards in irrigation water. The SAR is calculated by (Elsayed et al., 2020):

$$\mathrm{SAR} = \frac{\mathrm{Na^+}}{\sqrt{\frac{\mathrm{Ca^{2+}+Mg^{2+}}}{2}}} \times 100 \quad (1)$$

(All the concentrations of ions are expressed in milliequivalent per liter (meq/l))

This indicator is valuable to classify the water's appropriateness for irrigation purposes.

(b) Sodium Percentage (Na%)

The sodium percentage (Na%) is another indicator of the sodium hazard, which, like the SAR, is an index that is significant when classifying the water for its suitability for irrigation purposes. Water with high contents of sodium is not appropriate for irrigation because it produces undesirable effects whereby sodium, relative to calcium and magnesium, reacts with the soil and thereby reduces the permeability of the latter, consequently supporting little or no plant growth (Emmu and Nwakwaola, 2018; Elsayed et al., 2020). This poses a threat to food security. Thus, the assessment of Na% is important for managing the supply of water for irrigation purposes to protect soils from losing their permeability properties and preventing retardation in plant yields.

The Na% is calculated by:

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

(All the concentrations of ions are expressed in milliequivalent per liter (meq/l))

(c) The Permeability Index (PI)

The permeability index (PI) is a suitable indicator in the assessment of water for its suitability for irrigation purposes. The long-term use of irrigation water affects the permeability of the soil. This parameter is valuable in that the movement of water in the soil is governed by the long-term use of irrigation water that has high contents of salts affected by ions of the soil, particularly Na+, Ca^{2+}, HCO_3^- and Mg^{2+} ions (Rawat et al., 2018). The formula that was developed to assess the capacity of water movement in the soil as the appropriateness of any kind of water source for irrigation, is:

$$\mathrm{PI} = \frac{\mathrm{Na^+ + \sqrt{HCO_3^-}}}{\mathrm{Ca^{2+} + Mg^{2+} + Na^+}} \times 100 \quad (3)$$

(All the concentrations of ions are expressed in milliequivalent per liter (meq/l))

The permeability index is classified into three categories: category I (>75%, suitable), category II (25-75%, good), and category III (<25%, unsuitable) (Rawat et al., 2018). The water under categories I and II is recommended for irrigation. Whereas water in category I may require treatment before being used for irrigation purposes.

(d) The Kelly's Index (KI)

The Kelly's Index (KI), also known as the Kelly's Ratio (KR), was introduced by W P Kelly and K V Paliwal (Rawat et al., 2018), an indicator to evaluate the quality and classification of water for irrigation based on the concentration of Na+ versus Ca^{2+} and Mg^{2+}.

The KI is calculated by:

$$\mathrm{KI} = \frac{\mathrm{Na}^{+}}{\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}} \quad (4)$$

(All the concentrations of ions are expressed in milliequivalent per liter (meq/l))

When the Kelly's Index is greater than 1, it is an indication of an excessive level of Na^{+} in the waters. By implication, water with a KI ≤ 1 is recommended for irrigation purposes, while water with a KI value that is ≥ 1 is not recommended for irrigation purposes because of the alkali hazard (Rawat et al., 2018).

(e) The Magnesium Adsorption Ratio (MAR)

The magnesium adsorption ratio (MAR) is also known as the magnesium hazard. It is a hazard indeed, as it brings in Mg^{2+} and Ca^{2+} ions (alkaline earths), which are connected to the friability and aggregation of the soil, although these ions are both important nutrients for the crop. When the Mg^{2+} and Ca^{2+} concentrations in the water are high, the pH of the soil can increase, thus converting it into an alkaline state. This will result in the decline of the availability of phosphorus (Rawat et al., 2018). Furthermore, the conversion of the soil into an alkaline state because of excessive magnesium concentration will adversely affect the yield of crops. The magnesium adsorption ratio is calculated by:

$$\mathrm{MAR} = \frac{\mathrm{Mg}^{2+}}{\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}} \times 100 \quad (5)$$

(All the concentrations of ions are expressed in milliequivalent per liter (meq/l))

In terms of analyses, water with MAR > 50 is not recommended for purposes of irrigation (Rawat et al., 2018).

(f) The Potential Salinity (PS)

The concentrations of soluble salts in water have no control over its appropriateness for irrigation purposes (Emmu and Nwakwaola, 2018). The understanding is that low-soluble salts precipitate in the soil and accumulate with successive irrigation. Contrary, the concentrations of highly soluble salts increase the salinity of the soil. The potential salinity (PS) that is less than 3 meq/l gives an indication of water that is suitable for irrigation purposes. The PS is calculated by:

$$PS = Cl^{-} + 0.5 \times SO_4^{2-} \quad (6)$$

(All the concentrations of ions are expressed in milliequivalent per liter (meq/l))

(g) Residual Sodium Carbonate (RSC)

The Residual Sodium Carbonate brings in the effects of carbonate (sodium carbonate) and bicarbonate (sodium bicarbonate) on the suitability of the water for irrigation purposes. RSC is the collective representation of the amount of sodium carbonate and sodium bicarbonate that is present in the irrigation water. The concentrations of CO_3^{2-} and HCO_3^{-} ions in the irrigation water affect its suitability. When the concentrations of these ions exceed those of Ca^{2+} and Mg^{2+}, the latter ions precipitate (Elsayed et al., 2020). The precipitation of Mg^{2+} and Ca^{2+} in the soil impairs its structural properties and possibility activate the soil's sodium. This will further aggravate the sodium hazard. Furthermore, water that has a high Residual Sodium Carbonate has a high pH, and therefore, soils that are irrigated with such water lose fertility because of the deposition of sodium carbonate.

Residual Sodium Carbonate is expressed in milliequivalents per liter (meq/l) of Sodium Carbonate ($NaCO_3$). RSC is calculated by:

$$RSC = (HCO_3^{-} + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \quad (7)$$

(All the concentrations of ions are expressed in milliequivalent per liter (meq/l))

(h) The United States' Salination Laboratory (USSL) and Wilcox Diagrams

To further assess the water sources for their suitability for irrigation purposes, more analyses were undertaken by plotting the analytical data on USSL and Wilcox diagrams. Electrical conductivity and the Sodium Adsorption Ratio are represented on the USSL diagram. The USSL diagram gives four levels of water quality: low, medium, high, and very high. Whereas the Wilcox diagram shows the electrical conductivity and sodium percentage. The Wilcox diagram classifies the water quality into five categories: excellent to good, good to permissible, permissible to doubtful, doubtful to unsuitable, and unsuitable. (Alsubih et al., 2022). The diagrams software was used to generate the diagrams.

3.3.2 Profiling of bacterial community composition and potential food safety risks in irrigation water sources used for fresh produce in Namibia

Water and Sediment Sampling

At each site, duplicate water samples were collected in bottles, 10-15 cm below the water surface to minimise contamination and maximise recovery of waterborne microorganisms. Parallel sediment samples were collected to evaluate soil and benthic microbial communities influencing water quality and transported to the Microbiology Laboratory at the Namibia University of Science and Technology (NUST) for processing.

Sample preparation and filtration

Water samples were subjected to sequential vacuum filtration to concentrate microbial biomass. The filtration process was performed using the Millipore All-Glass Filter Holder Kit (EMD Millipore Corporation, Billerica, MA, USA). Initially, the water samples were passed through a Whatman filter paper to remove coarse debris. This was followed by filtration through an 8 µm sterile mixed cellulose ester (MCE) membrane (Merck Millipore Ltd., Ireland), and subsequently through a 0.22 µm sterile MCE membrane filter to capture bacteria. Filters were stored at −80°C until DNA extraction.

DNA extraction

Genomic DNA was extracted from both water filters and sediment samples using the ZymoBIOMICS DNA MiniPrep Kit (Zymo Research, USA), following the manufacturer's recommended protocol. The kit is optimised for high-efficiency lysis and purification of microbial DNA from complex matrices such as soil and water. Elution was performed using RNase-free water, and DNA concentration and purity were assessed using the Qubit 4 Fluorometer and the Qubit dsDNA HS Assay Kit (Thermo Fisher Scientific, USA). DNA replicates from each sample type were pooled to ensure representativeness and stored at −80°C for downstream analyses.

Gene library preparation and PacBio sequencing

The bacterial 16S rRNA gene was amplified using barcoded universal primers 27F (5'-AGAGTTTGATCMTGGCTCAG-3') and 1492R (5'-TACGGYTACCTTGTTACGACTT-3'), targeting conserved regions flanking the V1-V9 hypervariable segments. For high-throughput multiplex sequencing, 12 uniquely barcoded 27F forward primers and 8 barcoded 1492R reverse primers were used in the PCR strategy. Post-amplification, amplicons were quantified using a Qubit 4.0 Fluorometer with the dsDNA HS Assay kit, pooled in equimolar concentrations, and purified with AMPure PB magnetic beads (Pacific Biosciences) to eliminate primer dimers and contaminants.

The purified amplicon pool was converted into a SMRTbell library utilizing the PacBio SMRTbell Express Template Prep Kit 2.0, adhering to the manufacturer's protocol from pooling to cleanup. Library quality control was conducted using the Agilent 5200 Fragment Analyzer with the HS NGS Fragment Kit (1-6000 bp) to verify insert size distribution and assess adapter contamination. Final library quantification was performed using the Qubit dsDNA HS Assay for optimal sequencing loading concentrations. Following PacBio's SMRT Link v13.1 guidelines, library annealing and polymerase binding reactions were executed to prepare the sequencing template. The prepared library was loaded onto the PacBio Revio sequencing platform with SMRT Cell 25M chips, generating high-fidelity (HiFi) circular consensus sequences (CCS) with >99% single-molecule accuracy through multiple passes. The Revio system's long-read capability enabled full-length 16S rRNA gene coverage (~1,500 bp), providing superior taxonomic resolution by capturing all nine hypervariable regions in a single read. This approach facilitated precise microbial classification at the species level and enhanced the detection of rare taxa within the complex irrigation water and sediment microbiomes studied.

Bioinformatics and sequence data processing

Raw sequencing reads were processed using QIIME2 (version 2024.10) following established workflows for amplicon sequence analysis (Bolyen et al., 2019). Initial quality control was performed by generating summary visualisations of the demultiplexed reads using the demux summarise command. Sequence data were then quality-filtered based on Phred quality scores (Q≥30) using QIIME2's quality-filter q-score function to remove low-quality reads and truncate sequences at positions with poor quality. Amplicon sequence variants (ASVs) were inferred by dereplicating identical sequences using the vsearch dereplicate-sequences command, which produces a feature table of ASV counts and representative sequences. Taxonomic classification was performed using a pre-trained Naive Bayes classifier (Pedregosa et al., 2011) trained on the SILVA 138 16S rRNA reference database (Quast et al., 2013). Sequences were aligned using MAFFT (Katoh & Standley, 2013) to enable phylogenetic analysis. To improve taxonomic accuracy, eukaryotic, mitochondrial, and chloroplast sequences were filtered out of downstream analyses. Due to technical limitations, all bioinformatics processing was conducted on the University of the Free State's high-performance computing clusters, with resource allocation scaled appropriately for each analytical step (8–16 CPU threads, 16–128 GB RAM).

Data visualisation and statistical analysis in R

After processing the initial sequences and assigning taxonomy in QIIME2, we conducted downstream statistical analysis and visualisation in R (version 4.5.0) using a collection of

packages tailored for microbiome data interpretation. Key QIIME2 artifacts, including the feature table, taxonomic classifications, rooted phylogenetic tree, and sample metadata, were imported into R via the qiime2R package (Bisanz, 2018). These components were combined into a cohesive phylogenetic object using the phyloseq package (McMurdie and Holmes, 2013), facilitating in-depth community-level analyses. Alpha diversity metrics such as the Shannon and Simpson indices were used to evaluate within-sample diversity. For beta diversity, ordination analyses, including Principal Coordinates Analysis (PCoA) based on Bray–Curtis dissimilarity, which allowed us to compare microbial community composition among sample groups. Ordination plots were created using the ggplot2 package (Wickham, 2016). To analyze taxonomic composition, amplicon sequence variant (ASV) abundances at various taxonomic ranks (phylum, class, genus, and species) were aggregated using the tax_glom() function in phyloseq. The top 30 most abundant taxa at each rank and visualized with stacked bar plots, which provided clear comparisons of dominant microbial groups across samples.

3.3.3 Assessment of the impact of climate change on water availability and food security

Climate change to does not only affect the quality of the water but also the quantity, thereby impacting food security. To assess the impact of climate change on the water availability and its impact on food security, historical data on major food crop production of white maize, pearl millet and wheat were obtained from the Namibian Agronomic Board for the period of 2010 to 2024 for the whole of Namibia, which is actually the only available historical data. Furthermore, monthly climatic parameter data of precipitation, minimum, mean and maximum temperature, relative humidity and evapotranspiration were obtained from CHIRPS' gridded data and from the NASA Climatology Resource for Agroclimatology for the period of 1972-01-01 to 2023-12-01. The climate data that was obtained from the Namibian Weather Bureau for regions and places of interest had a lot of missing data; some weather stations are closed and therefore, could not be utilised. The data was used to investigate the Spatio-temporal trend in rainfall/precipitation using appropriate non-parametric trend analysis tests, and also relate precipitation to food production to assess the impact of climate change on food security.

3.3.3.1 Spatio-temporal trend analysis of precipitation across the study locations

Mann-Kendall Test

The Mann-Kendall technique is commonly used to detect trends in time series hydro-meteorological data. This test is accomplished by employing the formula of the test statistic (S)

devised for the data series $x_1, x_2, x_3, x_4 \ldots \text{and } x_n$, hence, the test is called the Mann-Kendall Test. The test statistic (S) was calculated with the equation:

$$S = \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} \text{sign}(y_k - y_j) \quad (8)$$

In which S is the test statistic, n is for the total number of data, and the $y_j \text{ and } y_k$ denoting the data points of the time $k \text{ and } j$.

$$\text{Sign}(x_j - x_k) = \begin{array}{rl} = +1 & if \quad y_k - y_i > 0 \\ = 0 & if \quad y_k - y_i = 0 \\ = -1 & if \quad y_k - y_i < 0 \end{array} \quad (9)$$

Moreover, the variance of S, VAR (S), is calculated with the formula:

$$VAR\ (S) = \frac{1}{18}\left\{n(n-1)(2n+5) - \sum_{j=1}^{g} t_j\ (t_j - 1)\ (2t_j + 5)\right\} \quad (10)$$

In which g denotes the tied groups' number and t_j indicates the extent of jth tied number. The tied group refers to a set of sample data that has similar values.

Furthermore, for time series data the statistics (S) is identified with Kendall's tau (τ) which is calculated by:

$$\tau = \frac{S}{B} \quad (11)$$

Whereby B is calculated by,

$$B = \sqrt{\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{j=1}^{g} t_j\ (t_j - 1)}\ \sqrt{\frac{1}{2}\ n(n-1)} \quad (12)$$

The estimation of $(S) \text{ and } VAR\ (S)$ is done as an important measure to establish a standardised test measurement Z, when $n > 10$ according to Gilbert (1987).

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & ,if \quad S > 0 \\ 0 & ,if \quad S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & ,if \quad S < 0 \end{cases} \quad (13)$$

Normally, the negative and positive values of the Z Statistic indicates decreasing and increasing trends in the time series, respectively.

Furthermore, the Mann-Kendall trend test was utilised for seasonal variations in terms of wet (November–April) and dry (May–October) seasons, and the Hirsch–Slack Test for seasonal trends.

The Modified Mann-Kendall Test (mMK)

To modify the Mann-Kendall test, the $VAR\ (S)$ Statistics is by considering the correction factor to the equation as:

$$VAR(S) = \left(\frac{n(n-1)(2n+5)}{18}\right).\left(\frac{n}{n_e^*}\right) \quad (14)$$

The $\left(\frac{n}{n_e^*}\right)$ is for the autocorrelation of the data, and it is calculated as:

$$\left(\frac{n}{n_e^*}\right) = 1 + \left(\frac{2}{n^3-3n^2+2n}\right) \sum_{f=1}^{n-1}(n-f-1)\,(n-f-2)\,\rho_e(f) \quad (15)$$

In addition, to assess variation in precipitation over time, the modified Mann-Kendall test was performed and graphically presented on annual scales (1972 – 2023) and calculated for five (5) subperiods, 1972 – 1980 (period 1), 1981 – 1990 (period 2), 1991 – 2000 (period 3), 2001 – 2010 (period 4), 2011 – 2023 (period 5). The mMK test analyses were further analysed for trend variations with respect to the Namibian Season, Summer (December – March), Autumn (March – May), Winter (June – August), Spring (September – November).

Sen's Slope Estimator

Estimating the magnitude of the rainfall is a key feature in analysing the impact of climate change on water and food security. Sen's Slope (Sen, 1968) estimator $Slope\ Q$ was utilised to assess the magnitude of the rainfall trend. The $Slope\ Q$ is calculated from N pairs of data as:

$$Q_i = \frac{x_k - x_j}{k-j}, i = 1, 2, 3, \ldots N, k > j \quad (16)$$

In which x_k and x_j represent the values of data at time k and j respectively while Q_i is the median slope.

Precipitation Concentration Index (PCI)

The precipitation concentration index (PCI) is a useful indicator for temporal precipitation distribution introduced by J.E. Oliver and later developed by De Luis et al (1997) (Salameh, 2024) was used to characterise the homogeneity of total precipitation among the months on an annual scale. Increasing values of the PCI would indicate increasing monthly Precipitation Concentration (PC) throughout the year (Salameh, 2024). It is also used to characterise climate regimes and detect changes in these regimes over time as a result of climate variability. The PCI was used to determine the concentration of rainfall and rainfall erosivity. This was accomplished with the formula:

$$\mathrm{PCI}_{\mathrm{annual}} = \frac{\sum_{i=1}^{12} R_i^2}{\left(\sum_{i=1}^{12} R_i\right)^2} \times 100 \quad (17)$$

Whereby, $\mathrm{PCI}_{\mathrm{annual}}$ denotes the precipitation concentration index, and R_i is the rainfall in the month i.

Oliver (1980) recommended that the precipitation concentration would be low, or the distribution of precipitation would be uniform, when the values of PCI are less than 10%. PCI values ranging between 11 and 15% represent a moderate precipitation concentration; values of PCI ranging between 16 and 20% means the irregular distribution of precipitation. While the values of PCI greater than 20% would mean that there is a high precipitation concentration or a strongly irregular precipitation concentration (**Table 3-1**). In this study, the RStudio software version 4.4.2 was used to analyse the precipitation for the precipitation concentration indices.

Table 3-1. SI value-wise rainfall regime

Values of SI	**Rainfall regime**
< 0.19	Rainfall extent throughout the year
$0.20 - 0.39$	Rainfall extent throughout the year, but with certain hazier seasons
$0.40 - 0.59$	Relative seasonal with a little drier season
$0.60 - 0.79$	Seasonal rainfall
$0.80 - 0.99$	Markedly seasonal with a long dry season
$1.00 - 1.19$	Most rainfall occurs for less than 3 months.
> 1.20	Extreme seasonal with all rainfall occurring for 1 – 2 months

The precipitation concentration index was incorporated in this study with an understanding that the impacts of climate change on food production and security are connected to both the quality and quantity of the water used for irrigation. The availability of water is significant and of utmost importance in countries that are dependent on rainfall, such as Namibia, and particularly in communities that heavily rely on rain-fed agriculture due to limited irrigation possibilities. Hence, the PCI was utilized due to its simplicity to compute and plainness to comprehend in giving helpful information on determining the seasonal and annual concentration. Furthermore, the PCI also provides data for comparing precipitation regimes across the climate of the year (Salameh, 2024). The PCI is deemed a powerful tool to characterize precipitation trends by this wide application by several authors globally (Brahimi et al., 2023; Salameh, 2024; Llano, 2023).

This study makes a primary contribution by using the PCI to characterise the precipitation of the selected areas in Namibia, of which the results could be relevant as a warning too in water resources management, agricultural planning, and readiness for droughts.

Standard Precipitation Index (SPI) and Standard Precipitation Evaporation Index (SPEI)

The Standard Precipitation Index (SPI) and Standard Precipitation Evaporation Index (SPEI) were utilised to effectively associate the changes in climate with meteorological drought, and by extension, with water and food security. The SPI only focuses on precipitation, while the SPEI integrates both precipitation and evapotranspiration (Chisadza et al., 2024). The significance of SPEI over SPI is that the former helps to overcome the problem of underrepresentation of the drought severity in areas where temperature-induced evapotranspiration plays a major role, such as Namibia.

The SPI-3, SPI-6, and SPI-12 were calculated using R (version 4.4.2) based on the acquired precipitation data. These analyses allowed for the assessment of climatic drought severity across the various time scales. The 3-month timescale (SPI-3) was particularly important to capture the seasonal variation in the moisture conditions, aligning it with the growth stages for many crops, and thereby making it relevant to assess the impacts of climate change through drought assessment on agricultural crop production. While at the longer timescales of 6-month and 12-month (especially the latter), the SPI is related to groundwater and reservoir storage (Das et al., 2024). The assessment of SPI-6 is very important for understanding the impacts of prolonged droughts and their frequencies on water security and all-seasons crops cultivation.

The SPI is calculated with the formula:

$$\mathrm{SPI} = \frac{(Z_{ir} - P_i)}{\sigma_i} \tag{18}$$

Where σ_i is the standard deviation for the ith location, $Z_{ir}$is the rainfall for the ith location and rth observation, and P_i is the mean rainfall for the ith location. The classification of the drought analyses is given in **Table 3-2,** which was essential to characterise the drought events across the respective timescales of analyses.

Table 3-2. Classification of drought events using the SPI and SPEI (Chisadza et al., 2024)

SPI or SPEI values	Drought classification
>2.00	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderate wet
0 to -0.99	Near normal
-0.50 to -0.99	Mild drought
-1.00 to 1.49	Moderate drought
-1.50 to -1.99	Severe drought
<-2.00	Extreme drought

The different timescales for the Standardised Precipitation Evapotranspiration Index (SPEI-3, SPEI-6, and SPEI-12) were also performed in R (version 4.4.2). The SPEI was calculated using both precipitation and potential evapotranspiration (PET) data. The inclusion of the potential evapotranspiration data in the calculation makes it the most appropriate drought assessment tool for Namibia, which is characterised by arid to semi-arid climatic conditions in which evapotranspiration is a significant parameter of climate. In contrast to the SPI, which only considers precipitation, the SPEI accounts for both precipitation and PET, giving a better understanding of drought by covering both meteorological and agricultural aspects of the precipitation. Again, while the SPI analysis concentrates on the absolute reduction in rainfall, the SPEI analysis considers the reduction in rainfall relative to potential evapotranspiration. This difference allows SPEI to reflect the combined effects of water availability and demand. The three timescales were utilised to capture the seasonal to the long-term variations in drought severity within each location.

Crop Production Trend Analysis

The historical variations in the production of the three major food crops (white maize, wheat, and Pearl Millet (commonly known as Mahangu) in Namibia were performed in R. The annual production of the crops was related to the annual precipitation of the same period to assess the impacts of precipitation on crops production. Furthermore, to unravel the robust impacts of climate change on food security, the crops were assessed in terms of the local consumption with respect to local production and imports, the average domestic price of floor per ton, sources of imported crops, monetary values of the local and imported crops, sources and quantities of

imported crops, the demand of the major crops and the crop production during the years of drought.

3.3.4 Statistical Analysis

The STATA 18.0 software was used to give descriptive statistics of mean, minimum, and maximum to describe the distribution and relationship among the different physico-chemical parameters and irrigation water quality indices from different locations and water sources. This software was further utilized to perform correlations, regression, and grouping analyses of the physico-chemical parameters and water quality indices. The measure of significance in the correlation analysis was customized at $p < 0.05$ level. Processing of initial high sequences and assigning of taxonomy were done in QIIME2, and the downstream statistical analysis and visualization were performed in R (version 4.50) by using a collection of packages tailored for microbiome data interpretation. Alpha diversity metrics such as the Shannon and Simpson indices were used to evaluate within-sample diversity, and for the beta diversity, ordination analyses, including Principal Coordination Analysis (PCoA) based on Bray-Curtis dissimilarity, which allowed for comparison of microbial community composition among the sample groups. Lastly, statistical analyses to assess the impact of climate change on water sources and food security were performed and visualised in R (version 4.4.2).

Chapter 4: Results and Data Analysis

This chapter outlines the findings of the research, beginning with an appropriate presentation of the raw data (the complete raw data is annexed). The results for each of the three(3) specific objectives is provided and analysed accordingly.

4.1 Objective 1: Evaluation of the physico-chemical characteristics of the water used for irrigation of horticultural crops with the application of irrigation water quality indices

4.1.1 Characterisation of the physico-chemical quality of the irrigation water

The results presented in **Table 4-1** on the irrigation water physicochemical parameters were utilised to characterise the quality of the water used for irrigation, and further assess its suitability for irrigation usage by evaluating the irrigation water quality indices. The results of the physicochemical parameters indicated that pH values ranged from 6.90 to 8.00 (**Table 4-2**), with a mean of 7.47. These collectively indicate waters with high alkalinity (pH >6.5). The implication is that these waters are suitable for irrigation purposes (Elsayed et al., 2020; Ayers and Westcott, 1985). The values of the electrical conductivity (EC) (**Table 4-2** and **Figure 4-1**) ranged from 15.05 to 1,339.67 µS/cm, with a mean of 518.11 µS/cm. This range is characteristic of a hypotonic environment and lotic freshwater ecosystem, and was at suitable levels for use in agricultural purposes. The lower electrical conductivity values were mainly from the surface water samples, while higher EC values were recorded on groundwater samples. Generally, the lower EC values speak to the fast soil-water ion exchange, insoluble geologic rocks and mineral form, and little solute dissolution. It is important to point out that EC, which indicates the risk of salinity, is the most important water quality indicator for crop productivity (Salifu et al., 2017). According to Ayers and Westcott (1985), water with an EC value >3,000 µS/cm is classified as “Fair” and would greatly affect crop yield. The water with the EC ranging between 700 to 3,000 µS/cm is termed “Good”, whereas the classification “Excellent” is assigned to water with EC values <700 µS/cm. By these classifications, all the water samples were suitable for irrigation. However, based on the classifications of Wilcox (1955), 86.2% of the samples were safe and 13.8% were tolerable for use in irrigation purposes. This result may be an affirmation of the satisfactory crop productivity in the study area, and a good motivation for increased cultivation in the future. Contrary, water with elevated levels of electrical conductivity affects the ability of the crops to compete for ions in the soil, hence causing physiological drought and subsequently resulting in crop yield reduction. This further implies that though the field may appear to have

plenty of moisture, the high EC will make the crops wilt because of the inability of their roots to absorb water. Another parameter of interest is the Total Dissolved Solids (TDS) in the irrigation water. TDS is a very important irrigation water quality parameter because of the possibility of the presence of toxic solid particles in water (Salifu et al., 2017). A salinity problem would emanate when salts accumulate in the crop root zone to such levels whereby they cause a loss in crop yield, as in the case of EC. Generally, salts come from saline, high water table, or from salts in the water used for irrigation. Once the salts accumulate in the root zone to high levels, the crop can no longer extract sufficient water from the salty soil solution, hence causing a water stress for a prolonged period of time, which will result in a reduction in yields (Salifu et al., 2017). Furthermore, if the water uptake of the plant is significantly reduced, its growth rate also slows down (Salifu et al., 2017). The TDS values in this study ranged from 15.19 to 671.33 mg/l, with a mean of 264.79 mg/l. According to Salifu et al. (2017), waters with TDS values <450 mg/l are termed "None" and thus are considered suitable or appropriate for irrigation purposes. Waters with TDS values between 450 to 2,000 mg/l are regarded as "Slight to Moderate", whereas those with TDS values >2,000 mg/l are classified as "Severe". By this classification, the waters in this study belong to the "None" and "Slight to moderate" groupings. Therefore, the water is suitable for irrigation purposes based on the TDS concentrations.

The Na^+ concentration of the collected water samples ranged from 0.1 to 9.01 mg/l with a mean of 1.94 mg/l, which indicates it is the dominant cation, followed by Mg^{2+}, which ranged from 0.11 to 3.65 mg/l with a mean of 1.64 mg/l, as the second most common cation. These values are acceptable for irrigation purposes according to Elsayed et al. (2020) and Ayers and Westcott (FAO, 1985). The alkalinity of the water ranged from 16.00 to 482.00 mg/l with a mean of 240.87 mg/l, indicating that it is the most dominant anion in the water, followed by SO_4^{2-}, which ranged between 1.00 and 203.00 mg/l with a mean of 39.57 mg/l. This is within the acceptable limits for irrigation set by FAO. The content of Cl^- varied from 1.00 to 80.00 mg/l with a mean value of 19.57 mg/l and was within the acceptable limits for irrigation (0.0 – 1,050.0 mg/l) according to FAO (1985). While the content of NO_3^- ranged from 0.50 to 13.80 mg/l with a mean of 2.98 mg/l, indicating a low concentration with no effect on the appropriateness of the water for use on irrigation.

The ion concentrations of the irrigation water samples occurred in the following order: $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and alkalinity $> SO_4^{2-} > Cl^- > NO_3^- > F^- > NO_2^-$. Moreover, the alkalinity values from the samples collected recorded much higher concentrations in the groundwater than surface water. The area has karst aquifers, characterised by carbonate rocks (Ihemba &

Esterhuyse, 2020), and this accounts for the carbonate dissolution in the groundwater (Elsayed et al., 2020).

Table 4-1. Physicochemical Quality of Irrigation Water (expressed in mg/L except for pH, T (oC), and EC (µS/cm)

Location Name	Sampling Point	pH	T	EC	TDS	SO_4^{2-}	Cl-	F-	NO_3^-	Alka.	Ca^{2+}	Mg^{2+}	K^+	Na^+	NH_4^+
SHADIKONGORO GSIP*	SHA – SS1	7.00	24.70	30	15	1	1	0.1	0.5	32	0.14	0.12	0.16	0.04	0.01
	SHA – SS2	7.20	26.00	30	15	1	1	0.1	0.5	32	0.14	0.12	0.14	0.02	0.01
	SHA – SS3	7.20	30.53	32	16	1	1	0.1	0.5	30	0.14	0.12	0.14	0.04	0.01
	SHA – SS4	7.30	37.00	3	17	1	1	0.1	0.5	32	0.14	0.11	0.13	0.01	0.01
	SHA – SS5	6.90	23.30	15	16	5	1	0.1	0.5	32	0.14	0.11	0.14	0.05	0.02
	SHA – Pump A	7.20	22.40	-	-	1	1	0.1	0.5	36	0.14	0.11	0.14	0.01	0.01
	SHA – Pump B	7.10	22.40	17	17	4	1	0.1	0.5	30	0.14	0.11	0.14	0.02	0.02
	SHA – Pump C	7.10	21.80	15	16	2	2	0.1	0.5	32	0.14	0.11	0.14	0.02	0.02
SIKONDO GSIP*	SIK – Pump 1	7.10	23.71	41	21	5	6	0.1	0.5	20	0.16	0.14	0.12	0.20	0.01
	SIK – Pump 2	7.00	21.53	39	20	3	3	0.1	0.5	20	0.16	0.14	0.11	0.18	0.01
	SIK – MSF 1	7.00	22.70	46	23	1	1	0.1	0.5	16	0.16	0.14	0.12	0.18	0.01
	SIK – MSF 2	7.20	22.97	47	23	3	1	0.1	0.5	16	0.16	0.14	0.12	0.20	0.02
	SIK – CSF	7.30	22.50	45	23	4	1	0.1	0.5	20	0.16	0.13	0.12	0.17	0.01
	SIK – RIVER	7.30	23.23	43	22	7	1	0.1	0.5	20	0.16	0.14	0.12	0.23	0.02
GROOTFONTEIN	GRO – RIET 1	7.80	27.80	733	367	9	4	0.1	1.1	408	1.43	2.49	0.04	0.02	0.01
	GRO – RIET 2	7.80	27.00	809	405	9	4	0.1	2.4	416	1.39	2.87	0.03	0.22	0.01
	GRO – HAR 1	7.80	24.10	834	417	14	1	0.1	4.2	440	1.76	2.55	0.26	0.09	0.02
	GRO – HAR 2	7.90	27.80	711	356	12	3	0.1	0.6	370	1.41	2.31	0.09	0.12	0.01
	GRO – DER 1	7.70	31.20	788	399	1	1	0.1	0.5	422	-	-	-	-	0.01

	GRO – DER 2	7.80	24.70	840	420	6	1	0.1	2.2	446	1.57	2.67	0.69	0.32	0.01
TSUMEB	TSU – MAN 1	7.80	25.76	1143	609	149	71	0.2	3.7	424	1.94	3.35	0.20	6.06	0.01
	TSU – MAN 2	8.00	26.23	920	424	145	69	0.2	3.6	440	1.92	3.34	0.17	5.84	0.01
	TSU – MAN 3	8.00	32.7	1235	620	159	80	0.2	2.5	444	1.74	3.44	0.37	7.73	0.01
	TSU – MUR 1	7.70	24.04	824	416	129	68	0.3	5.9	480	1.75	3.65	0.20	7.54	0.01
	TSU – MUR 2	7.40	31.61	759	381	72	34	0.3	2.9	468	1.79	3.10	0.18	3.05	0.01
	TSU – KEY 1	7.50	27.29	920	479.33	28	17	0.3	5.3	482	1.55	3.01	0.29	1.90	0.01
	TSU – KEY 2	7.60	26.66	1208	603.33	87	57	0.3	13.8	450	1.78	3.26	0.20	5.16	0.02
	TSU – KEY 3	7.80	26.92	869	522.67	97	69	0.2	11.8	382	1.83	3.28	0.16	5.30	0.01
	TSU – UIT 1	7.70	29.22	1340	671.33	203	62	0.6	10.6	352	2.12	3.57	0.42	9.01	0.02
	TSU – COR	7.80	27.01	657	343.67	28	24	0.4	11.4	434	1.62	2.96	0.28	2.54	0.01

Table 4-2. Descriptive Statistical Summary of Key Physico-Chemical Parameters

Descriptive Summary of pH – NH_4^+					
Variable	**Obs.**	**Mean**	**Std. dev.**	**Min**	**Max**
pH	30	7.47	0.35	6.90	8.00
T	30	26.16	3.68	21.53	37.00
EC	29	518	469	15	1340
TDS	29	265	239	15	671
SO_4^{2-}	30	39.56	59.83	1.00	203.00
Cl^-	30	19.57	28.36	1.00	80.00
F^-	30	0.17	0.12	0.10	0.60
NO_3^-	30	2.98	3.91	0.50	13.80
Alkalinity	30	241	206	16	482
Ca^{2+}	29	0.95	0.81	0.14	2.12
Mg^{2+}	29	1.64	1.52	0.11	3.65
K^+	29	0.19	0.13	0.03	0.69
Na^+	29	1.94	2.89	0.01	9.01
NH_4^+	30	0.01	0.004	0.01	0.02

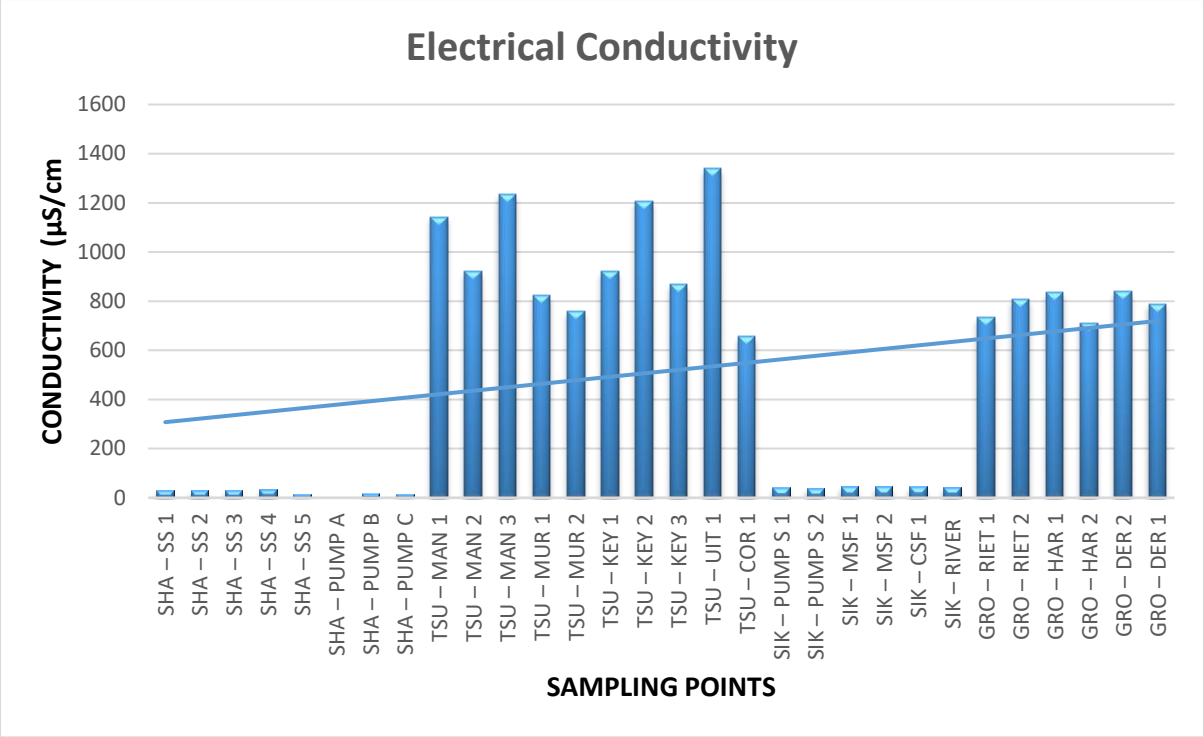


Figure 4-1. Electrical conductivity temporal variations

(a) Robust Regression Analysis of the Physico-chemical parameters

Table 4-3 shows the robust analysis of the physicochemical properties of the water used for irrigation, and thus were statistically classified to assess the relatedness of the various parameters with respect to different places.

Table 4-3. Robust Regression Analysis of the Physico-chemical Characteristics of the Irrigation Water

Parameter	R-Square	Prob > F	HETTEST	
			Chi2(1)	Prob > Chi2
pH	0.8353	0.0000	0.35	0.5543
T	0.2529	0.0522	0.47	0.4909
EC	0.9237	0.0000	15.82	0.0001
TDS	0.9237	0.0000	16.28	0.0001
SO_4^{2-}	0.7121	0.0000	29.52	0.0000
Cl^-	0.8124	0.0000	29.32	0.0000
F^-	0.6557	0.0000	30.00	0.0000
NO_3^-	0.6050	0.0000	25.11	0.0000
Alkalinity	0.9844	0.0000	13.45	0.0002
Ca^{2+}	0.9816	0.0000	13.84	0.0002
Mg^{2+}	0.9901	0.0000	13.91	0.0002
K^+	0.1829	0.1613	7.53	0.0061
Na^+	0.7873	0.0000	27.44	0.0000
NH_4^+	0.0384	0.7926	0.65	0.4187

(b) Pairwise Compare for Group Sort Analysis

The pairwise compare analysis in **Table 4-4** for group sorting of the various physicochemical parameters showed that electrical conductivity, nitrate, total dissolved solids, calcium, and magnesium were significantly different at 5% for the locations Shadikongoro, Sikondo, Tsumeb, and Grootfontein.

Table 4-4. Pairwise comparison of the group of water sources

	pH	**T**	**EC**	**TDS**	**SO_4^{2-}**	**Cl^-**	**F^-**	**NO_3^-**	**Alka**	**Ca^{2+}**	**Mg^{2+}**	**K^+**	**Na^+**	**NH_4^+**
SHA	A	AB	*	*	A	A	A	*	*	*	*	B	*	A
SIK	A	A	*	*	A	A	B	*	*	*	*	A	A	A
TSU	B	B	*	*	*	*	*	*	A	*	*	C	*	A
GRO	B	B	*	*	*	A	AB	*	A	*	*	ABC	A	A

Note: Margins sharing a letter in the group label are not significantly different at the 5% level.

*= Does not share a letter with anyone

The water at Shadikongoro and Tsumeb had concentrations of Na^+ that were significantly different from each other and from those of Sikondo and Grootfontein, while the waters of Sikondo and Grootfontein did not have significantly different concentrations. The pH of the waters at Shadikongoro and Sikondo were not significantly different at 5%, but were significantly different from the waters at Tsumeb and Grootfontein, while the pH of the water at the latter locations was not significantly different from each other. Furthermore, the grouping of K^+ showed the variation in the water quality used for irrigation. The water quality at Grootfontein did not show any statistical differences with that of Tsumeb, Shadikongoro and Sikondo for K^+, while the last three locations were statistically different from each other.

(c) Spearman Correlation of the Physico-chemical Parameters, Stats (rho p) star(0.05)

Key
rho *p-value*

	pH	T	EC	TDS	SO_4^{2-}	Cl^-	F^-	NO_3^-	Alka	Ca^{2+}	Mg^{2+}	K^+	Na^+	NH_4^+
pH	1.0000													
T	0.5697* 0.0019	1.0000												
EC	**0.7800*** 0.0000	0.4637* 0.0136	1.0000											
TDS	**0.7692*** 0.0000	0.4079* 0.0319	**0.9852*** 0.0000	1.0000										
SO_4^{2-}	**0.7535*** 0.0000	0.3949* 0.0382	**0.8584*** 0.0000	**0.8898*** 0.0000	1.0000									
Cl^-	0.6023* 0.0010	0.4159* 0.0286	**0.7227*** 0.0000	**0.7366*** 0.0000	0.8523* 0.0000	1.0000								
F^-	0.4566* 0.0151	0.4481* 0.0175	0.6986* 0.0000	**0.6935*** 0.0001	0.7960* 0.0000	0.8024* 0.0000	1.0000							
NO_3^-	**0.7247*** 0.0000	0.4662* 0.0133	**0.8479*** 0.0000	0**.8502*** 0.0000	0.8650* 0.0000	0.7556* 0.0000	0.8399* 0.0000	1.0000						
Alka	0.6828* 0.0001	0.5318* 0.0041	0.6843* 0.0001	**0.6694*** 0.0002	0.7141* 0.0000	0.6106* 0.0000	0.6718* 0.0002	0.8164* 0.0000	1.0000					
Ca^{2+}	**0.7544*** 0.0000	0.3956* 0.0378	**0.9130*** 0.0000	**0.9037*** 0.0000	0.9093* 0.0000	0.7712* 0.0000	0.7530* 0.0000	0.8784* 0.0000	0.6740* 0.0001	1.0000				
Mg^{2+}	**0.7349*** 0.0000	0.4071* 0.0322	**0.9211*** 0.0000	**0.9112*** 0.0000	0.9223* 0.0000	0.8506* 0.0000	0.7988* 0.0000	0.8725* 0.0000	0.7047* 0.0001	0.9460* 0.0000	1.0000			
K^+	0.3564 0.0630	0.2890 0.1352	0.5360* 0.0037	**0.5259*** 0.0045	0.5597* 0.0023	0.4020* 0.0348	0.6841* 0.0001	0.6339* 0.0004	0.6749* 0.0001	0.5475* 0.0030	0.5298* 0.0042	1.0000		
Na^+	0.5378* 0.0036	0.2280 0.2416	**0.8227*** 0.0000	**0.8320*** 0.0000	0.8488* 0.0000	0.7828* 0.0000	0.7992* 0.0000	0.7366* 0.0000	0.5212* 0.0050	0.8415* 0.0000	0.9118* 0.0000	0.5489* 0.0029	1.0000	
NH_4^+	-0.2620 0.1774	-0.3720 0.0517	-0.1272 0.5168	-0.0587 0.7654	0.0049 0.9794	-0.2601 0.1778	-0.0745 0.7224	-0.0619 0.7603	-0.1966 0.3141	-0.1274 0.5163	-0.2156 0.2690	0.0931 0.6359	-0.0881 0.6541	1.0000

Figure 4-2. Spearman Correlation Analysis of the Physico-chemical parameters of the irrigation water, Stats (rho p) star(0.05)

The Spearman correlation analysis of the physicochemical characteristics of the water used for irrigation of horticultural crops in **Figure 4-2** showed that pH was significantly correlated to temperature, electrical conductivity, total dissolved solids, SO_4^{2-}, Cl^-, nitrate, alkalinity, Mg^{2+}, Ca^{2+} and Na^+. However, significantly strong correlations of pH were observed with EC, TDS, SO_4^{2-}, Mg^{2+}, NO_3^- and Ca^{2+}. The electrical conductivity showed strong significant correlations with TDS, SO_4^{2-}, Mg^{2+}, Cl^-, NO_3^- and Ca^{2+}.

(d) Standardisation of the Multi-variability of Physico-chemical Characteristics of Irrigation Surface and Water

The physicochemical characteristics of the irrigation water were standardised (**Table 4-5**) for the multi-variability of the water with respect to its sources, as ground and surface water. The presentation of the multi-variability shown in **Figure 4-3** showed that ground and surface water were different for Na^+, Cl^-, SO_4^{2-}, temperature, and pH (these parameters were further away from the standardised means). The parameters TDS, EC, K^+ and Mg^{2+} were closest to the standardised mean concentrations for both ground and surface water. Generally, the groundwater quality showed to be a lot closer to the standardised mean compared to the quality of the surface water, thereby indicating that the water quality of the surface water was much better than that of the groundwater.

Table 4-5. Multi-Variability of Standardised Physico-chemical Characteristics of Irrigation Surface and Water

	pH	T	EC	TDS	SO_4^{2-}	Cl^-	F^-	NO_3^-	Alka	Ca^{2+}	Mg^{2+}	K^+	Na^+	NH_4^+
Ground	7.53	25.49	522.83	268.97	26.80	12.13	0.16	3.19	252.13	1.004	1.682	0.190	1.340	0.013
Surface	7.40	26.83	513.05	260.31	52.33	27.00	0.17	2.78	229.60	0.905	1.603	0.182	2.499	0.013
Total	7.47	26.16	518.11	264.79	39.57	19.57	0.17	2.98	240.87	0.95	1.64	0.19	1.94	0.013
SD	0.35	3.68	469.43	238.73	59.83	28.36	0.12	3.91	205.93	0.81	1.52	0.13	2.89	0.004
Standardisation of the parameters														
	pH	**T**	**EC**	**TDS**	SO_4^{2-}	Cl^-	F^-	NO_3^-	**Alka**	Ca^{2+}	Mg^{2+}	K^+	Na^+	NH_4^+
Ground	0.19	-0.18	0.01	0.018	-0.213	-0.262	-0.056	0.052	0.055	0.063	0.027	0.033	-0.207	0.000
Surface	-0.19	0.18	-0.01	-0.019	0.213	0.262	0.056	-0.052	-0.055	-0.059	-0.025	-0.031	0.193	0.000
Mean	0.00	0.00	0.00	-0.001	0.000	0.000	0.000	0.000	0.000	0.002	0.001	0.001	-0.007	0.000

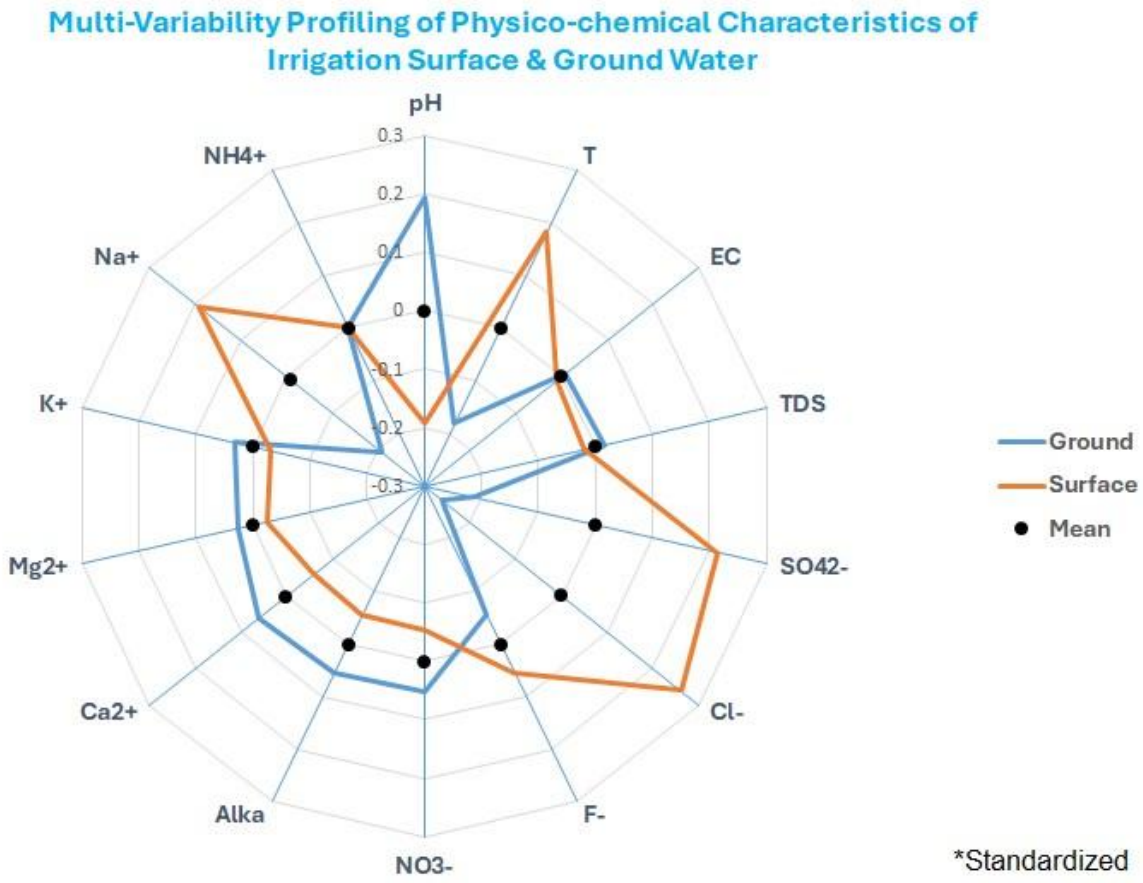


Figure 4-3. Presentation of the multi-variability of the standardised Physico-chemical Characteristics of the Irrigation Water

4.1.2 Application of water quality indices

Sodium Percentage (Na%)

In natural waters, sodium percentage (Na%) is a common parameter that is used to determine its appropriateness for irrigation purposes. This is because Na% indicates the soluble sodium content of the water and is also used to evaluate for the sodium hazard (Salifu et al., 2017). High contents of sodium ions (Na^+) in water relative to the Ca^{2+} and Mg^{2+} concentrations react with the soil, thereby decreasing its permeability. This contributes to the deterioration of the soil structure, thereby stunting the development of crops or plants (Elsayed et al., 2020; Salifu et al., 2017). According to Salifu et al. (2017), water with a Na% >60% may result in sodium accumulations that will cause a breakdown in the soils' physical properties. Again, excess combinations of Na with carbonate result in the formation of alkaline soils, and when combined with chloride, form saline soils. Both the alkaline and the saline soils do not support (normal) plant growth. The Na% of the water under study varied from 0.6 to 50.2, with a mean value of 27.75 (**Table 4-6**). With respect to the Na% values, 83% of the samples were either good or excellent for irrigation, whereas the remaining 17% were in the category of being permissible for irrigation suitability. The Wilcox Diagrams (**Figures 4-6 to 4-7**) showed that all the samples (100%) were excellent-to-good in terms of their suitability for irrigation. Hence, both the groundwater and surface water in the area of study were suitable for irrigation.

Table 4-6 shows the results of the water quality indices (WQIs) of the irrigation water, which determined the suitability of the water for the purpose of irrigation. The results were related to the classifications that describe the category of suitability of the water.

Table 4-6. Irrigation Water Quality Indices

LOCATION NAME	SAMPLING POINT	SAR	Na%	RSC	PI	MAR	KI (KR)	PS
SHADIKONGORO GSIP*	SHA – SS1	1.7	25.6	0.62	405	57.04	0.09	0.20
	SHA – SS2	0.8	20.6	0.62	426	56.87	0.04	0.20
	SHA – SS3	1.7	23.1	0.58	409	57.67	0.09	0.20
	SHA – SS4	0.6	19.6	0.62	439	57.01	0.04	0.20
	SHA – SS5	2.4	26.5	0.62	408	37.05	0.13	0.09
	SHA – Pump A	0.6	20.5	0.7	435	56.87	0.04	0.20
	SHA – Pump B	1.0	21.8	0.58	427	57.23	0.06	0.10
	SHA – Pump C	0.8	21.6	0.62	431	57.01	0.05	0.28
SIKONDO GSIP*	SIK – Pump 1	8.9	37.9	0.38	320	59.72	0.45	0.52
	SIK – Pump 2	7.9	35.6	0.38	328	60.03	0.40	0.34
	SIK – MSF 1	7.8	35.4	0.30	331	59.69	0.40	0.20
	SIK – MSF 2	9.1	38.2	0.30	322	59.52	0.46	0.11
	SIK – CSF	7.7	35.6	0.38	332	59.36	0.39	0.10
	SIK – RIVER	10.0	40.0	0.38	313	59.42	0.51	0.07

GROOTFONTEIN	GRO – RIET 1	0.2	0.6	7.88	97	74.06	0.00	0.26
	GRO – RIET 2	2.4	3.3	8.01	87	77.19	0.03	0.26
	GRO – HAR 1	1.0	3.5	8.10	100	70.43	0.01	0.16
	GRO – HAR 2	1.4	2.5	7.14	102	72.83	0.02	0.17
	GRO – DER 1							0.20
	GRO – DER 2	3.6	9.5	3.62	95	73.61	0.05	0.08
TSUMEB	TSU – MAN 1	61.1	41.9	8.11	91	73.92	0.71	1.14
	TSU – MAN 2	59.0	41.1	8.43	91	74.00	0.69	1.12
	TSU – MAN 3	78.2	48.3	8.51	90	76.40	0.91	1.24
	TSU – MUR 1	74.6	46.3	9.21	87	77.41	0.85	1.17
	TSU – MUR 2	32.0	28.5	9.02	91	73.96	0.39	0.78
	TSU – KEY 1	20.6	21.8	9.32	89	76.07	0.26	0.63
	TSU – KEY 2	53.2	39.2	8.64	90	75.01	0.63	1.19
	TSU – KEY 3	54.3	39.4	7.28	90	74.64	0.64	1.37
	TSU – UIT 1	87.7	50.2	6.64	91	73.40	0.98	0.84
	TSU – COR	27.4	26.6	8.36	91	75.05	0.34	0.89

*GSIP = Green Scheme Irrigation Projection

Sodium Adsorption Ratio (SAR)

The Sodium Adsorption Ratio index is an important irrigation water quality parameter for assessing the suitability of irrigated water as it relates to the sodium hazard (Elsayed et al., 2020). This index measures the content of the salt that will be absorbed in the soil (Anuja et al., 2024). The continued irrigation with water having high SAR leads to a breakdown in the physical structure of the soil (Salifu et al., 2017). The absorbed sodium gets adsorbed and attached to the soil particles. This hardens and compacts the soil, making it increasingly impervious to water penetration (Salifu et al., 2017). In this study, the SAR values ranged from 0.2 to 87.7 with a mean of 21.3 (**Table 4-7**). Of the water samples, 62% and 3% were excellent and good for irrigation, respectively, while 34% of the water samples were classified as poor (SAR > 26) (**Table 4-8**). Since SAR affects the soil, irrigation water with high salt levels is of special concern and symbolises the sodium hazard.

Residual Sodium Carbonate (RSC)

The term "Residual Sodium Carbonate" (RSC) is generated from the alkalinity concentration that is in excess of alkaline earth metals (Mg^{2+} and Ca^{2+}). This RSC indicates the risk effects of alkalinity on the water quality for irrigation (Elsayed et al., 2020). The RSC usually affects other water quality parameters such as pH, EC, and Sodium Adsorption Ratio (SAR) of the water used for irrigation (Anuja et al., 2024). Again, the assessment of RSC plays an important role in the determination of the amount of gypsum or sulphuric acid required as measures of remediation to neutralise residual carbonate effects in the soil (Khatri et al., 2022). According to Anuja et al. (2024), most of the natural water does not have carbonate and bicarbonate ions, hence it does not precipitate calcium and magnesium ions in the water and thus does not cause the alkalinity hazard. However, elevated carbonate and bicarbonate ions in water are inappropriate for agricultural purposes as they increase the pH value of the soil (Khatri et al., 2022), and thereby lead to the accumulation of sodium in the soil, which will eventually induce the deposition of lime on the roots and leaves of the crops and in the soil. In this study, the RSC values ranged from 0.30 to 9.32 with a mean of 4.49 (**Table 4-7**). **Table 4-8** on the classifications of the water quality indices for irrigation water indicated that 48% of the water samples were of water that can be used safely, and 52% of the water samples were of water that was not suitable for irrigation purposes.

Permeability Index (PI)

The Permeability Index (PI) is one of the parameters that is used widely to assess the suitability of water for irrigation purposes (Khatri et al., 2022). The concept of permeability refers to the capacity of water movement in the soil, and this potential is influenced by the structure, porosity and texture

of the soil. In semi-arid and arid areas, the permeability problem is exacerbated by the long-term use of irrigation water, and generally results in increased concentrations of salts in water (Khatri et al., 2022). PI is based on Na^+, Ca^{2+} and HCO_3^- contents in the irrigation water (Anuja et al., 2024; Stanly et al., 2021; Elsayed et al., 2020; Kumar et al., 2019). The classification of water for irrigation purposes based on the permeability index dates as far back as 1964 by Doneen, by taking into consideration the aforementioned ions that highly influence the PI (Salifu et al., 2017). The PI value of the irrigation water also helps to determine the profile of the soil in terms of its porosity (Anuja et al., 2024). The permeability index values in this study varied from 86.90 to 438.60 with a mean value of 231.64 (**Table 4-7**). All the water samples (100%) were classified as of excellent quality for irrigation purposes (PI > 75), as shown in **Table 4-8**. This indicates that the irrigation water would not affect the permeability properties of the soil.

Magnesium Adsorption Ratio (MAR)

The assessment of the Magnesium Adsorption Ratio (MAR) focuses on the magnesium content of the irrigation water (Anuja et al., 2024). MAR is a significant parameter for determining the suitability of water for irrigation as it affects both the soil and crop yield (Anuja et al., 2024; Khatri et al., 2022; Shil et al., 2019). It is therefore, referred to as the magnesium hazard (MH) by some researchers (Giri et el., 2022; Shil et al., 2019). The magnesium ion is a crucial element that determines water quality. Both Ca^{2+} and Mg^{2+} maintain the cationic equilibrium of the water; however, elevated Mg^{2+} alters the agricultural yields after releasing the Na+ from the soil. The released Na^+ promotes the sodium hazard by affecting the soil chemical structure, eventually leading to reduced crop yields (Giri et al., 2022). Again, the high levels of MAR (>50%) in water make the soil alkaline, which decreases the availability of phosphorus, an important soil-fertility parameter, thereby reducing the soil's infiltration potentials and adversely affecting crop yields (Anuja et al., 2024; Mukiza et al., 2021; Kundu and Ara, 2019; Salifu et al., 2017). In this study, the MAR value of the irrigation water ranged from 56.87 to 77.41 with a mean of 66.64 (**Table 4-7**). With respect to **Table 4-8**, all water samples (100%) were not suitable for irrigation purposes (MAR>50). The karst that characterises the groundwater sources with elevated magnesium ions, agricultural activities, and domestic waste discharges may account for the unsuitable categorisation of the waters for irrigation.

Kelly's Index (KI)/ Kelly's Ratio

Kelly's Index (KI) is an indicator of the alkali hazard (Khatri et al., 2022). It is used to classify water for irrigation purposes, whereby sodium is measured against calcium and magnesium, which constitute the alkali hazards (Anuja et al., 2024). Waters with higher sodium concentrations negatively affect the

soil structure by reducing the rate of water movement in the soil (Mukiza et.al., 2021). The KI values in this study varied from 0.003 to 0.98 with a mean of 0.33 (**Table 4-7**). The suitability of the water for irrigation purposes requires that the KI <1 to be classified as suitable or KI >1 as unsuitable. All the samples in this study were classified as suitable for irrigation purposes (**Table 4-8**). This indicates that there was excess sodium in the water, and the soil structure was not altered.

Potential Salinity (PS)

Potential Salinity (PS) is an output of the sum of Cl- and SO_4^{2-} concentrations (El-Amier et al., 2021; Xu et al., 2019). PS is a significant water quality-based index for assessing the suitability of water for irrigation. It is understood that salts that are less soluble precipitate and accumulate in the irrigation soils, while the highly soluble salts increase the salinity of the soil (El-Amier et al., 2021). This comprehension was made by Doneen (1964) by explaining that the suitability of water for irrigation is not dependent on the total concentration of soluble salts, as low-solubility salts precipitate out and get deposited into the soil yearly. Water with low salt is considered suitable for irrigation. The values of PS in this study ranged from 0.07 to 1.37, with a mean of 0.47 (**Table 4-7**). All the water samples were classified as excellent-to-good categories for irrigation.

Table 4-7. Descriptive Summary of Water Quality Indices (SAR-PS)

Descriptive Summary of SAR - PS					
Variable	**Obs.**	**Mean**	**Std. dev.**	**Min**	**Max**
SAR	29	21.30	27.96	0.20	87.70
Na%	29	27.75	14.21	0.60	50.20
RSC	29	4.50	3.96	0.30	9.32
PI	29	231	151	87	439
MAR	29	66.64	8.461	56.87	77.41
KI	29	0.33	0.31	0.00	0.98
PS	30	0.48	0.43	0.07	1.37

(a) Spearman Correlation of SAR – PS, Stats (rho p) star(0.05)

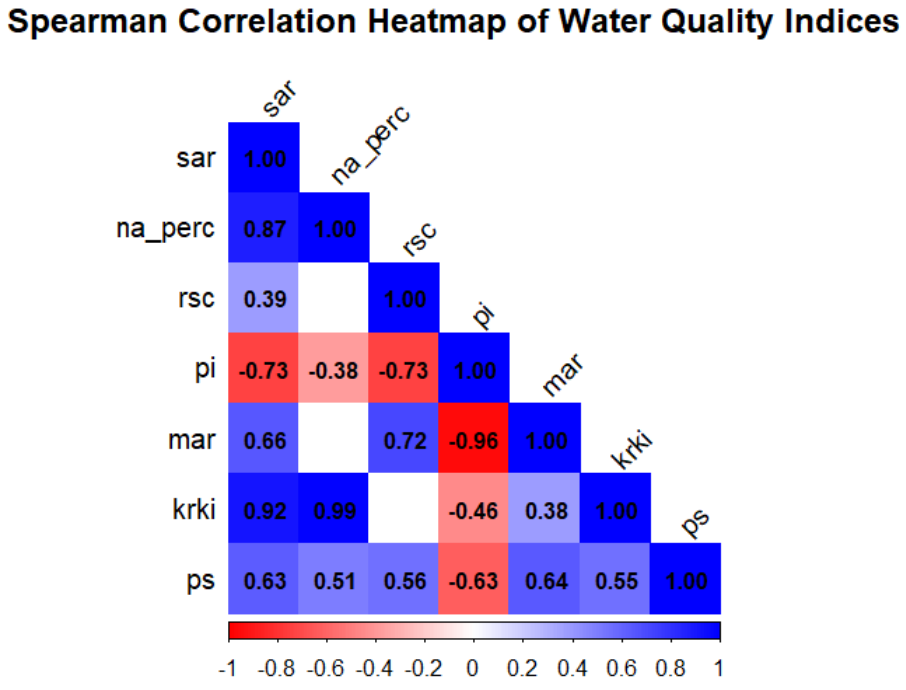


Figure 4-4. Spearman correlation heatmap of the irrigation water quality indices

Figure 4-4 above shows Spearman's rank correlation coefficient (ρ) among the irrigation water quality indices (SAR, Na^+%, RSC, PI, MAR, KI and PS) together with p-values. The relationship existing among the irrigation water quality indices is significantly expressed by using the non-linear or monotonic approaches. It is noted that strong and significant positive correlations exist between SAR and KI (ρ = 0.916, and p < 0.001). This shows a strong relationship. In this case, as the sodium hazard connotated by SAR, so does the Kelly's Ratio or Index increase, and thus pointing to a situation of sodium dominance.

Furthermore, a strong and positively significant correlations were shown by SAR and Na% (ρ = 0.871, and p < 0.001. This high SAR corresponds with the increased sodium percentage in water. Similarly, SAR and MAR also showed a strong and significantly positive relationship (ρ = 0.656, and p = 0.0002), with an indication that as SARS increases, so does the magnesium adsorption ratio tend to increase in a like manner.

On the other hand, another positively significant correlation was observed between PS and KI (ρ = 0.553, and p = 0.0002), PS and SAR (ρ = 0.634, and p = 0.0003), and PS with Na^+ % (ρ = 0.509 and p = 0.0052). On the contrary, a strong and negatively significant correlation was shown by the permeability index (PI) with:

- SAR (ρ = - 0.732, and p < 0.001)

- Na^+ % (ρ = - 0.380, and p = 0.0425)
- RSC (ρ = - 0.731, and p < 0.001)
- MAR (ρ = - 0.960, and p < 0.001)
- KI (ρ = - 0.459, and p = 0.0128)
- PS (ρ = - 0.629, and p = 0.0003)

These correlations are indicative that as the SAR, MAR, or sodium indicators rise, the ability of the waters to maintain permeability would, on the contrary, decrease (low PI) and thereby affect the suitability of the water for the purpose of irrigation in the long run. The correlation relationship between RSC and Na^+ % was non-significant (ρ = 0.019, and p = 0.9209), a confirmation of the non-existence of a relationship between these two indices.

It is remarkable to establish that SAR, Na^+ %, KI, Ps and MAR are closely related and constitute the "sodicity–salinity complex". The permeability index serves as an early warning indicator since it declines with the rise in sodium and magnesium. Hence, policymakers and regulators should consider a mandatory interval monitoring of PI on the water used for irrigation, particularly in places of serious and substantial contamination due to anthropogenic activities.

Table 4-8. Classification of the Water Quality Indices for Irrigation

Water Quality Indices	Classification	Range	Percentage	Number of samples
Sodium Adsorption Ratio (SAR)	Excellent	<10	62	18
	Good	10-18	3	1
	Fair	18-26	0	0
	Poor	>26	34	10
	Hard	>200-300	0	Nil
	Very Hard	>300	0	Nil
Sodium Percentage (Na%)	Excellent	<20	21	6
	Good	20-40	62	18
	Permissible	>40-60	17	5
	Doubtful	>60-80	0	Nil
	Unsuitable	>80	0	Nil
Residual Sodium Carbonate (RSC)	Water can be used safely	<1.25	48	14
	Water can be used with certain management	1.25-2.5	0	0
	Water not suitable for irrigation purposes	>2.5	52	15
Magnesium Adsorption Ratio (MAR)	Acceptable	<50	0	29
	Not acceptable	>50	100	0
Kelly's Index (KI)	Suitable	<1	100	29
	Unsuitable	>1	0	0
Salinity Potential (PS)	Excellent to good	<5	100	30
	Good to injurious	5-10	0	0
	Injurious to unsatisfactory	>10	0	0
Permeability Index (PI)	Excellent	>75	100	29
	Good	25-75	0	0
	Unsuitable	<25	0	0

(b) Multi-variability profiling of the surface and groundwater irrigation quality indices

The irrigation water quality indices were standardised to profile the multi-variability of the indices according to their respective water sources, as ground and surface water (**Table 4-9**). Standardisation helps to make the differences between the groups graphically comparable across the variables.

Methods for standardisation of Ground and Surface Water Physico-chemical Characteristics:

a) standardised 'p' means = (mean p - total mean) / SD, where p = individual parameter and SD is the Standard Deviation.
b) standardised mean = average of ground and surface standardised means

Table 4-9. Standardisation of the multi-variability of surface and ground irrigation water quality indices

	SAR	Na%	RSC	PI	MAR	KI	PS
Ground	39.75	28.74	8.24	91.71	74.57	0.47	0.75
Surface	4.08	26.82	1.00	361.53	59.24	0.21	0.20
Total	21.30	27.74	4.49	231.27	66.64	0.33	0.48
SD	27.96	14.21	3.96	150.81	8.46	0.31	0.43
Standardization							
	SAR	Na%	RSC	PI	MAR	KI	PS
Ground	0.66	0.07	0.95	-0.93	0.94	0.43	0.63
Surface	-0.62	-0.07	-0.88	0.86	-0.87	-0.40	-0.63
Mean	0.02	0.00	0.03	-0.03	0.03	0.01	0.00
Pt	0.0008	0.7292	0.0000	0.0000	0.0000	0.0268	0.0004
Pu	0.0007	0.2750	0.0000	0.0000	0.0000	0.1305	0.0036

Figure 4-5 below shows the radar plot of the standardised water quality indices (WQIs) comparing the groundwater to surface water. The axes showed the different irrigation water quality indices: SAR (Sodium Adsorption Ratio), Na% (Sodium Percentage), RSC (Residual Sodium Carbonate), PI (Permeability Index), MAR (Magnesium Adsorption Ratio), KI (Kelly's Index), and PS (Potential Salinity). The profiles were the groundwater quality profile shown by the blue polygon, the surface water

quality profile shown by the red polygon, and the mean/standardised values shown by the back dot. The Pt and Pu values were the statistical evaluation of each index.

The presentation of the multi-variability profile of the standardised irrigation water quality indices indicated that groundwater quality and surface water quality were significantly different for SAR, PI, RSC, MAR, KI, and PS (these parameters were further away from the standardised means). The Na% was the only index that was closest to the standardised mean for both groundwater and surface water quality, and there was no significant difference between the groups of water sources. However, significantly, the surface water quality showed that all the indices were below the standardised mean except for the permeability index. This observation was the complete opposite of the groundwater quality. The surface water was generally more suitable for irrigation than the groundwater, especially in soils that are sensitive to sodium, while the groundwater may require management to prevent long-term sodicity risks associated with higher Na%, due to water that has higher sodium concentrations.

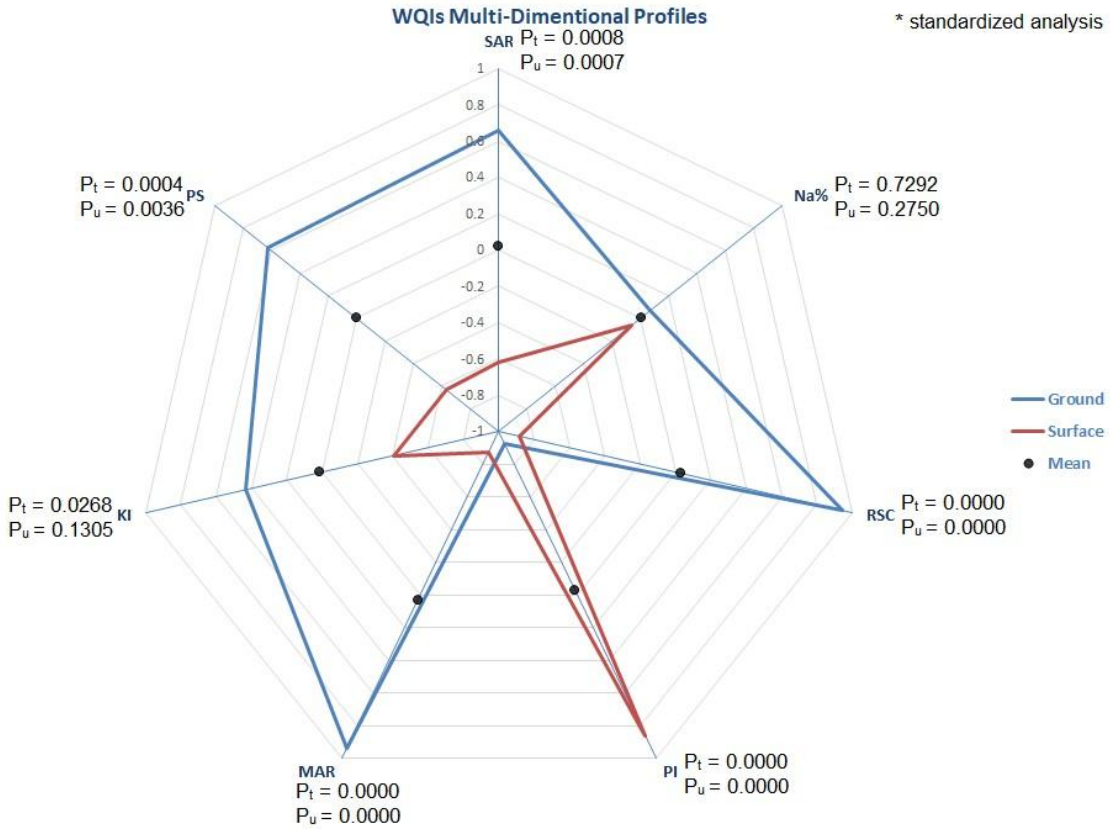


Figure 4-5. Presentation of the Standardised Multi-variability of Irrigation Surface and Ground Water Quality Indices

(c) USSL and Wilcox Diagrams

To further ascertain the suitability of well water in the study area for irrigation purposes, more detailed analyses were conducted by plotting analytical data on USSL and Wilcox diagrams as shown in Figures (**4-6**) and (**4-7**), respectively. In the USSL diagram, EC has been taken as the salinity hazard and SAR as the alkalinity hazard. The measured EC values of the water sources in the current study range from 15 – 1,300 µS/cm. The high concentration of salinity content might be due to the geological formations of the area, where rainwater washes the soil and releases the salt, as well as the domestic and agricultural fertilisers into the groundwater. Through the USSL diagram, it is noted that all (100%) of the water samples were suitable for irrigation and belong to the low salinity hazard category (C2) (**Figure 4-6**).

Table 4-10. EC (µS/cm) Classification (Wilcox, 1955)

Conductivity range	Quality	Sampling points	Percentage of samples in the study
< 1000	Safe	SHA – SS 1, SHA – SS 2, SHA – SS 3, SHA – SS 4, SHA – SS 5, SHA – Pump B, SHA – Pump C, TSU – MAN 2, TSU – MUR 1, TSU – MUR 2, TSU – KEY 1, TSU – KEY 3, TSU – COR 1, SIK – PUMP S 1, SIK – PUMP S 2, SIK – MSF 1, SIK – MSF 2, SIK - CSF 1, SIK – RIVER, GRO – RIET 1, GRO – RIET 2, GRO – HAR 1, GRO – HAR 2, GRO – DER 1, GRO – DER 2 = 25	86.21%
1000 – 1500	Tolerable	TSU – MAN 1, TSU – MAN 3, TSU – KEY 2, TSU – UIT 1 = 4	13.79%
1500 – 2000	Tolerable to some extent	None	0%
2000 – 2500	Intolerable	None	0%
> 2500	Health Hazard	None	0%

Based on the classification scheme of Wilcox for irrigation water, it was again confirmed that all the water sources (100%) fall under the Excellent to Good category. However, based on the individual samples' classification (**Table 4-10**), 86.2% and 13.8% of the irrigation water is safe and tolerable for such use, respectively.

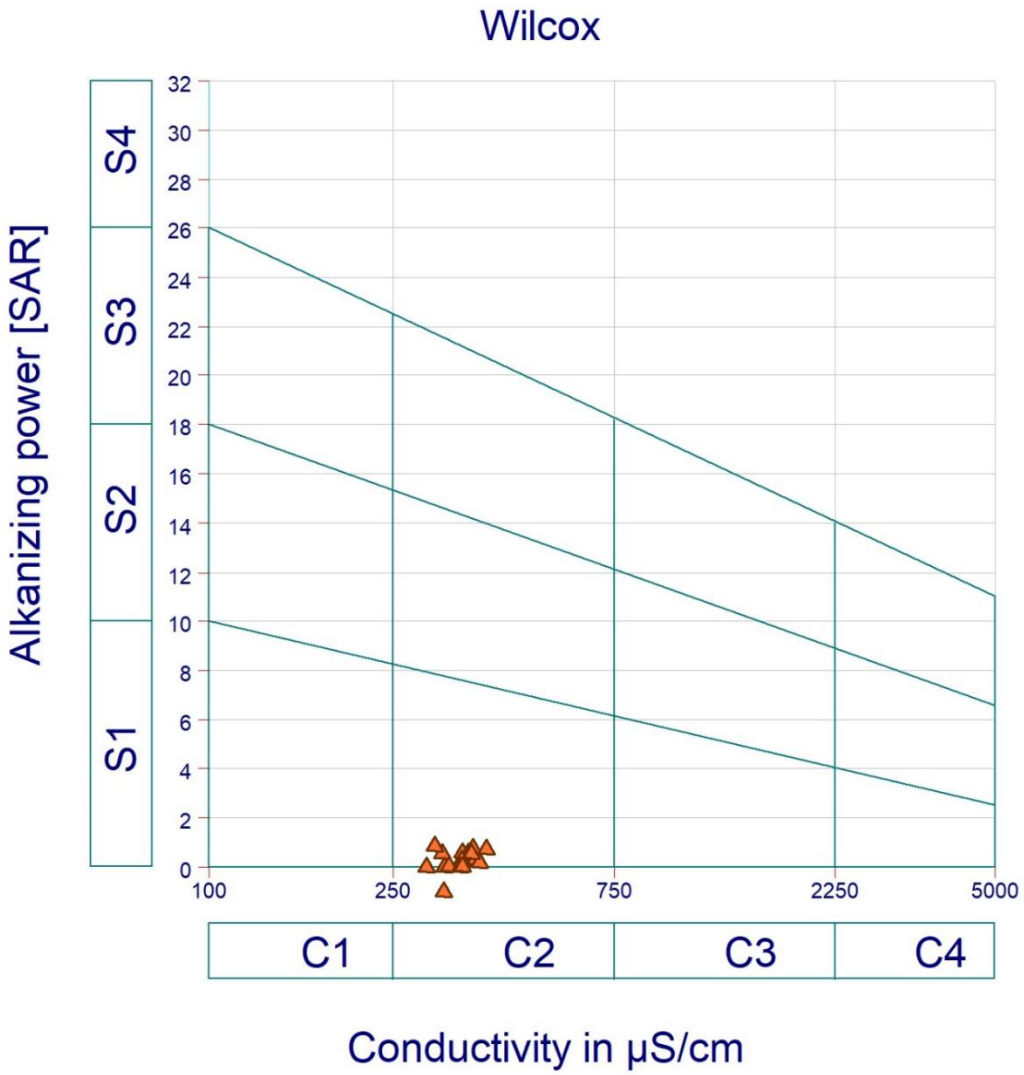


Figure 4-6. Irrigation water quality classification (USSL, 1954)

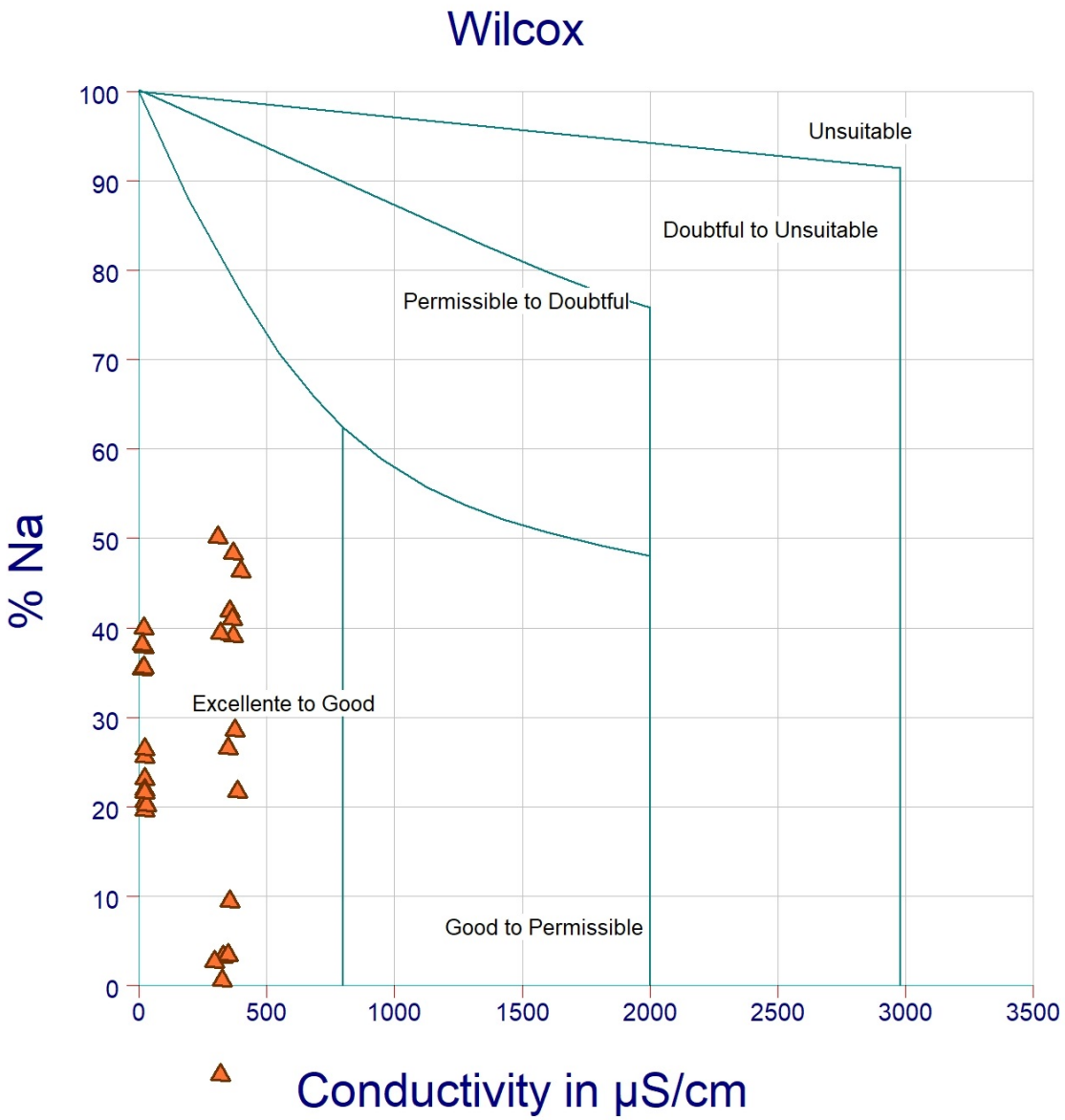


Figure 4-7. Irrigation water quality classification (Wilcox, 1955)

4.1.3 Multiple Mixed Model Profiling of Seasonal and Source of Water Variations

Figures 4-8 to 4-11 below show the variation in some physicochemical parameters across two seasons, namely season 1 (dry) and season 2 (wet), for groundwater and surface water sources used for irrigation. A multi-mixed model profile was performed to establish seasonal and source of water variations and thereby relate them to the suitability of the water for irrigation of horticultural crops. It provided a clear understanding of which sources are appropriate for irrigation, and during which season the particular water source is suitable for such purposes. The irrigation water suitability matrix for horticultural crops in **Figure 4-8** indicates that use of groundwater for irrigation varies around low, moderate, and permissible suitability for the parameters potassium, EC and TDS during both seasons,

except for sodium, which faired as ideal. Nonetheless, during the wet season, the suitability of the groundwater for irrigation is much better than during the dry season. While surface water showed excellent and ideal suitability for irrigation for parameters TDS, EC and Na. Only potassium (K) was less suitable during the dry season and moderately suitable during the wet season. The use of surface water for irrigation is most appropriate during the wet season, and based on the irrigation water suitability matrix, surface water should be the source of choice for the irrigation of horticultural crops, especially during the wet season. Hence, in meeting both national and international goals for sustainable development and poverty eradication while protecting the environmental health and that of the consumers, it is evident that the promotion of increased cultivation of horticultural crops should be made through greens scheme projects and farms that mainly depend on surface water sources for irrigation, while those that rely on groundwater should do so with the exercise of caution by monitoring certain parameters (**Figure 4-8**).

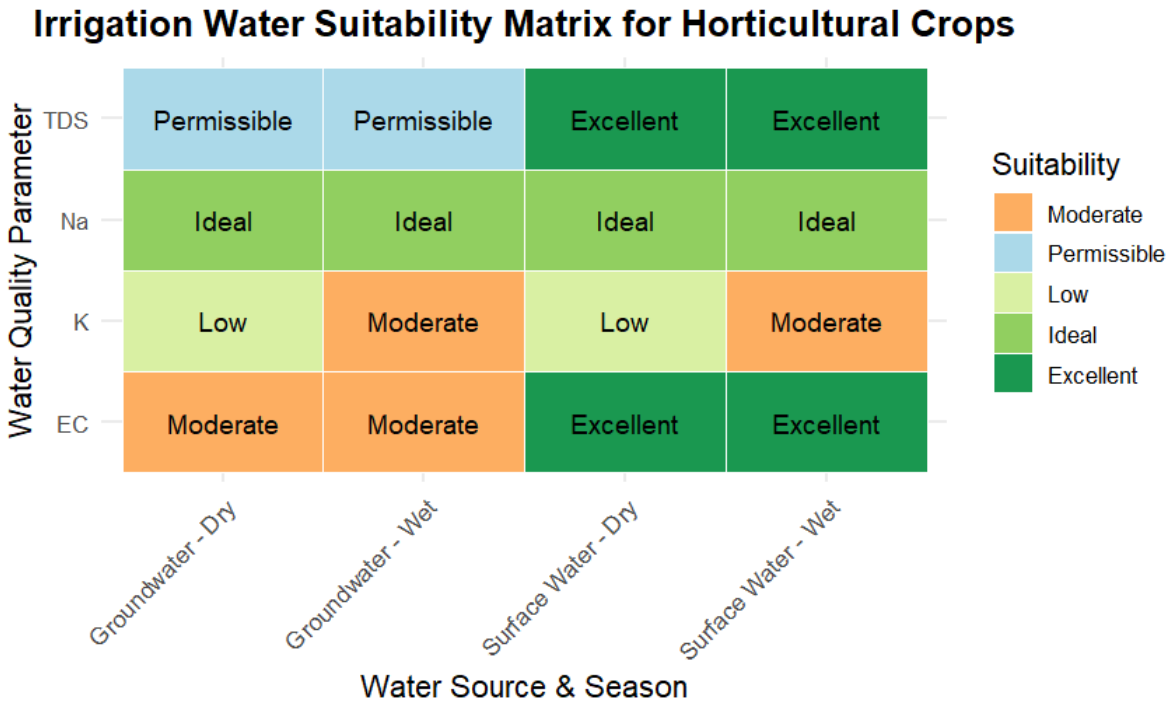


Figure 4-8. Irrigation water suitability matrix for key parameters

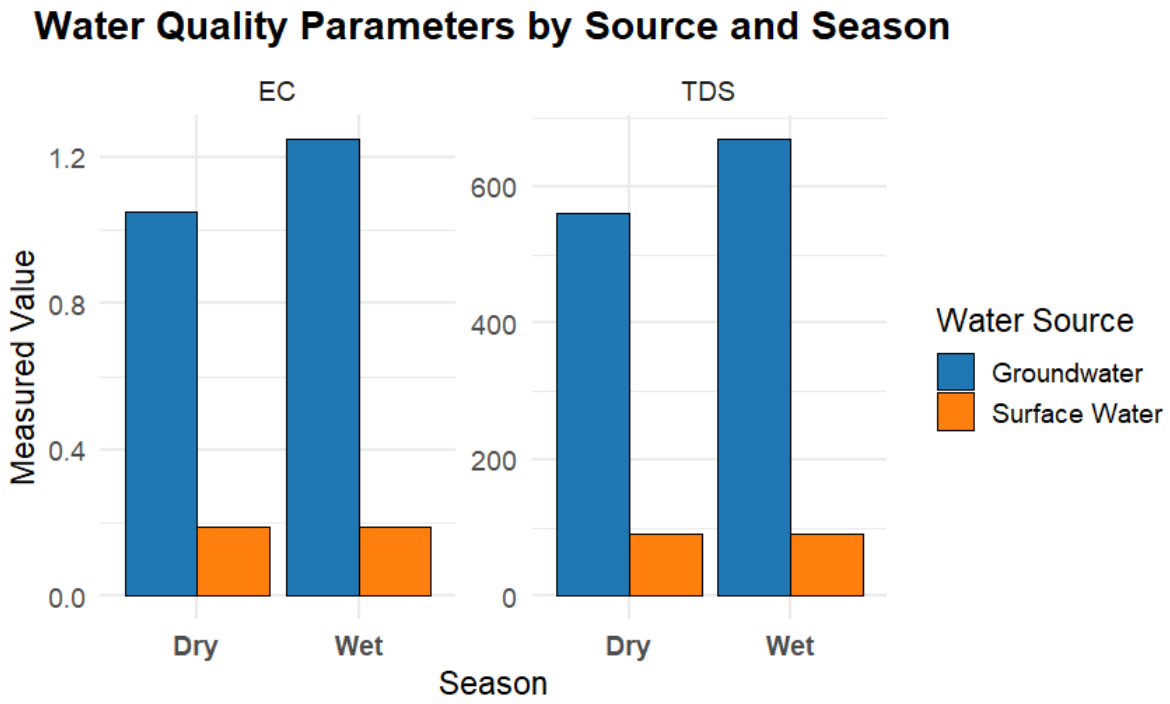


Figure 4-9. EC and TDS seasonal and source variations

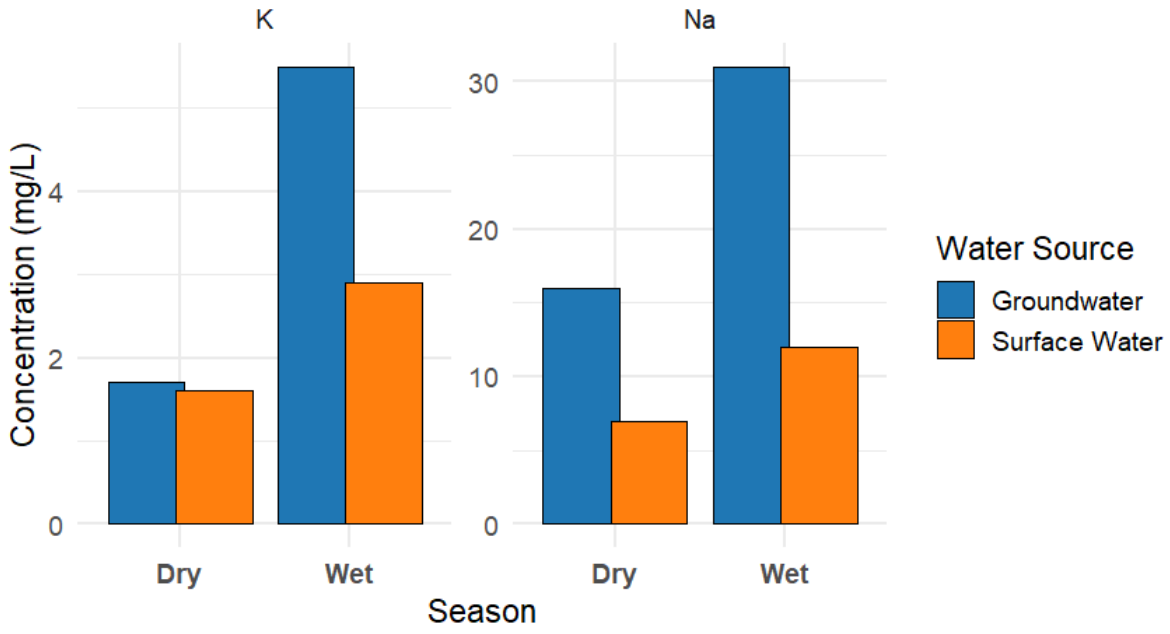


Figure 4-10. Potassium (K) and Sodium (Na) seasonal and source variations

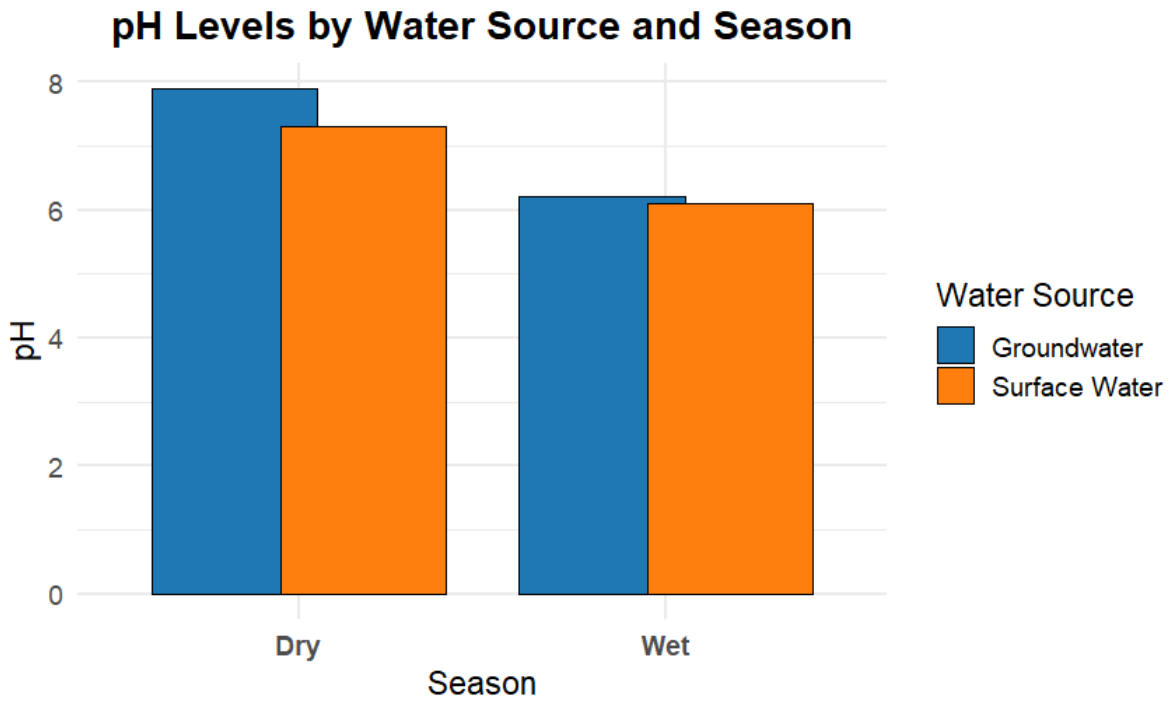


Figure 4-11. pH seasonal and source variations

The pH (**Figure 4-11**) of the groundwater showed slightly saline conditions (7.9 – 8.0) during the dry season, while during the wet season it was slightly acidic (6.2 – 6.3). The change in pH is notable because of the decline of about 1.7 units from the dry to the wet season. While the surface water indicated a near-neutral pH of about 7.3 during the dry season, and with 6.1, the water was more acidic during the wet season, a considerable decline of about 1.2 units. These seasonal trends indicated, therefore, that both the groundwater and surface water experienced a sharp drop in pH from the dry to the wet season. Such declines are probable indicators of increased dilution, runoffs, and inputs of organics during the wet season that introduce acids such as humic and carbonic acids from carbon dioxide. Furthermore, the considerable decrease in the pH of the groundwater can be attributed to recharge with acidic rainwater or leached organics, and indicated even the possibility of less buffering capacity in the aquifers during the rapid recharge periods. Comparing the water types, during the dry season, the groundwater was more alkaline than surface water, and during the wet season, both groundwater and surface water were more acidic (pH of 6.1 – 6.3).

The ideal pH range for the irrigation of most horticultural crops varies between 6.5 and 7.5, i.e., slightly acidic to neutral. At pH < 6.0 and below, solubilising metals causes toxicity, while at pH > 8.0, the solubility of metals is reduced, leading to a deficiency of essential nutrients for the crops. The surface water proved to be very suitable for the irrigation of horticultural crops in the dry season and, with a slight caution, also suitable in the wet season. The groundwater is generally suitable for irrigation, but

during the dry season, there might be a need to monitor for nutrient deficiencies, especially of iron and zinc, while during the wet season, the low pH warrants caution regarding long-term irrigation on poorly buffered soils.

The EC (**Figure 4-9**) of the groundwater was around 1,050 – 1,200 µS/cm during the dry season, and around 1,200 – 1,250 µS/cm during the wet season. Therefore, the EC of the groundwater for both seasons ranged between 1,050 – 1,250 µS/cm. This was indicative of moderate salinity conditions of the water. For both seasons, the water would be suitable for irrigation mainly of salt-tolerant horticultural crops, yet may also result in yield reductions of more salt-sensitive crops such as beans and lettuces. The EC of the surface water had very low salinity (80 – 90 mg/L during both seasons), and could thus be classified as excellent water for irrigation of all types of crops.

The TDS (accounts for the overall mineral content of the water) (**Figure 4-9**) of the groundwater was around 550 – 560 mg/L during the dry season, and around 650 – 670 mg/L during the wet season. While the TDS concentration of the surface water was roughly the same during both seasons, at around 80 – 90 mg/L. Therefore, groundwater showed a permissible range for irrigation (450 – 2000 mg/L) during both the dry and wet seasons, and the surface water indicated to be ideal for irrigation of all horticultural crops during both seasons.

The sodium ion values (Na^+) in **Figure 4-10** showed that the groundwater had concentrations close to 15.5 – 16.0 mg/L during the dry season and about 30.5 – 31.0 mg/L during the wet season. While the surface water had Na^+ concentrations of around 6.5 – 7.0 mg/L in the dry season and, close to 11.5 – 12.0 mg/L in the wet season. All the Na^+ values are well below the limit of 70 mg/L, and therefore, both the groundwater and surface water in all seasons would pose a minimal risk associated with the buildup of sodium during either of the seasons when the water is utilised for irrigation of horticultural crops.

The potassium ion (K^+) is an important parameter for crops that demand potassium, such as tomatoes and peppers. In **Figure 4-10**, had a concentration of about 1.6 – 1.7 mg/L during the dry season and around 5.4 – 5.5 mg/L during the wet season for the groundwater. While in the surface water, the concentration was around 1.5 – 1.6 mg/L in the dry season and close to 2.8 to 2.9 mg/L during the wet season. It is indicative that both the groundwater and surface water had higher K^+ concentrations during the wet season.

It is conclusive from the performed multi-mixed model profiling of the irrigation water sources and seasons that surface water was most suitable for irrigation across both seasons (dry and wet) and is highly recommended for the irrigation of sensitive and high-value horticultural crops. While the use of groundwater for irrigation is acceptable, though it may require the monitoring of the soil's electrical conductivity. The overall recommendation would be for salt-tolerant cultivars for irrigation during the wet season with groundwater.

4.2 Objective 2: Investigation of the microbial community composition of the water sources in Namibia and its relationship with water-borne diseases

4.2.1 Sequence processing, quality filtering, and annotation

A total of 13 environmental samples (**Table 4-11**), including both water and sediment, were analysed for sequence count, average GC content, and average read length. Sediment samples generally yielded higher sequence counts compared to their corresponding water samples, with Ndonga L-Sediment (38,845 sequences) and Shitemo-Sediment (32,290 sequences) among the highest, while Shadikongoro–Sediment produced the lowest sequence count (5,009). Water samples from sites such as Shadikongoro and Otavi also produced relatively high sequence counts (34,743 and 31,998, respectively). GC content varied across samples, ranging from 118,778 to 140,025, with sediment samples typically showing higher GC content values than water samples, suggesting a more diverse or compositionally distinct microbial community. Read lengths were relatively consistent across all samples, averaging around 1,490 bp, with minor variation (range: 1,481.23–1,498.55 bp), indicating uniform sequencing performance. These results highlight both spatial and matrix-specific variability in microbial community composition and sequencing quality across the sampled sites.

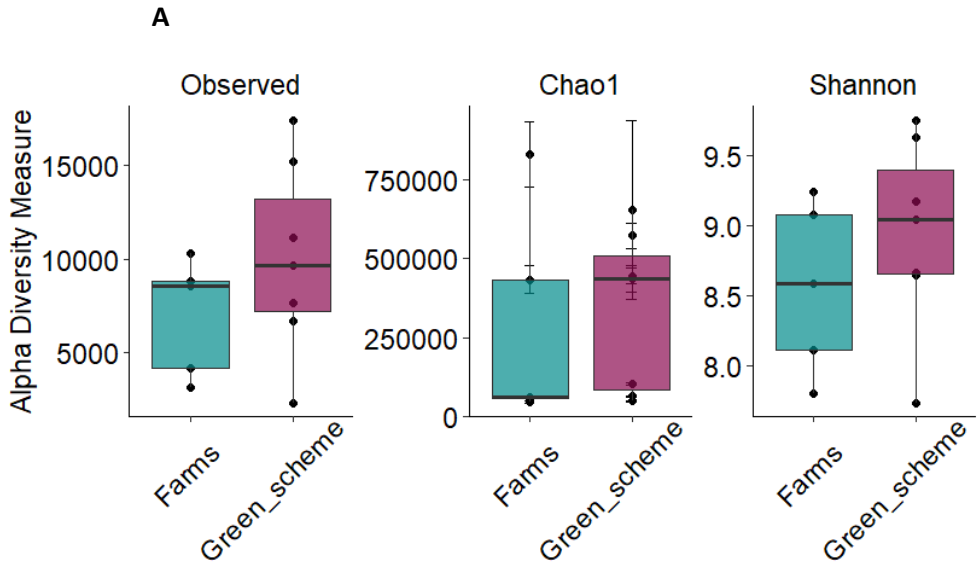
Table 4-11. DNA sequence read metrics of the metagenomic samples

Samples	**Sequences count**	**Average GC content (%)**	**Reads average length (bp)**
Groot – Sediment	22110	134.8	1498.6
Groot – Water	9465	118.8	1486.8
Ndonga L – Water	8867	120.9	1485.1
Ndonga L Sediment	38845	135.4	1491.62
Otavi – Water	31998	122.1	1483.63
Shadikongoro – Sediment	5009	140.0	1492.47
Shadikongoro – Water	34743	121.5	1485.23

Shitemo – Sediment	32290	133.4	1493.99
Shitemo – Water	27758	120.8	1487.24
Sikondo – Sediment	21866	135.1	1496.06
Sikondo – Water	23210	123.9	1481.23
Tsumeb – Sediment	19556	135.5	1494.89
Tsumeb – Water	7199	118.9	1491.41

4.2.2 Alpha and beta diversity analysis

Non-parametric diversity metrics (ACE, Chao1, Shannon) indicate greater bacterial diversity in water from green schemes compared to conventional farms (**Figure 4-12A**). Among the four Namibian regions analysed, Kavango East consistently exhibits the highest microbial diversity, as evidenced by elevated Observed richness, Chao1, and Shannon index values. Oshikoto demonstrates the lowest diversity, characterised by a scarcity of unique and rare taxa. Otjozondjupa and Kavango West present intermediate diversity levels. Overall, Kavango East supports the most diverse and balanced microbial communities, while Oshikoto reflects the most restricted diversity, highlighting significant regional variations in microbial composition (**Figure 4-12B**).



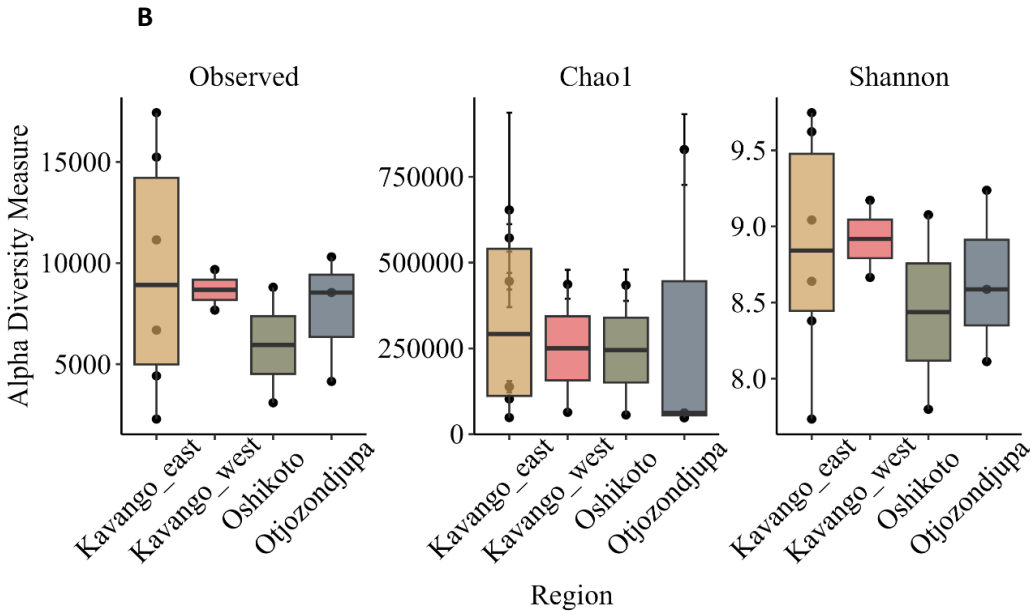


Figure 4-12. Diversity indices of irrigation water from (A) government green schemes and farms (B) and samples from different regions of Namibia

A Pearson correlation analysis (**Figure 4-13**) was conducted to explore the relationships between microbial alpha diversity indices and physicochemical parameters in irrigation water and sediment samples. The heatmap reveals several significant correlations. Strong negative correlations were observed between diversity metrics such as Chao1, ACE, Fisher, Pielou, InvSimpson, Simpson, and Shannon with heavy metals including copper, cobalt, cadmium, and chromium ($r < -0.5$, $^{**}p < 0.001$), suggesting that higher concentrations of these metals are associated with reduced microbial diversity and evenness. Conversely, significant positive correlations were identified between se.ACE, se.chao1, and certain variables like boron, nitrate, sodium, total alkalinity, and electrical conductivity ($r > 0.5$, $^{*}p < 0.01$), indicating potential roles of these parameters in influencing microbial estimation variability. A weak to moderate yet significant positive correlation was observed between pH and the coverage index ($r \sim 0.3$, $p < 0.05$). The dendrogram clustering further highlights groupings of co-varying physicochemical variables and diversity indices, implying potential shared environmental gradients or contaminant influences.

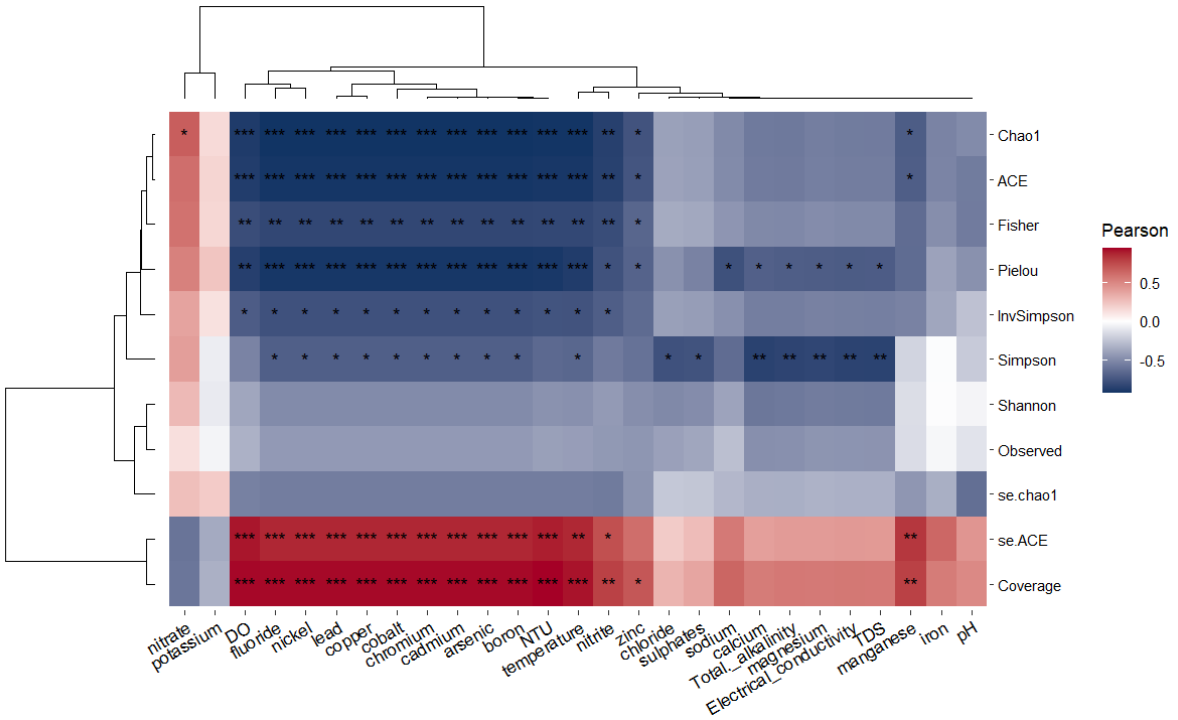


Figure 4-13. Heatmap showing Pearson correlation coefficients between alpha diversity indices and physicochemical parameters of water and sediment samples. Red indicates a positive, while blue indicates a negative correlation. The intensity of the colour corresponds to the strength of the correlation, and asterisks represent the level of statistical significance ($p < 0.05$: *, $p < 0.01$: **, $p < 0.001$: ***). Hierarchical clustering was applied to both alpha diversity metrics (rows) and environmental variables (columns)

The PCoA plot (**Figure 4-14**) visualises beta diversity among microbial communities based on sample type and region. From the plot, clear clustering patterns emerge, suggesting that microbial communities are influenced by both region and sample type. For instance, water and sediment samples from the same site often appear near each other, such as the paired Shitemo and Sikondo samples. Kavango West appears to show the greatest spread along PCoA1, while samples from Otjozondjupa are distinctly separated from the others along PCoA1 and PCoA2, indicating region-specific microbial communities. Similarly, Tsumeb water and sediment samples are located near each other but are distinct from other regions' samples.

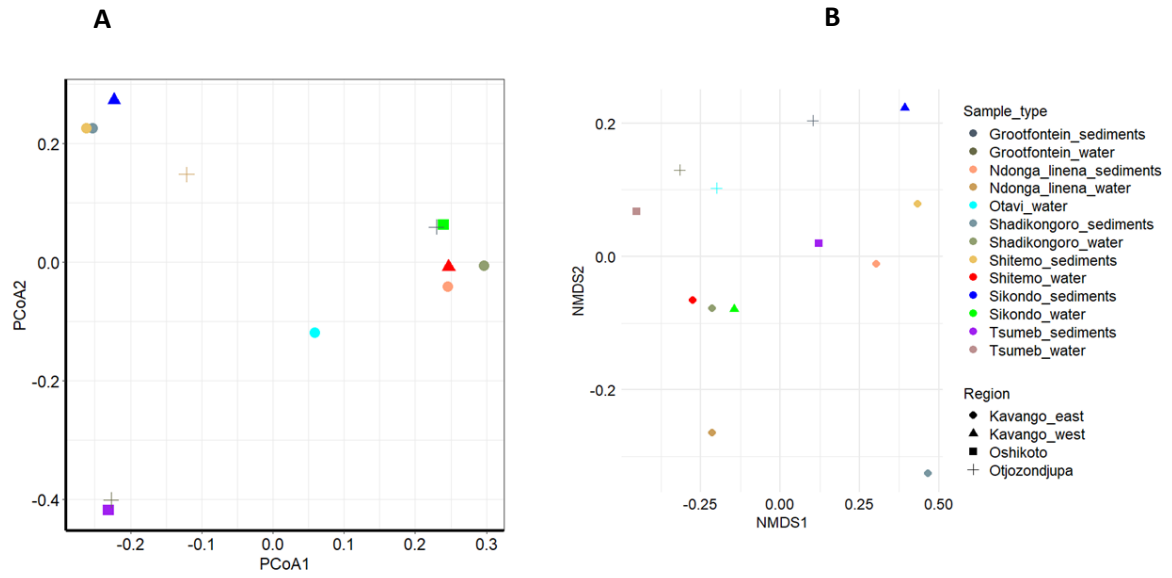


Figure 4-14. Principal coordinate analysis (PCoA) (A) and Non-metric multidimensional scaling (NMDS) (B) ordinations of bacterial communities from irrigation water collected in different sites across Namibia based on Bray–Curtis distances for 16S markers annotated by sampling type and region

To compare the relationship between bacterial communities in all the samples at the genus level, PCoA and unweighted pair group method with arithmetic mean (UPGMA) clustering based on the Bray–Curtis dissimilarity index were performed (**Figure 4-15**). The results reveal distinct microbial community structures across different sample types, as illustrated by the principal component analysis (PCA). The first principal component (PC1) explains 50% of the variance and is associated with specific bacterial genera, including *Pigmentiphaga*, *Lapillococcus*, *Nerskia*, *Pseudomonas*, Cl.500-29 (marine group), *Nocardioides*, *Tepidobacter*, and *Zymomonas*. A secondary clustering along PC1, accounting for 38.7% of the variance, further differentiates samples based on their environmental origins, such as sediments from locations like Grootfontein, Ndonga Linena, Shadikongoro, Shitemo, Sikondo, and Tsumeb. The second principal component (PC2), explaining 38.6% of the variance, highlights broader phylogenetic groupings, with *Thermodesulfobacteria* and *Pseudomonadota* as dominant phyla. Within *Pseudomonadota*, several subordinate taxa are identified, including *Chloroflexota*, *Myxococcota*, *Gemmatimonadota*, *Planctomycetota*, *Acidobacteriota*, *Bacillota*, and *Actinomycetota*. These patterns suggest that both sample type and geographic origin play significant roles in shaping microbial community composition. The findings underscore the influence of environmental conditions on microbial diversity, with distinct taxa associated with specific habitats.

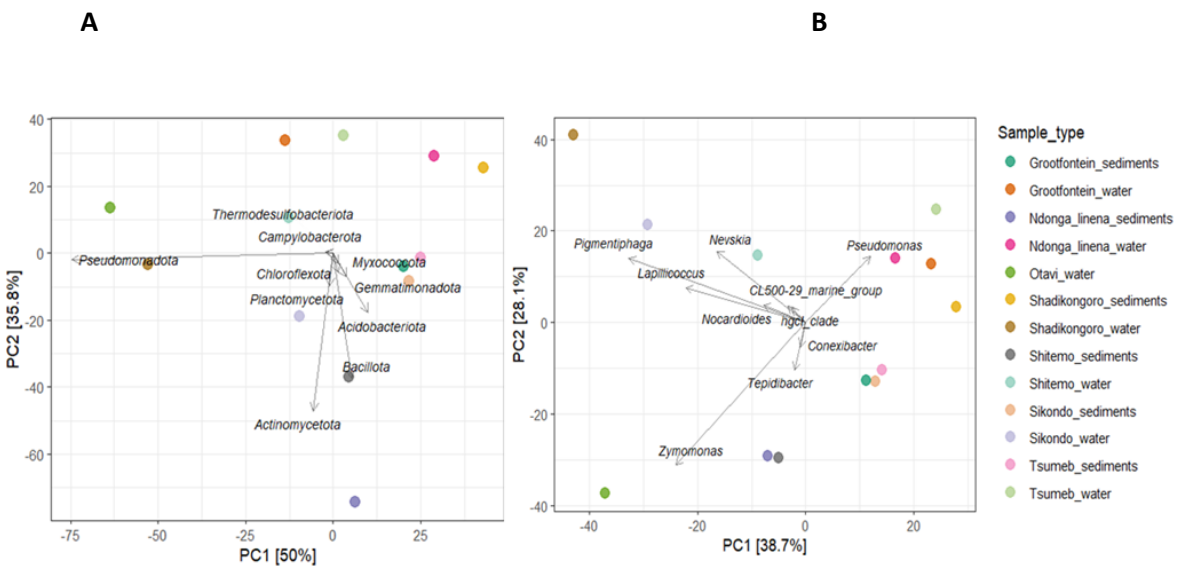


Figure 4-15. Principal Coordinates Analysis (PCoA) biplots showing microbial community composition across water and sediment samples from different sites in Namibia based on Bray–Curtis dissimilarity (A) phylum level and (B) genus level

4.2.3 Permutational Multivariate Analysis of Variance (PERMANOVA) test

The Permutational Multivariate Analysis of Variance (PERMANOVA) (**Table 4-12**) analysis revealed that microbial community composition differed significantly between water and sediment samples (R^2 = 0.0912, F = 1.1033, p = 0.002), indicating that sample type plays a critical role in shaping microbial assemblages. This significant distinction suggests that environmental conditions in water and sediment support distinct microbial populations. In contrast, no significant differences in microbial communities were observed across the four Namibian regions (R^2 = 0.2506, F = 1.0034, p = 0.360) or between green scheme and ordinary farm sites (R^2 = 0.2472, F = 0.9849, p = 0.818). Although the R^2 values for region and scheme suggest that these factors account for approximately 25% of the variation in microbial composition, the lack of statistical significance implies substantial overlap and variability within groups. These findings underscore the importance of sample type over geographic location or agricultural scheme in determining microbial community structure in these agroecosystems.

Table 4-12. PERMANOVA analysis assessing differences in microbial community composition across sample type (water vs. sediment), sampling region, and irrigation scheme

Comparison	df	R^2	F-value	p-value	Significance
Water vs Sediment	1	0.0912	1.1033	0.002	**
Region	3	0.2506	1.0034	0.360	ns
Scheme	3	0.2472	0.9849	0.818	ns

Significance levels: p < 0.01 = ();

ns = not significant.

4.2.4 Taxonomic classification at phylum, genus, and species levels

The analysis of the taxonomic community (**Figures 4-16 and 4-17**) showed that the relative abundance (%) of various bacterial phyla across different sample types collected from Oshikoto Farms, Kavango East, and Kavango West, with samples including Tsumeb L, Tsumeb S, Grootfontein L, Grootfontein S, Otavi L, Ndonga L, Ndonga S, Shadikongoro L, Shadikongoro S, Shitemo L, Shitemo S, Sikondo L, and Sikondo S. In Oshikoto and Otjozondjupa Farms, samples such as Tsumeb and Grootfontein predominantly feature *Actinomycetota* and *Pseudomonadota*, with additional contributions from *Bacteroidota* and minor phyla like *Acidobacteriota* and *Planctomycetota*. In contrast, Kavango East samples (Ndonga Linena, Shadikongoro) reveal a more diverse microbial composition, highlighting considerable abundances of *Actinomycetota*, *Pseudomonadota*, and *Methylomirabilota*, alongside *Cyanobacteria* and *Verrucomicrobiota*. Similarly, Kavango West samples (Sikondo) showed a comparable diversity, with *Actinomycetota* and *Pseudomonadota* remaining dominant, while *Candidatus_Eremiobacterota* and RCP2-54 also emerged as notable components in certain samples. A total of 19 phyla, including *Myxococcota*, *Gemmatimonadota*, *Bacteroidota*, *Chloroflexota*, *Verrucomicrobiota*, *Acidobacteriota*, *Planctomycetota*, *Bacillota*, *Actinomycetota*, *Pseudomonadota*, *Methylomirabilota*, *Nitrospirta*, *Armatimonadota*, *Thermodesulfobacteriota*, *Campylobacteria*, *Bdellovibrionota*, *Cyanobacteria*, *RCP2-54*, and others, with relative abundances varying strongly across samples. These results suggest that site-specific environmental or ecological factors play a crucial role in shaping the microbial community structures observed across the sampled regions.

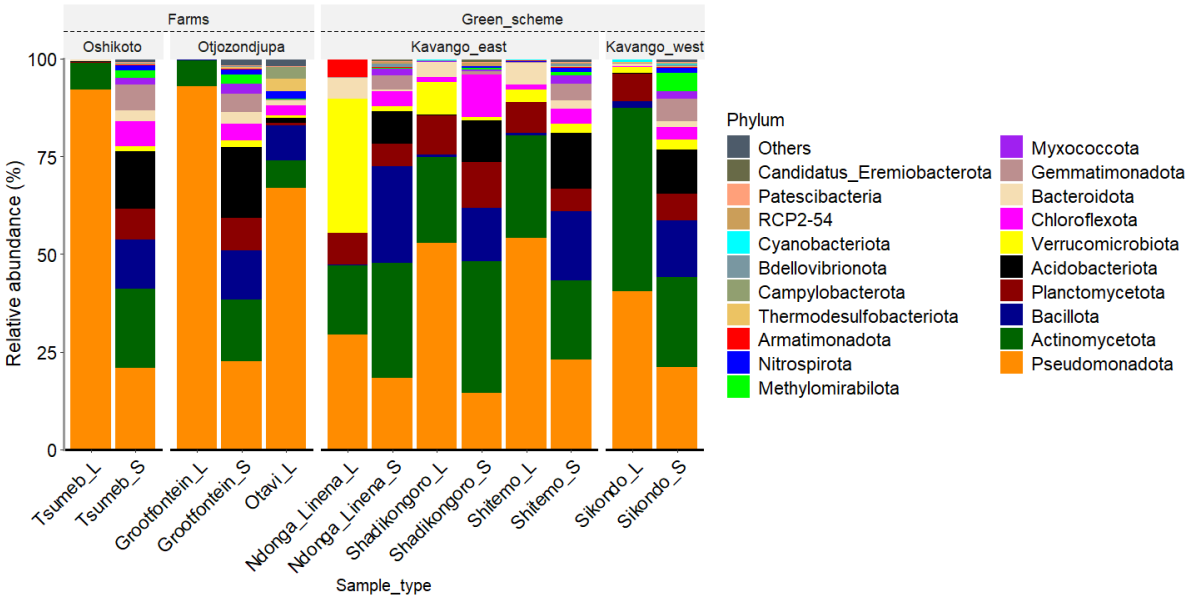


Figure 4-16. Relative abundance of bacterial phylum within microbial communities sampled from water & sediments used for irrigation across multiple sites in Namibia

The taxonomic analysis revealed that the most abundant genera were *Polynucleobacter* (~8% relative abundance) and *Bacillus* (~10%) in fresh water and soil from the vegetable crop, respectively. Low abundance (0.38%) of cyanobacterial groups were identified. Based on functional gene prediction, denitrification appears to be an important process in the soil community analysed here. Conversely, genes for nitrogen fixation were abundant in freshwater, indicating that the N-fixation plays a crucial role in this particular ecosystem. Moreover, pathogenicity islands, antibiotic resistance, and potential virulence-related genes were identified in both samples, but no toxigenic genes were detected. This study provides a better understanding of the community structure of an area under strong agricultural activity with regular irrigation and fertilisation with an organic compost made from animal carcasses. Additionally, the use of a metagenomic approach to investigate freshwater quality proved to be a relevant method to evaluate its use in an agricultural ecosystem.

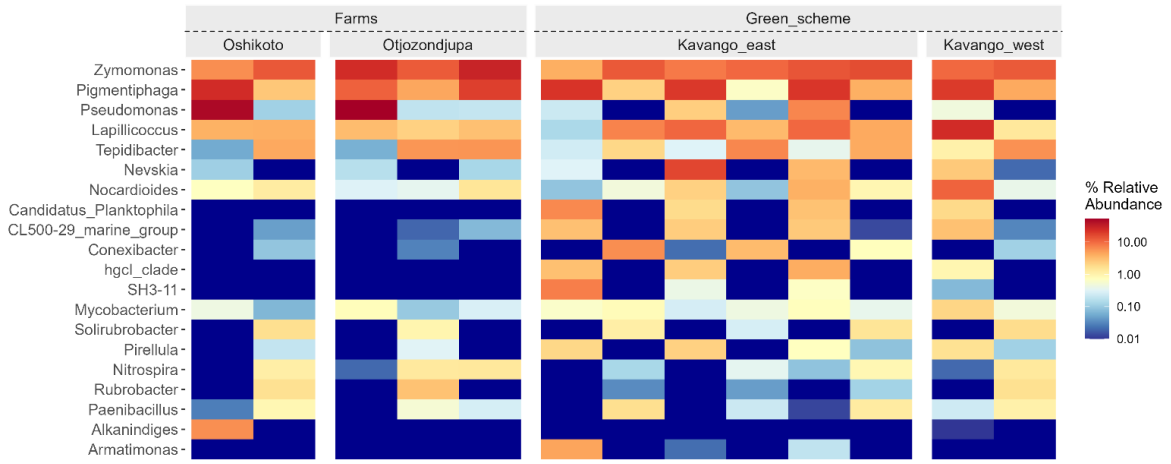


Figure 4-17. Relative abundance of bacterial genus within microbial communities sampled from water & sediments used for irrigation across Namibia

4.2.5 Venn Diagram

The Venn diagram (**Figure 4-18**) illustrates the distribution and overlap of unique and shared features among four regions: Kavango East, Kavango West, Otjozondjupa, and Oshikoto. Kavango East has the highest number of unique features, totalling 51,252 (46.3%), indicating a rich and distinct set of features not commonly shared with the other regions. This is followed by Otjozondjupa, with 22,571 (23.2%) unique features, and Kavango West, with 16,551 (15.1%). Oshikoto has the fewest unique features at 11,786 (10.5%).

There are several shared features among regions, but the overlaps are relatively minimal compared to the unique values. For example, Kavango East and Kavango West share 704 (3.2%) features, while Kavango East and Otjozondjupa share 190 (0.8%). Shared features among three or all four regions are very low, with only 2 features (0.1%) common to all four regions, and several intersections showing values of 1 or 7, representing negligible overlaps.

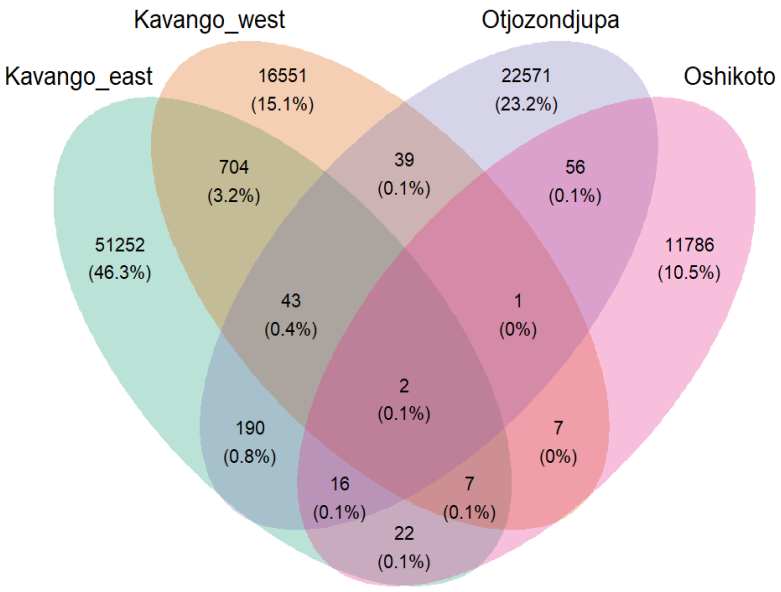


Figure 4-18. The Venn diagram illustrating the distribution and overlap of unique and shared features

4.2.6 Linear Discriminant Analysis Effect Size (LEfSe) Score

The Linear Discriminant Analysis Effect Size (LEfSe) score plot highlights the microbial taxa that are significantly different across four regions, Kavango East, Kavango West, Otjozondjupa, and Oshikoto, based on their relative abundance and discriminatory power. In Kavango East, several taxa, including *Thermoleophilia*, *Planctomycetes*, *Acidobacteriae*, and members of *Solirubrobacteraceae* and *Verrucomicrobiota* are highly enriched, suggesting a diverse and distinct microbial community structure in this region. Kavango West is predominantly characterised by taxa within the phylum *Actinomycetota*, such as *Intrasporangiaceae*, *Lapillicoccus*, and *Frankiales*, indicating a strong presence of actinobacterial groups likely influenced by specific soil or climatic conditions.

In Otjozondjupa, the microbial signature is marked by taxa like *Sphingomonadales*, *Zymomonas*, and *Campylobacterota*, pointing to a unique microbial profile that sets this region apart from the others. Oshikoto, while represented by fewer taxa, shows strong discriminatory markers such as *Alkanindiges* and *Actinomarinales*, which may be indicative of localised environmental adaptations. Overall, the LDA scores reveal that each region hosts a unique assemblage of microbial taxa, reflecting the influence of region-specific ecological, edaphic, or climatic factors on microbial community composition.

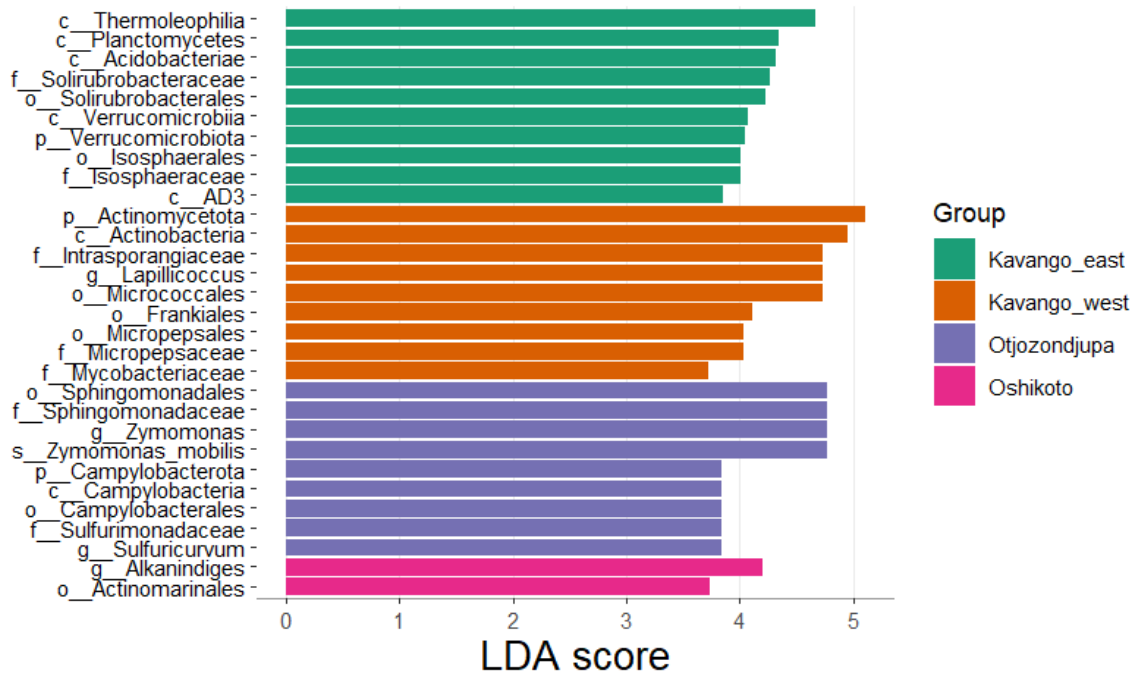


Figure 4-19. Linear Discriminant Analysis Effect Size analysis identifying differentially abundant bacterial taxa across four agricultural regions. The bar plot shows taxa with significant linear discriminant analysis (LDA) scores >2, representing biomarkers that significantly differ in relative abundance between the groups. Taxonomic ranks are abbreviated as follows: c – class, o – order, f – family, g – genus, s – species, and p – phylum

The visualisation (**Figure 4-19**) further supports earlier findings from the LDA analysis and Venn diagram, emphasising the strong biogeographical structuring of soil microbial communities in these Namibian regions. The cladogram (**Figure 4-20**) provides a phylogenetic overview of the differentially abundant microbial taxa across the four regions, Kavango-East, Kavango-West, Otjozondjupa, and Oshikoto, highlighting their evolutionary relationships and region-specific associations. Distinct coloured branches represent microbial groups enriched in each region: green for Kavango East, orange for Kavango West, purple for Otjozondjupa, and pink for Oshikoto. Kavango East shows a broad distribution of enriched taxa across several clades, particularly within phyla like *Verrucomicrobiota*, *Planctomycetes*, and *Thermoleophilia*, suggesting a highly diverse and phylogenetically spread microbiota. In contrast, Kavango West has a prominent cluster of enriched taxa within the phylum *Actinomycetota*, including orders such as *Micrococcales*, *Frankiales*, and families like *Intrasporangiaceae* and *Micropepsaceae*, reflecting a localised dominance of actinobacterial lineages. In Otjozondjupa, enriched taxa are mostly found within the phylum *Campylobacterota*, and include groups like *Sphingomonadales*, *Zymomonas*, and *Sulfurimonadaceae*, showing a distinct phylogenetic grouping that differentiates it from other regions. Oshikoto, while showing fewer enriched taxa, still

possesses distinct lineages such as *Alkanindiges* and *Actinomarinales*, indicating unique microbial signatures.

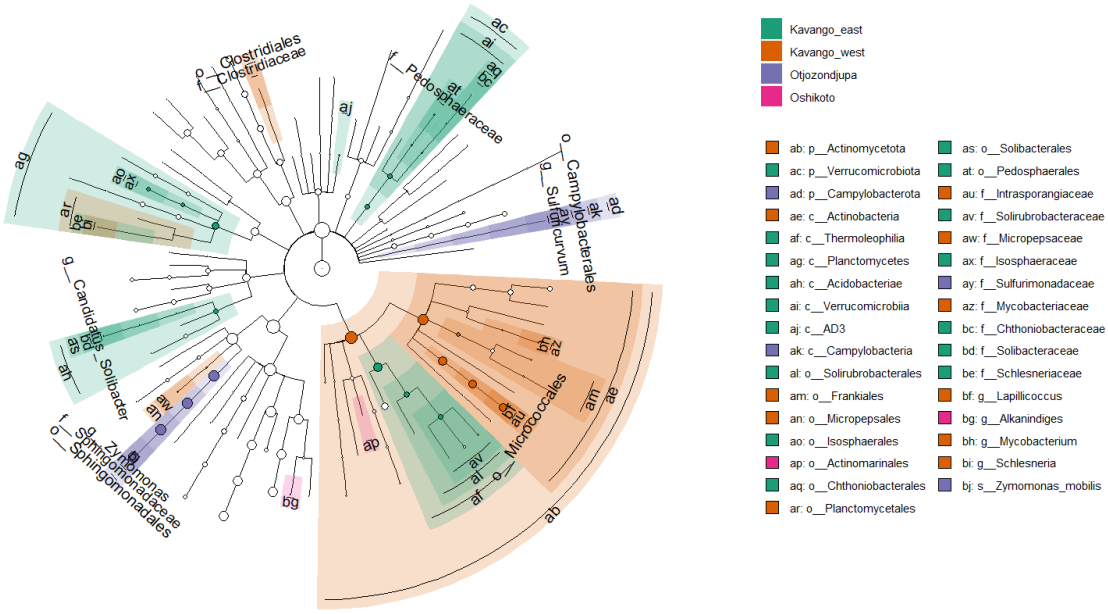


Figure 4-20. The taxonomic cladogram, showing results of LEfSe analysis of bacterial communities found across sampling sites in Namibia

4.2.7 Correlation analysis of the microbial taxa and environmental variables

Figure 4-21 illustrates significant correlations between environmental variables and the microbial phyla *Pseudomonadota* and *Actinomycetota*. Pearson's correlation matrix shows strong positive associations among factors like electrical conductivity, TDS, calcium, and heavy metals. Mantel test results reveal that both microbial groups are significantly influenced by several environmental parameters, particularly temperature, conductivity, TDS, and various metals. *Pseudomonadota* showed more strong and significant associations, while *Actinomycetota* was also affected by pH and trace metals. Overall, the analysis highlights that water chemistry, especially ionic strength and metal concentrations, plays a key role in shaping microbial community composition.

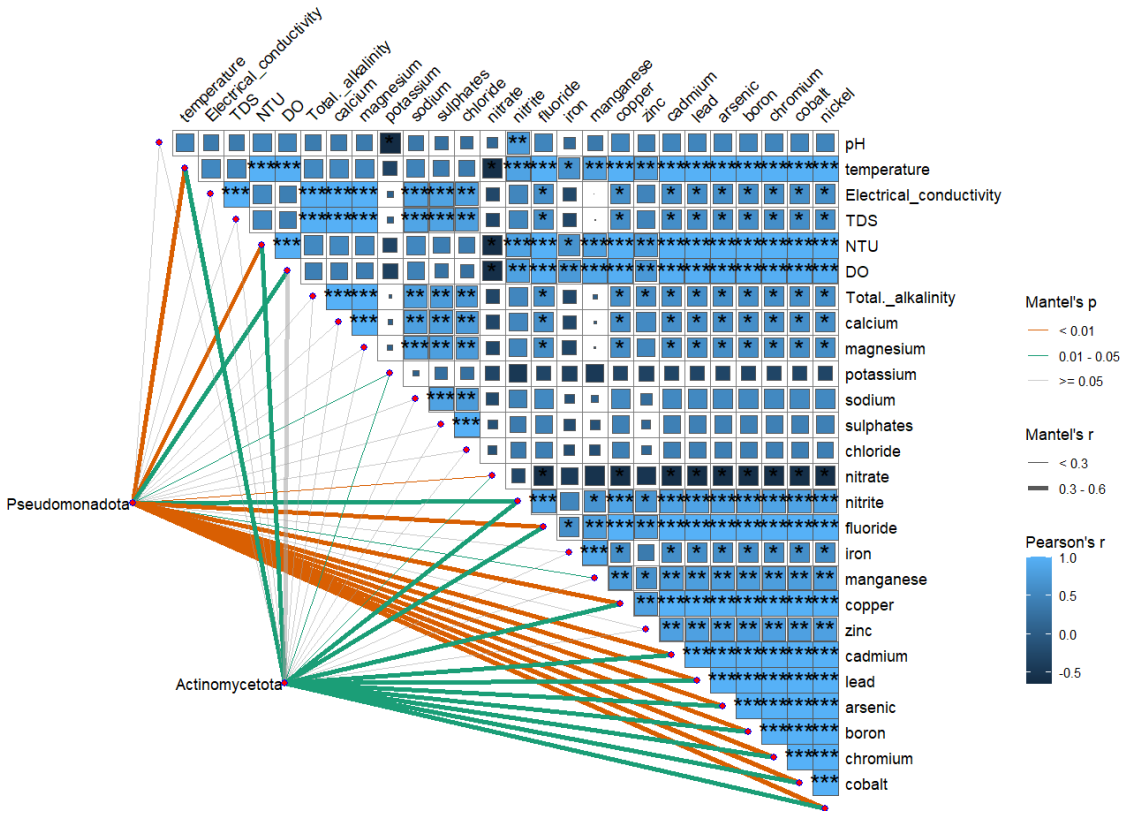


Figure 4-21. Correlation matrix and Mantel test plot showing relationships among environmental variables and their association with the relative abundance of dominant bacterial phyla (Pseudomonadota and Actinomycetota). The upper triangle presents pairwise Pearson correlation coefficients (color intensity indicates strength; blue: positive, white: neutral), with significance levels denoted by asterisks ($p < 0.05$: *, $p < 0.01$: **, $p < 0.001$: ***). The lower triangle depicts significant associations between environmental variables and bacterial phyla based on Mantel test results. Edge thickness represents Mantel's r values (with $r \geq 0.3$ shown), and edge colours represent p-value significance levels (green: $p < 0.01$, orange: $0.01 < p < 0.05$, gray: $p > 0.05$)

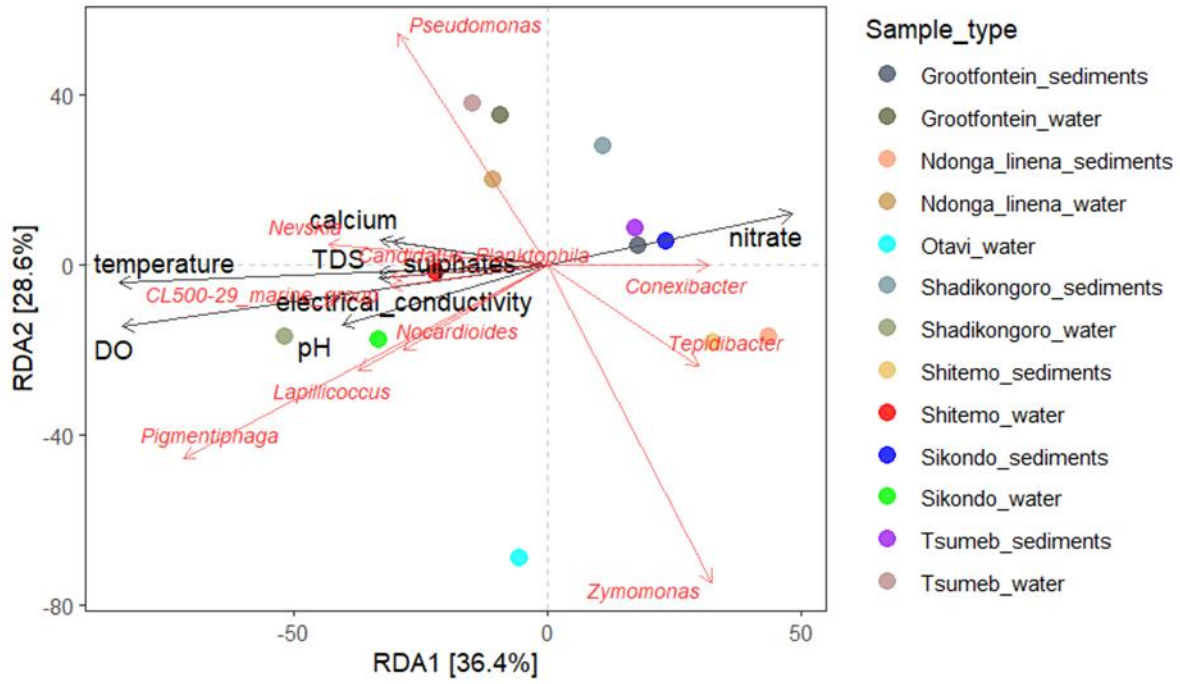


Figure 4-22. Redundancy analysis (RDA) of the various sample types and locations across Namibia

This Redundancy Analysis (RDA) plot (**Figure 4-22**) illustrates the relationships between environmental variables and bacterial community composition across different sample types, including both sediments and water samples from various locations. The first two RDA axes explain 36.4% (RDA1) and 28.6% (RDA2) of the total variation in the microbial community structure. Environmental vectors such as electrical conductivity, TDS, calcium, sulphates, and nitrate are strongly aligned along RDA1, indicating their major influence on microbial composition. Notably, *Pseudomonas*, *Conexibacter*, and *Tepidibacter* are associated with higher nitrate levels, while *Pigmentiphaga* and *Laplillicoccus* align with lower pH, temperature, and dissolved oxygen. Sample points cluster according to their types and locations, with clear separation between water and sediment samples, reflecting the influence of site-specific environmental conditions on microbial assemblages. This analysis underscores how physicochemical factors shape microbial diversity and distribution in aquatic and sediment environments.

4.2.8 Distribution of water and food-borne pathogens

The heatmap (**Figure 4-23**) revealed clear differences in the distribution of water- and food-borne pathogens between water (_*L*) and sediment (_*S*) samples across various sites. *Clostridium* was highly abundant in the Otavi water sample, while *Escherichia coli* was detected in multiple water samples, particularly at Shadikongoro and Grootfontein, indicating fecal contamination. Opportunistic pathogens such as *Klebsiella* and *Aeromonas* were also present, though at lower levels. In contrast, sediment samples showed minimal to no detectable levels of these pathogens. These findings suggest

that the water column in certain locations poses a greater public health risk than sediments, emphasising the need for targeted water quality monitoring and intervention strategies.

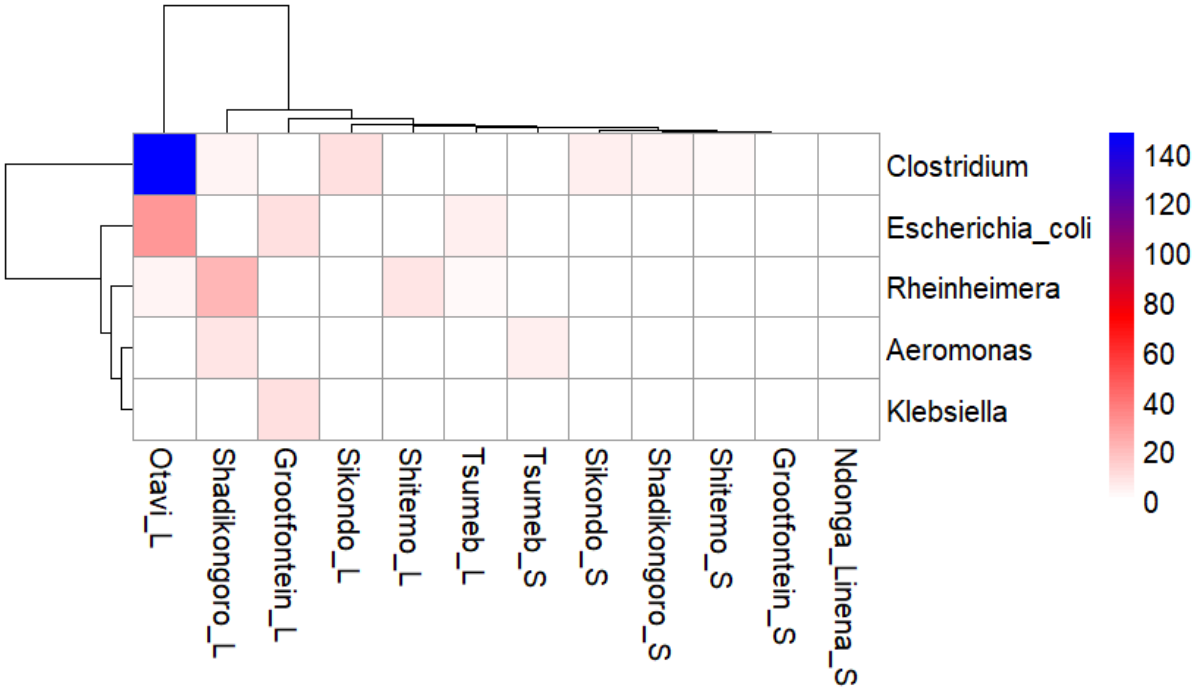


Figure 4-23. Heatmap of the food and water-borne pathogens

Lastly, the availability of water, in terms of both quality and quantity, is essential for the irrigation of crops and food processing. Climate change alters the patterns of rainfall, which could lead to droughts and impact water availability and quality, and this is crucial for irrigation (Hoxhua et al., 2025).

4.3 Objective 3: Assessment of the impact of climate change on water availability and food security

A detailed analysis of the precipitation characteristics over time is very important to assess the impacts of the changing climate on water resources, irrigation, and agriculture to a large extent (Das et al., 2021). Meteorological features such as the precipitation concentration index (PCI) and rainfall seasonality index are essential to characterise the spatial patterns of precipitation. The trends over the years are detected by employing the Mann-Kendall and the modified Mann-Kendall tests. Whereas the Sen's slope estimator was utilised to assess the magnitude of the changes.

4.3.1 SPATIO-TEMPORAL TREND ANALYSIS

The Mann-Kendall Test (**Table 4-13**) and modified Mann-Kendall Test (**Table 4-14**) were used to detect trends in the precipitation. All the irrigation places in the study showed no significant trends in precipitation ($p > 0.05$). However, the seasonal trends analysis (**Tables 4-15 to 4-18**) using the modified Mann-Kendall Trend analysis showed that during winter (**Table 4-17**), Grootfontein, Otavi, Tsumeb (parts of the maize-triangle), and Sikondo (green scheme) had statistically significant trends of precipitation ($p < 0.05$). During the spring season (**Table 4-18**), Ndonga Linena, Shadikongoro, Shitemo and Sikondo showed statistically significant trends but none from the maize triangle. Namibia's wet seasons are generally from November to April (**Table 4-19**); none of the places showed trends that were statistically significant. During the winter months, which are mainly May to October (**Table 4-18**), Grootfontein, Shadikongoro, and Sikondo showed statistically significant trends. Furthermore, applying the Hirsch-Slack test for the Seasonal Mann-Kendall test showed statistically significant trends for Grootfontein, Ndonga Linena, Shadikongoro, Shitemo and Sikondo. The Z-statistic and Mann-Kendall S statistic together showed strong decreasing trends (e.g., Grootfontein, $Z = -2.664$, $S = -1128$, and p-value = 0.0077). Lastly, the periodic assessment of the pattern of trends in the precipitation into Period 1 (1972-1980) in **Table 4-22**, Period 2 (1981 – 1990) in **Table 4-23**, Period 3 (1991 – 2000) in **Table 4-24**, Period 4 (2001 – 2010) in **Table 4-25**, and Period 5 (2011 - 2023) in **Table 4-26**, showed no statistically significant trends.

Table 4-13. Mann-Kendal Analysis for Precipitation, 1972 – 2023

PLACE	Precipitation, Mann-Kendall Test	
	Kendall's tau	p-value
Grootfontein	-0.0288	0.289
Ndonga Linena	-0.0235	0.389
Otavi	-0.0196	0.472
Shadikongoro	-0.0216	0.426
Shitemo	-0.0235	0.389
Sikondo	-0.0281	0.304
Tsumeb	-0.0212	0.438

Table 4-14. Modified Mann-Kendall Trend Analysis for Precipitation, 1972-2023

PLACE	Precipitation, Modified Mann-Kendall Test		
	*Kendall's tau	*p-value	Sen's slope
Grootfontein	-0.0283	0.207	0.000
Ndonga Linena	-0.0229	0.153	0.000
Otavi	-0.0192	0.397	0.000
Shadikongoro	-0.0229	0.136	0.000
Shitemo	-0.0229	0.153	0.000
Sikondo	-0.0274	0.129	0.000
Tsumeb	-0.0206	0.303	0.000

Nambian Seasons Modified Mann-Kendall Test Analyses

Table 4-15. Modified Mann-Kendall Test Analyses for the Summer Season

PLACE	Precipitation, Modified Mann-Kendall Test - SUMMER		
	*Kendall's tau	*p-value	Sen's slope
Grootfontein	0.052	0.323	0.109
Ndonga Linena	0.027	0.605	0.067
Otavi	0.057	0.307	0.142
Shadikongoro	0.036	0.102	0.081
Shitemo	0.070	0.605	0.168
Sikondo	0.027	0.515	0.067
Tsumeb	0.024	0.404	0.054

Table 4-16. Modified Mann-Kendall Test Analyses for the Autumn Season

PLACE	Precipitation, Modified Mann-Kendall Test - AUTUMN		
	*Kendall's tau	*p-value	Sen's slope
Grootfontein	-0.032	0.363	-0.004
Ndonga Linena	-0.044	0.177	-0.005
Otavi	-0.019	0.492	-0.002
Shadikongoro	-0.032	0.271	-0.004
Shitemo	-0.044	0.177	-0.005
Sikondo	-0.049	0.173	-0.005
Tsumeb	-0.012	0.711	-0.000

Table 4-17. Modified Mann-Kendall Test Analyses for the Winter Season

PLACE	Precipitation, Modified Mann-Kendall Test - WINTER		
	*Kendall's tau	*p-value	Sen's slope
Grootfontein	-0.016	0.017	0.000
Ndonga Linena	-0.020	0.692	0.000
Otavi	-0.137	0.020	0.000
Shadikongoro	-0.047	0.367	0.000
Shitemo	-0.020	0.692	0.000
Sikondo	-0.092	0.031	0.000
Tsumeb	-0.097	0.035	0.000

Table 4-18. Modified Mann-Kendall Test Analyses for the Spring Season

PLACE	Precipitation, Modified Mann-Kendall Test - SPRING		
	*Kendall's tau	*p-value	Sen's slope
Grootfontein	-0.081	0.096	-0.031
Ndonga Linena	-0.106	0.030	-0.039
Otavi	-0.074	0.200	-0.039
Shadikongoro	-0.115	0.013	-0.036
Shitemo	-0.106	0.030	-0.039
Sikondo	-0.100	0.036	-0.032
Tsumeb	-0.072	0.149	-0.019

WET & DRY SEASON MANN-KENDALL TREND ANALYSIS

Table 4-19. Wet Season (November to April)

PLACE	WET SEASON MANN-KENDALL TREND ANALYSIS			
	Z	**p-value**	**S**	**tau**
Grootfontein	0.557	0.578	1026	0.0211
Ndonga Linena	0.388	0.698	715	0.0147
Otavi	0.648	0.517	1194	0.0246
Shadikongoro	0.877	0.381	1615	0.0333
Shitemo	0.388	0.698	715	0.0147
Sikondo	0.464	0.642	856	0.0176
Tsumeb	0.376	0.707	694	0.0143

Table 4-20. Dry Season (May to October)

PLACE	DRY SEASON MANN-KENDALL TREND ANALYSIS			
	Z	**p-value**	**S**	**tau**
Grootfontein	-2.581	0.0100	-4618	-0.103
Ndonga Linena	-1.778	0.0759	-3137	-0.072
Otavi	-1.866	0.0621	-3331	-0.075
Shadikongoro	-2.201	0.0278	-3955	-0.087
Shitemo	-2.775	0.0759	-3137	-0.072
Sikondo	-2.376	0.0175	-4182	-0.096
Tsumeb	-1.841	0.0656	-3204	-0.075

SEASONAL MANN-KENDALL TREND TEST (HIRSCH-SLACK TEST)

Table 4-21. Seasonal Trend Variations using the Hirsch-Slack Test

PLACE	SEASONAL MANN-KENDALL TREND TEST (HIRSCH-SLACK TEST)			
	Z	p-value	S	VarS
Grootfontein	-2.664	0.0077	-1128	179024
Ndonga Linena	-2.100	0.0357	-883	176426
Otavi	-1.919	0.0550	-813	179122
Shadikongoro	-2.087	0.0369	-891	181887
Shitemo	-2.100	0.0357	-883	176426
Sikondo	-2.772	0.0067	-1131	173660
Tsumeb	-1.775	0.0759	-731	169174

PERIODIC MANN-KENDALL TREND ANALYSIS

Table 4-22. Precipitation Trend Variation, Period 1 (1972 – 1980)

PLACE	PERIOD 1 (1972-1980)			
	Z	p-value	S	tau
Grootfontein	0.0186	0.985	8	0.0014
Ndonga Linena	0.157	0.875	60	0.0106
Otavi	0.152	0.879	58	0.0102
Shadikongoro	0.149	0.882	57	0.0100
Shitemo	0.157	0.875	60	0.0106
Sikondo	0.208	0.836	79	0.0139
Tsumeb	0.306	0.759	116	0.0204

Table 4-23. Precipitation Trend Variation, Period 2 (1981 – 1990)

PLACE	PERIOD 2 (1981-1990)			
	Z	p-value	S	tau
Grootfontein	-0.454	0.650	-201	-0.0284
Ndonga Linena	-0.478	0.633	-211	-0.0300
Otavi	-0.323	0.747	-143	-0.0203
Shadikongoro	-0.518	0.604	-229	-0.0324
Shitemo	-0.478	0.633	-211	-0.0300
Sikondo	-0.439	0.661	-194	-0.0276
Tsumeb	-0.545	0.586	-240	-0.0345

Table 4-24. Precipitation Trend Variation, Period 3 (1991 – 2000)

PLACE	PERIOD 3 (1991-2000)			
	Z	p-value	S	tau
Grootfontein	0.205	0.984	10	0.0014
Ndonga Linena	0.032	0.975	15	0.0022
Otavi	0.175	0.861	78	0.0111
Shadikongoro	0.048	0.962	22	0.0032
Shitemo	0.032	0.975	15	0.0022
Sikondo	0.112	0.911	50	0.0072
Tsumeb	0.149	0.882	66	0.0095

Table 4-25. Precipitation Trend Variation, Period 4 (2001 – 2010)

PLACE	PERIOD 4 (2001-2010)			
	Z	p-value	S	tau
Grootfontein	-0.103	0.918	-46	-0.0066
Ndonga Linena	-0.057	0.955	-26	-0.0037
Otavi	-0.171	0.864	-76	-0.0109
Shadikongoro	-0.096	0.924	-43	-0.0061
Shitemo	-0.057	0.955	-26	-0.0037
Sikondo	-0.128	0.898	-57	-0.0082
Tsumeb	-0.268	0.789	-118	-0.0172

Table 4-26. Precipitation Trend Variation, Period 5 (2011 – 2023)

PLACE	PERIOD 5 (2011-2023)			
	Z	p-value	S	tau
Grootfontein	-0.487	0.627	-316	-0.0270
Ndonga Linena	-0.227	0.820	-148	-0.0127
Otavi	-0.586	0.558	-381	-0.0323
Shadikongoro	-0.508	0.611	-331	-0.0280
Shitemo	-0.227	0.820	-148	-0.0127
Sikondo	-0.277	0.782	-180	-0.0155
Tsumeb	-0.510	0.610	-331	-0.0283

4.3.2 Annual Precipitation Variations

(a) Grootfontein

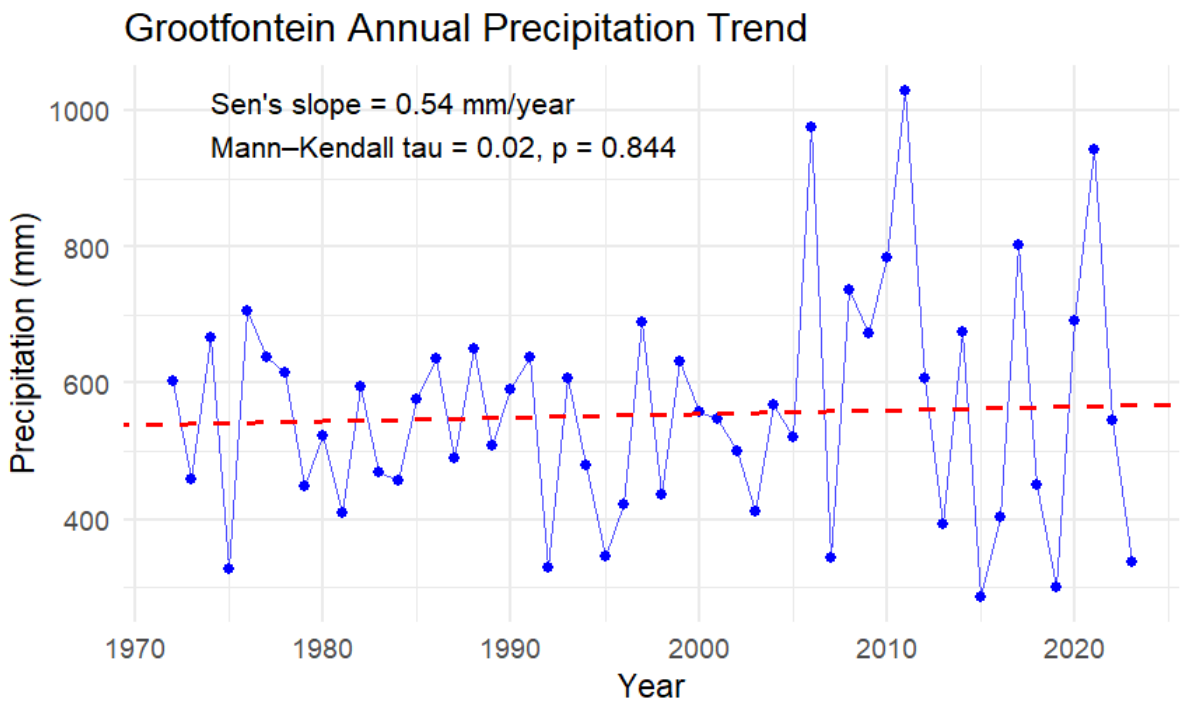


Figure 4-24. Annual precipitation for Grootfontein for the 1972 – 2023

(b) Ndonga Linena

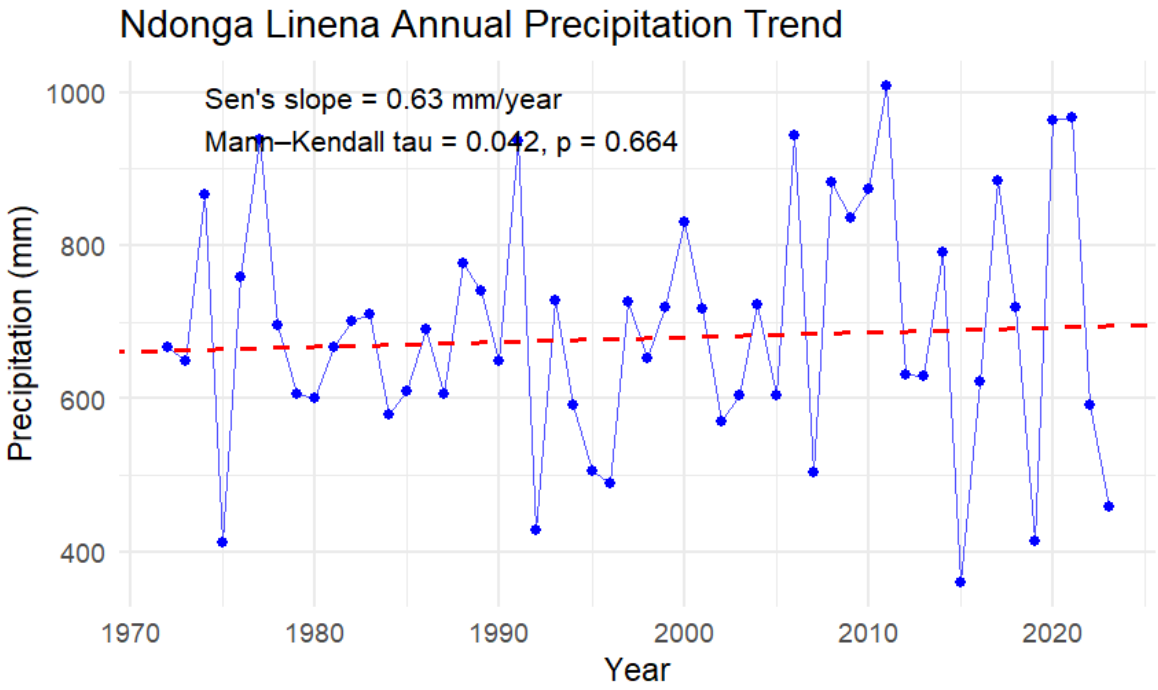


Figure 4-25. Annual precipitation trends for Ndonga Linena for the period 1972 – 2023

(c) Otavi

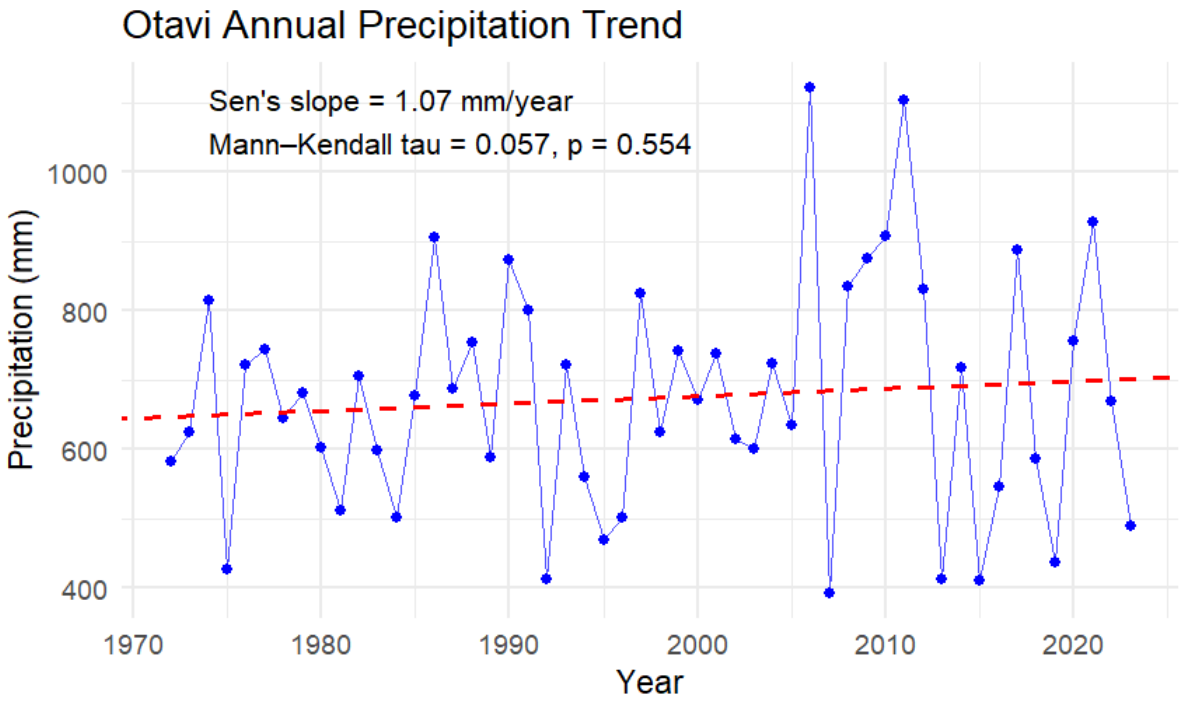


Figure 4-26. Annual precipitation trends for Otavi for the period 1972 – 2023

(d) Shadikongoro

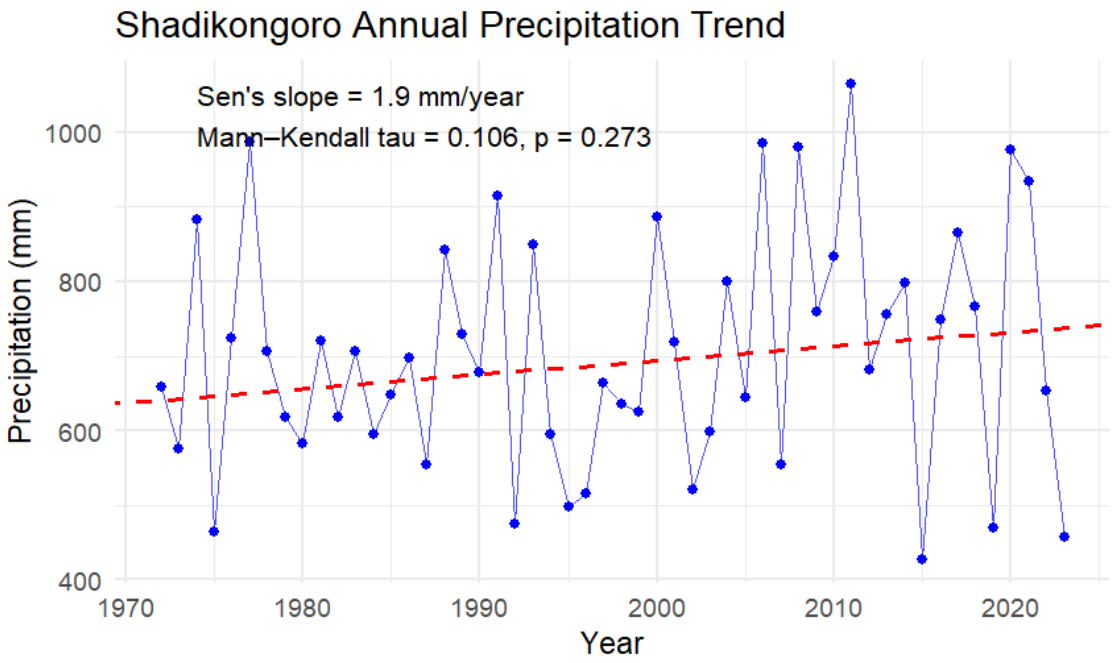


Figure 4-27. Annual precipitation trends for Shadikongoro for the period 1972 – 2023

(e) Shitemo

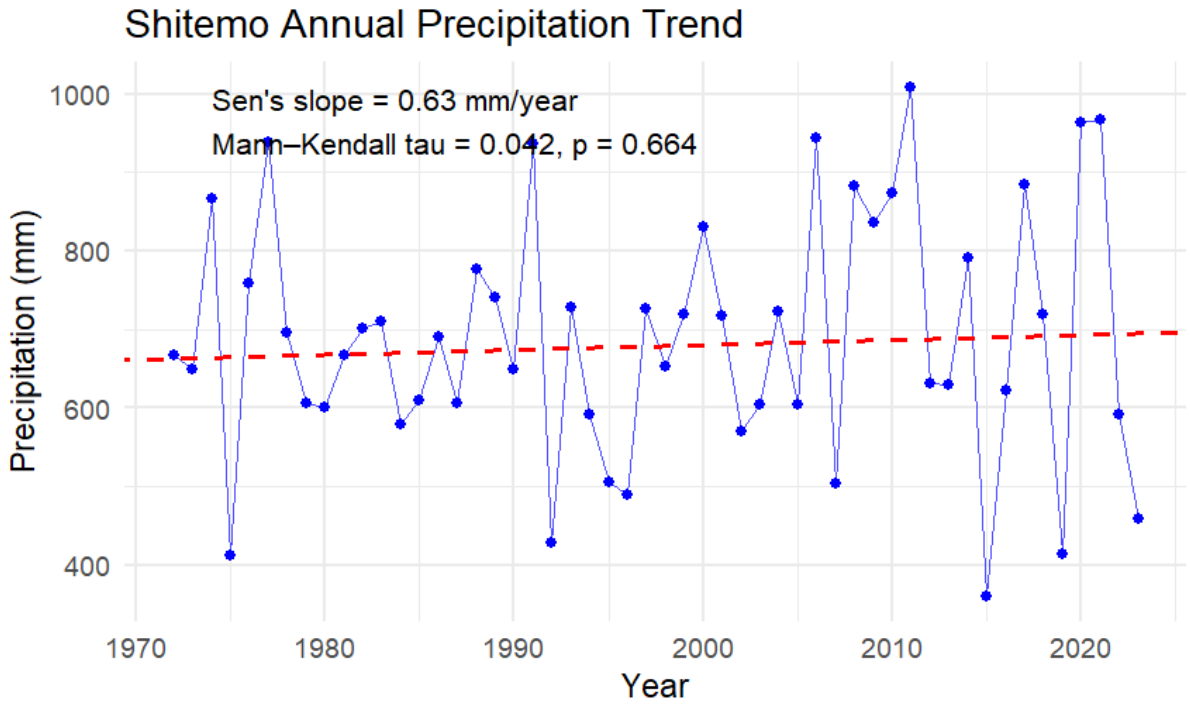


Figure 4-28. Annual precipitation trends for Shitemo for the period 1972 – 2023

(f) Sikondo

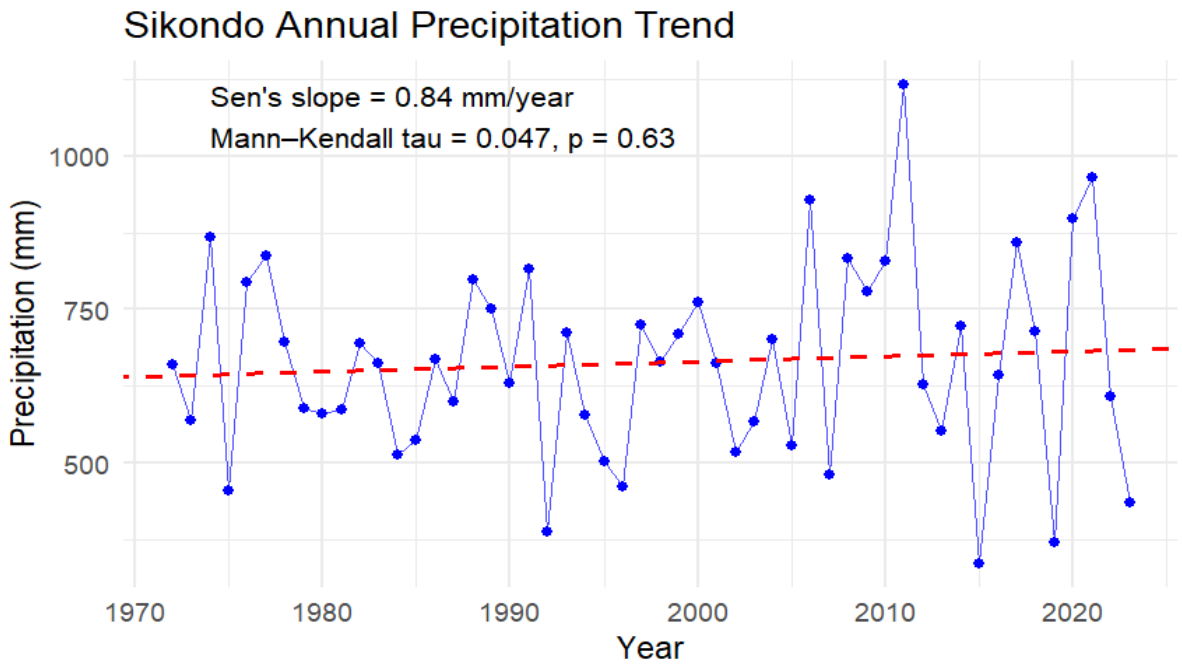


Figure 4-29. Annual precipitation trends for Shitemo for the period 1972 – 2023

(g) Tsumeb

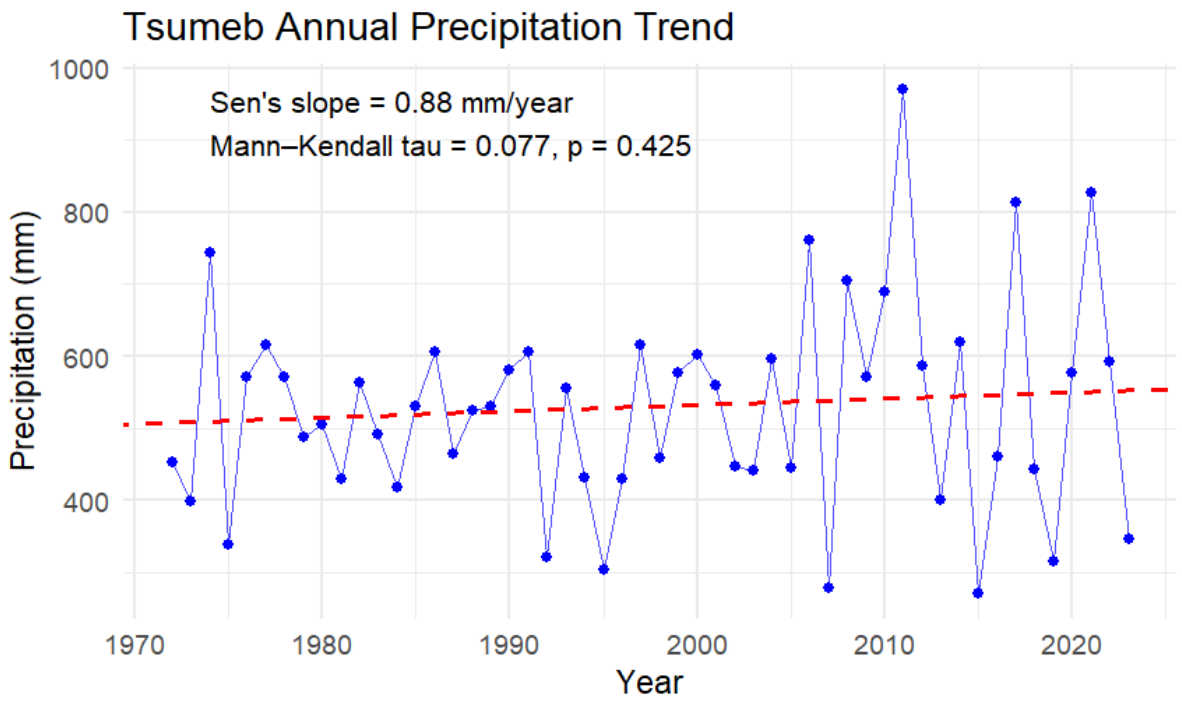


Figure 4-30. Figure Annual precipitation trends for Tsumeb for the period 1972-2023

Precipitation Concentration Index (PCI)

The descriptive statistical summary precipitation concentration index for various locations is shown in **Table 4-27**, for the period of 1972 – 2023. All the locations had a mean annual distribution of PCI values greater than 20. While **Table 4-28** indicated the classification ranges of the PCI. Grootfontein and Tsumeb recorded the highest PCI values of 36.64 and 36.19, respectively, and interestingly, it was recorded in the same year (2013), and these locations are just 60km apart. While places such as Otavi and Ndonga Linena had their highest PCI values recorded in different years (2021 and 1994, respectively). The lowest PCI values ranged from 16.00 at Grootfontein (in 1973) to 17.02 at Sikondo (in 2010).

Table 4-27. Descriptive Statistical Summary of the Concentration Index of Various Places across Namibia

PRECIPITATION CONCENTRATION INDEX					
PLACE	**Mean-PCI**	**Highest-PCI**	**Year**	**Lowest-PCI**	**Year**
Grootfontein	22.07	36.64	2013	16.00	1973
Ndonga Linena	22.03	34.24	1994	16.51	1984
Otavi	21.91	33.45	2021	16.19	2007
Shadikongoro	22.24	34.02	2021	16.17	1986
Shitemo	22.03	34.24	1994	16.51	1984
Sikondo	22.12	32.81	1994	17.02	2010
Tsumeb	23.14	36.19	2013	16.47	1973

According to **Table 4-27**, the uniform rainfall concentrations (PCI < 10) were never recorded for any of the locations, where the lowest mean PCI value was found at Otavi (PCI = 21.91) in 2007. Since all the locations had a mean that was greater than 20, the PCI classification, therefore, showed that they all experienced strongly irregular precipitation distributions due to the high precipitation concentrations attested by the values of the highest-PCIs. Furthermore, even during the periods of the lowest-PCI, all their values fell in the classification of $16 < PCI \leq 20$, thereby implying that the precipitation distribution was irregular. The irregularity of the precipitation concentrations was further shown graphically in **Figures 4-31 to 4-37**.

Table 4-28. Classification ranges of the precipitation concentration index (PCI)

PCI values and ranges	Description of Temporal Distributions
PCI ≤ 10	Uniform monthly precipitation (low precipitation concentration)
10 < PCI ≤ 15	Moderate precipitation distribution
16 < PCI ≤ 20	Irregular precipitation distribution
PCI > 20	Strongly irregular precipitation distribution (high precipitation concentration

a) Grootfontein

The PCI values for Grootfontein over time in **Figure 4-31** showed an inconsistent, from irregular to strongly irregular distribution of precipitation. There was no period when a uniform to moderate distribution was observed.

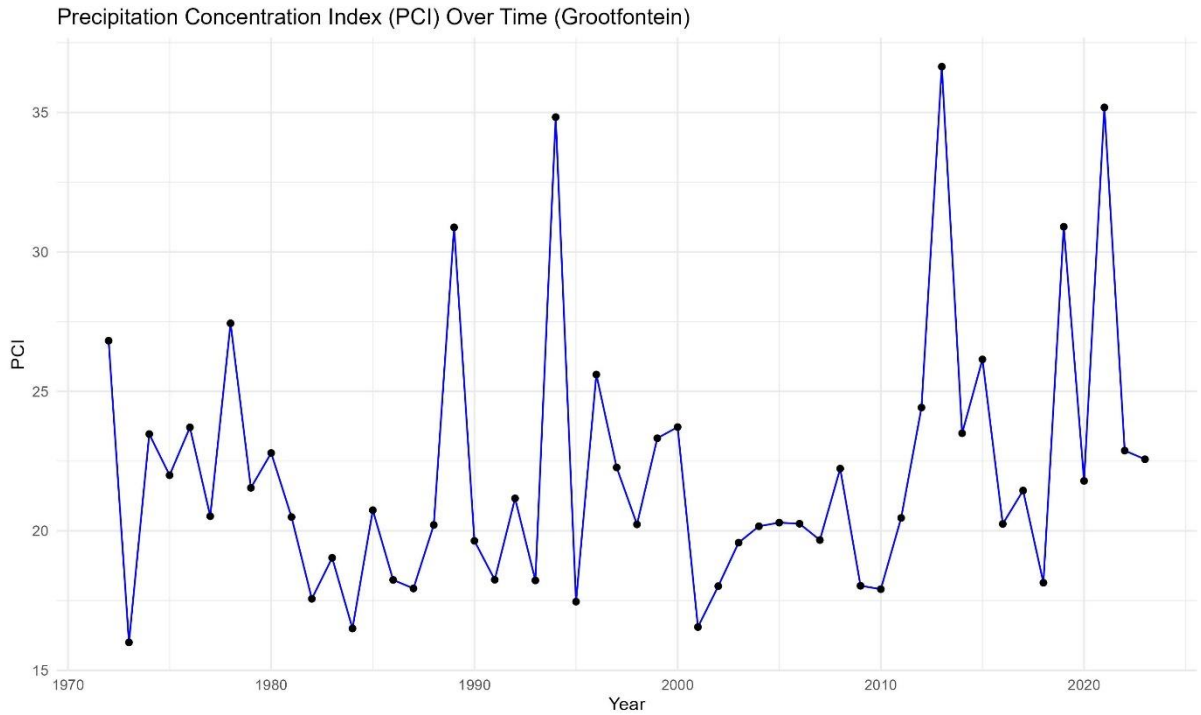


Figure 4-31. Precipitation Concentration Index for Grootfontein

b) Ndonga Linena

The PCI values for Ndonga Linena over time in **Figure 4-32** showed an inconsistent, irregular to a strongly irregular distribution of precipitation. There was no time when a uniform to moderate distribution was observed.

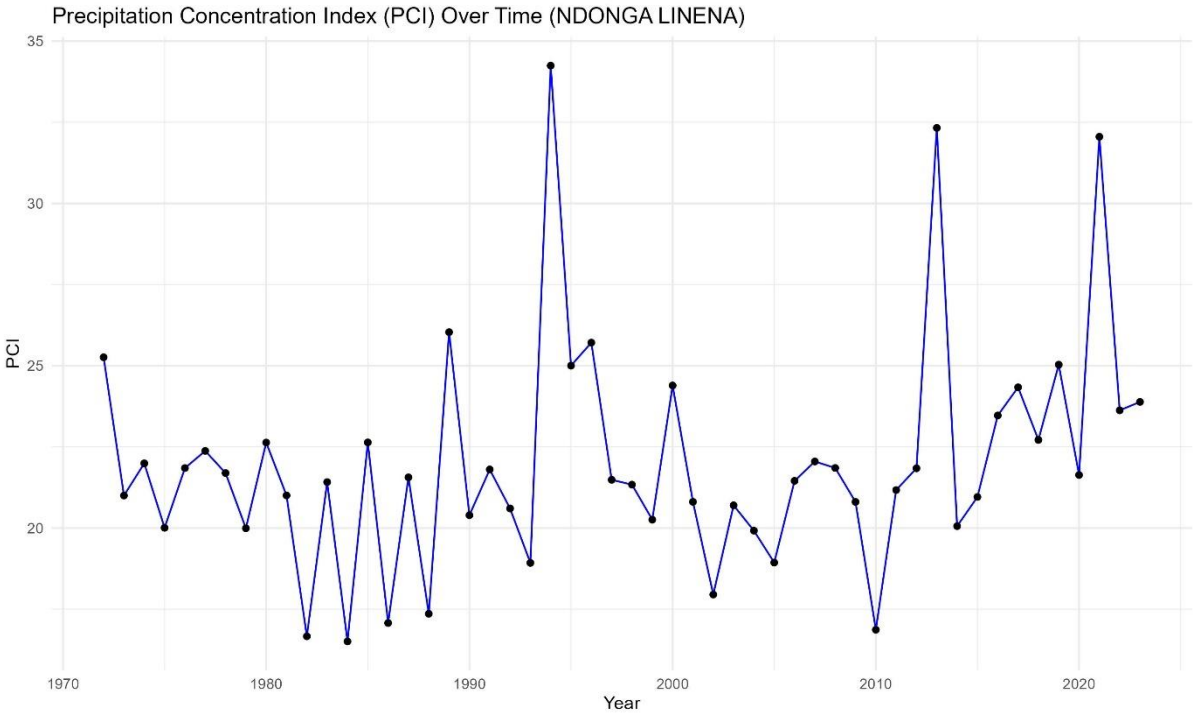


Figure 4-32. Precipitation Concentration Index for Ndonga Linena

c) Otavi

The PCI values for Otavi over time in **Figure 4-33** showed an inconsistent, irregular to a strongly irregular distribution of precipitation. There was no time when a uniform to moderate distribution was observed.

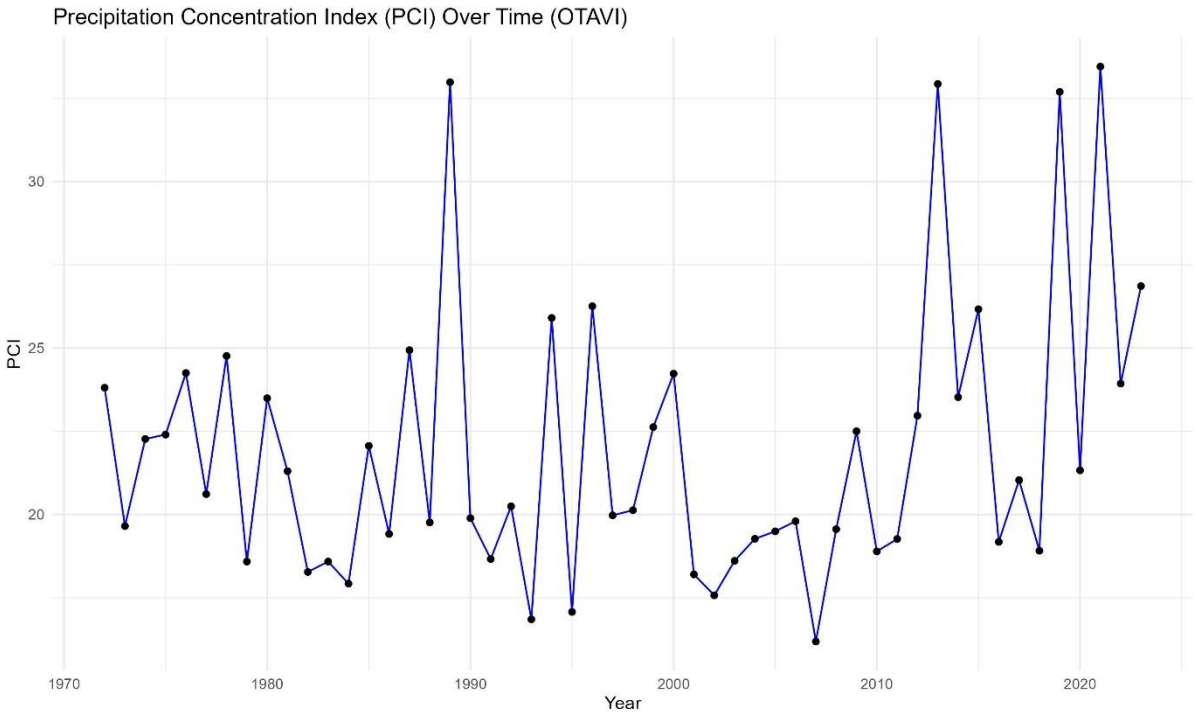


Figure 4-33. Precipitation Concentration Index for Otavi

d) Shadikongoro

The PCI values for Shadikongoro over time in **Figure 4-34** showed an inconsistent, irregular to a strongly irregular distribution of precipitation. There was no time when a uniform to moderate distribution was observed.

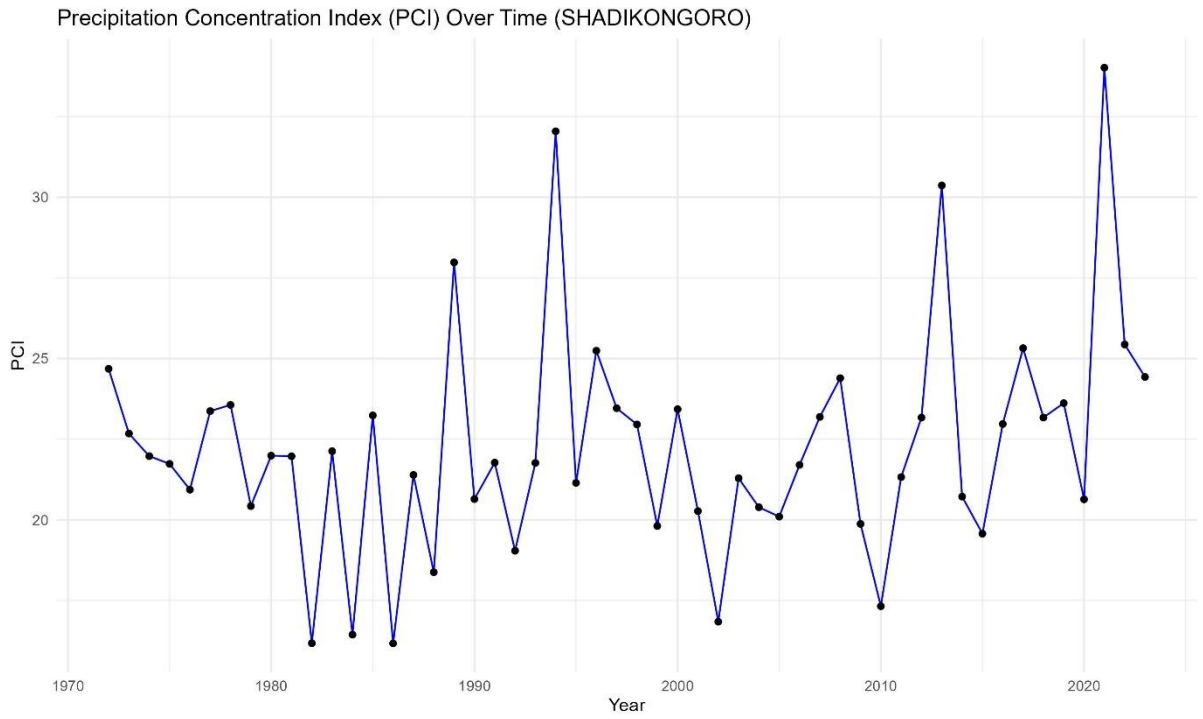


Figure 4-34. Precipitation Concentration Index for Shadikongoro

e) Shitemo

The PCI values for Shitemo over time in **Figure 4-35** showed an inconsistent, irregular to a strongly irregular distribution of precipitation. There was no time when a uniform to moderate distribution was observed.

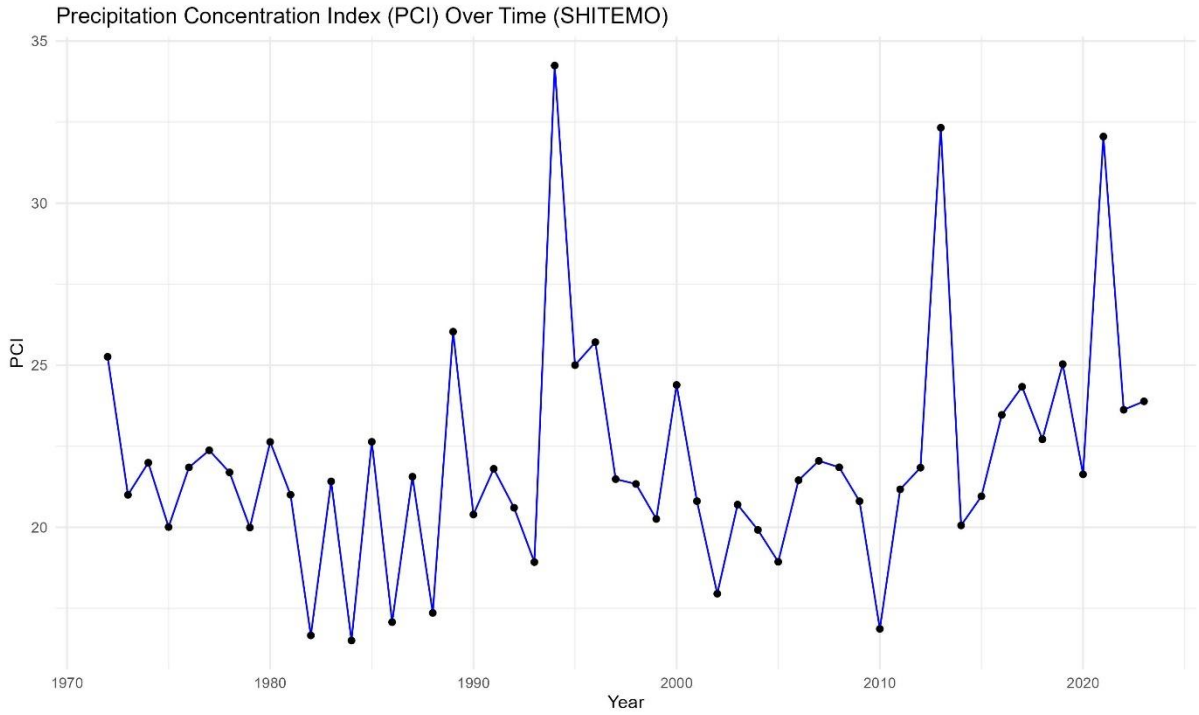


Figure 4-35. Precipitation Concentration Index for Shitemo

f) Sikondo

The PCI values for Sikondo over time in **Figure 4-36** showed an inconsistent, irregular to a strongly irregular distribution of precipitation. There was no time when a uniform to moderate distribution was observed.

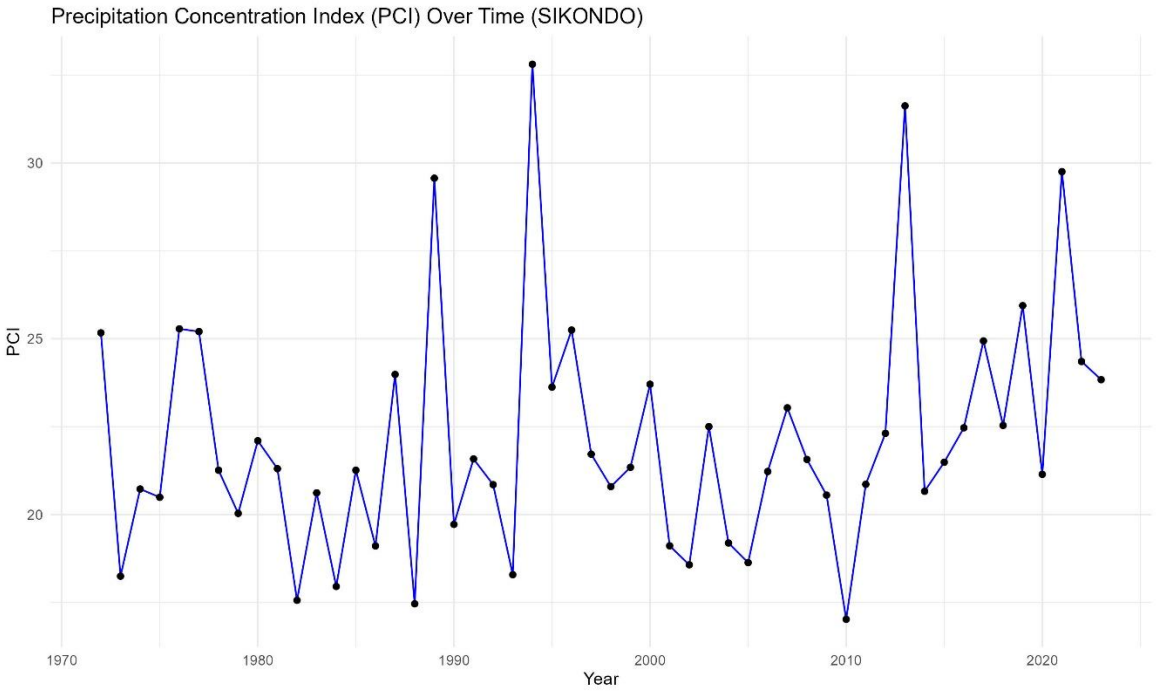


Figure 4-36. Precipitation Concentration Index for Sikondo

g) Tsumeb

The PCI values for Tsumeb over time in **Figure 4-37** showed an inconsistent, irregular to a strongly irregular distribution of precipitation. There was no time when a uniform to moderate distribution was observed.

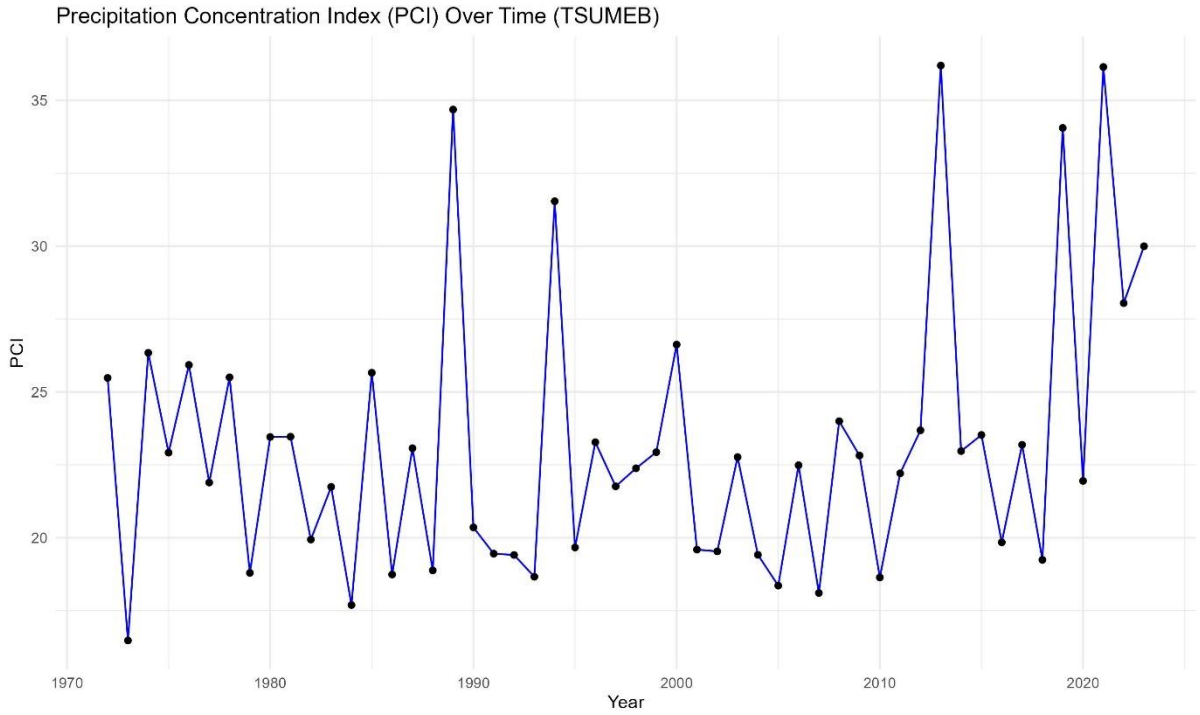


Figure 4-37. Precipitation Concentration Index for Tsumeb

Standard Precipitation Index (SPI) & Standard Precipitation Evapotranspiration Index (SPEI)

The analysis of the individual location for SPI and SPEI (**Figures 4-38 to 4-51**) gave meaningful insight into the localised drought trends. The indices were computed at 3-, 6-, and 12-month time scales for each study location. The SPI-3-month time scales gave understanding of the short-term wet or dry conditions, SPI-6-month time scales provided insight into the medium-term conditions, and the SPI-12-month time scales indicated the long-term drought or wet periods. The SPI-3-month time scales were particularly relevant for short-term rainfall variability to assess for seasonal wet and dry conditions, which could significantly be associated with crop growth and short-term water supply. Unlike the SPI-6-month, which showed medium-term patterns that are important for river flows, reservoir levels, and extended cropping systems.

Plots in **Figures 4-38 to 4-44** on the variation of the SPI, brow and blue colour coding would indicate dry and wet conditions, respectively. The drought thresholds (-1, -1.5, -2) were indicated by the dashed red lines, while the dashed green lines indicated the wet thresholds (+1, +1.5, +2). Again, the orange colour shading in these figures would also indicate mild, moderate, and severe drought, and blue shades for mild, moderate, and severe wet conditions.

The drought events examined on a 12-month time scale for Grootfontein showed that the most severe droughts occurred in 1995, 2013, 2015, 2019, and 2023 with severities of -24.14, -23.13, -19.91, -24.61, and -11.63, respectively. It was noted further that in the earlier decades (1970s, 1980s, and 1990s), although there were periods of severe droughts too, however the duration of the droughts was generally one month, except for 1979, when it lasted for 8 months and was much more severe than usual at -9.87. It started off at the peak of the summer season on 01/03/1979 until 01/10/1979. However, from the year 1975, the droughts not only became more severe and intense but with much longer durations. The most severe and intense drought occurred in 2019, with a drought severity of -24.61 and intensity of -2.46, the onset was 01/03/2019 and termination on 01/12/2019, thus with a duration of 10 months. The drought of 2015 lasted the longest for 13 months, and those of 2013 and 2023 lasted for 12 and 10 months, respectively. The overview for Grootfontein is that the droughts have generally increased in all descriptive characteristics over the years. With the changing climate, the expectation would remain the same, and thus, the challenge of water and food security remains high.

Ndonga Linena was hit the hardest by the droughts of 2013, 2015, 2019, and 2023, with severities of -13.19, -20.57, -19.81 and -21.97, respectively. The drought of 2023 was not only the peak of severity, but also the most intense (-1.83) and lasted the longest (onset at 01/01/2023 and termination on 01/12/20230), a duration of 12 months. The trends of the droughts across the years showed that the

intensity, severity and duration of the droughts had been on the increase. Otavi witnessed prolonged and much intense and severe droughts in the 1990s, 2010s, and 2020s. The severity of the droughts peaked in 2019 at -31.56 and was the most intense drought at -2.63. This drought event lasted the longest from the onset on 01/01/2019 to the termination on 01/12/2019, thus having a duration of 12 months. The trends of the drought occurrence for Otavi pointed to an increase in intensity, severity and duration of droughts in the later years. The drought events for Shadikongoro had been very severe, intense and lasted longer right from the 1970s (1973 and 1979 recorded severities of -17.61 and -12.96, and both lasted for the duration of 9 months. However, severe drought periods were observed in 2015 (-16.77 severity), 2019 (-16.71 severity) and 2023 (-20.45 severity). These severe droughts lasted for the duration of 11, 10 and 10 months, respectively. Across the years, there has been an increase in drought severity and duration. Shitemo, being close to Shadikongoro and Ndonga Linena in comparison to other locations, had similar drought characteristics. The droughts of 2013, 2015, 2019 and 2023 were notable with severities of -13.95, -20.57, -19.80 and -21.97, and lasted for durations of 10, 12, 11 and 12 months, respectively. Although there were periods of severe droughts in the 1970s and 1990s, the intensity, severity and duration of the droughts showed an increasing trend across the years. The drought severity peaked in 2023 at -21.97, the onset was 01/01/2023 and terminated on 01/12/2023, thus lasting for 12 months. Sikondo showed irregular but increasing trends in the severity of the droughts. The 1970s, 1990s, 2010s and 2020s showed high drought severities. The years 20213, 2015, 2019 and 2023 recorded the most severe droughts (-17.59, -20.05, -19.20 and -18.52, respectively. These drought periods were the most intense and had the longest duration. Tsumeb showed slightly similar drought characteristics to those of Otavi and Grootfontein, being together members of the maize triangle of Namibia. The 1970s and 1980s did not have prolonged events of severe droughts, except in 1979 when the severity was -13.22, which lasted for 9 months. Notable drought severities were recorded in 1995 (-28.19 severity, -2.35 intensity), 2013 (-19.15 severity, -1.91 intensity), 2015 (-1.75 intensity, -21.11 severity), and 2019 (peak) (severity of -30.43, intensity of -2.54). The droughts lasted for 12, 10, 12, 12 and 10 months respectively. The observed drought severity trends for Tsumeb showed that the duration, intensity and severity of the droughts had been on the increase over the years.

(i) Standard Precipitation Index (SPI)

The SPI assessment for Grootfontein over time, in **Figure 4-38,** showed a continuous occurrence of droughts. Droughts have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

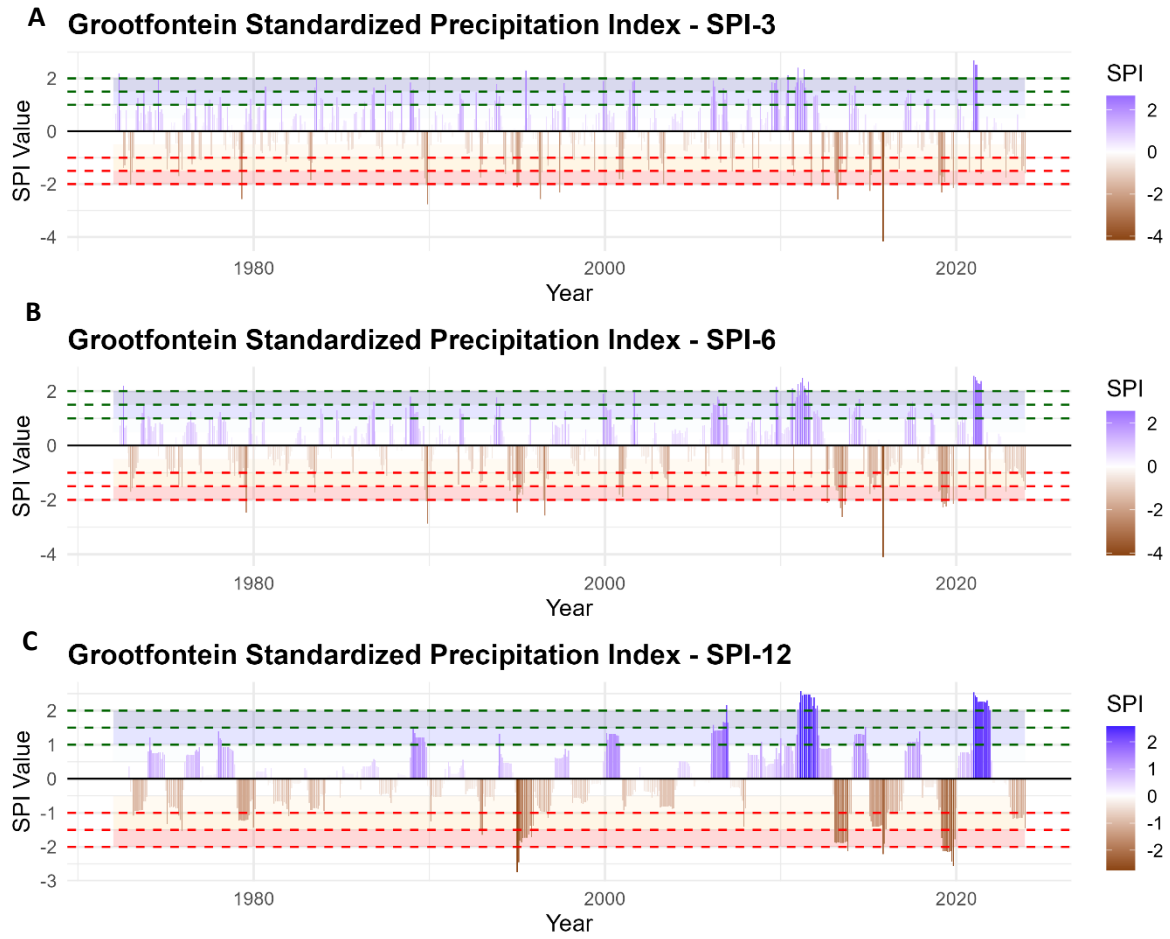


Figure 4-38. Standardised Precipitation Index for Grootfontein Computed at 3-, 6-, and 12-month time scales

The SPI assessment for Ndonga Linena over time, in **Figure 4-39,** showed a continuous occurrence of droughts. Droughts have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods. The drought situation for Ndonga Linena was similar to that of Grootfontein.

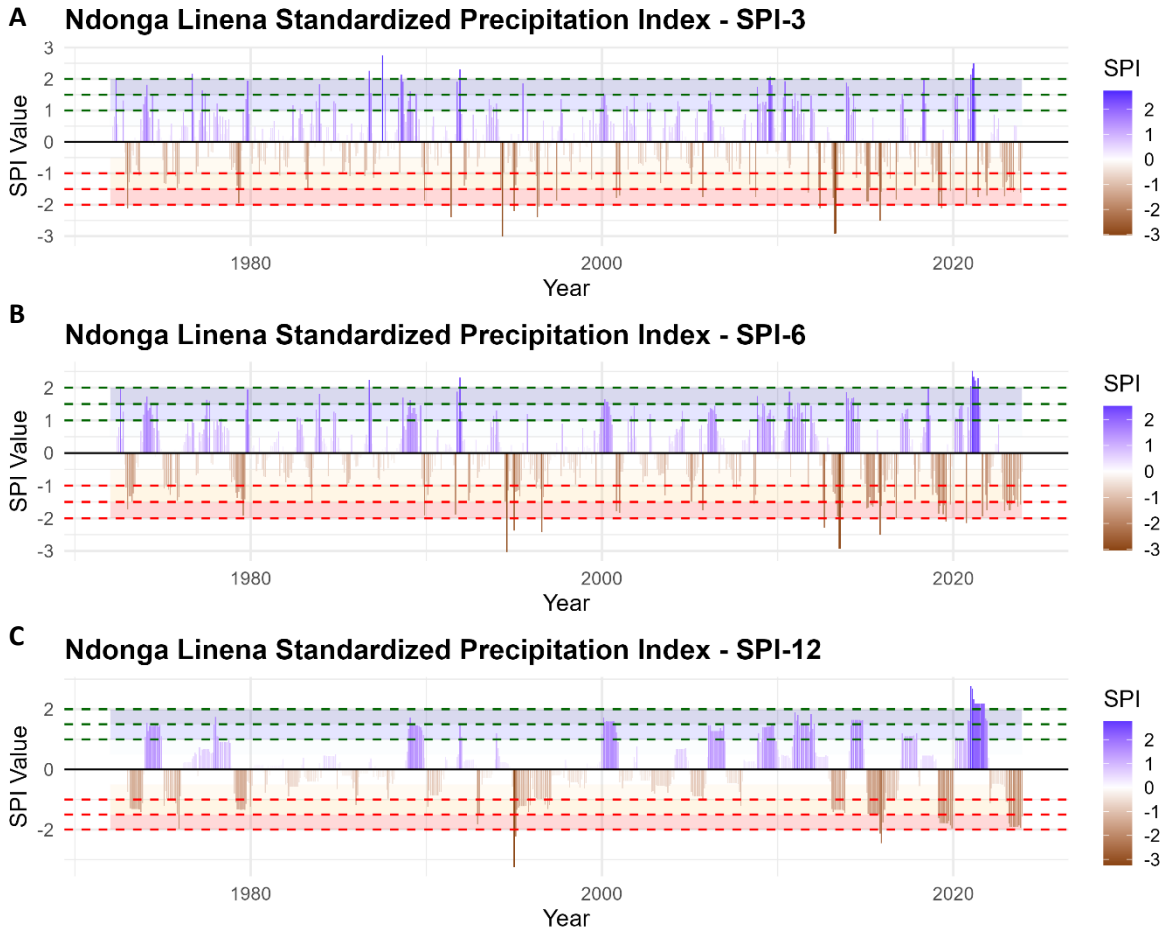


Figure 4-39. Standardised Precipitation Index for Ndonga Linena Computed at 3-, 6-, and 12-month time scales

The SPI assessment for Otavi over time, in **Figure 4-40,** showed a continuous occurrence of droughts. Droughts have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

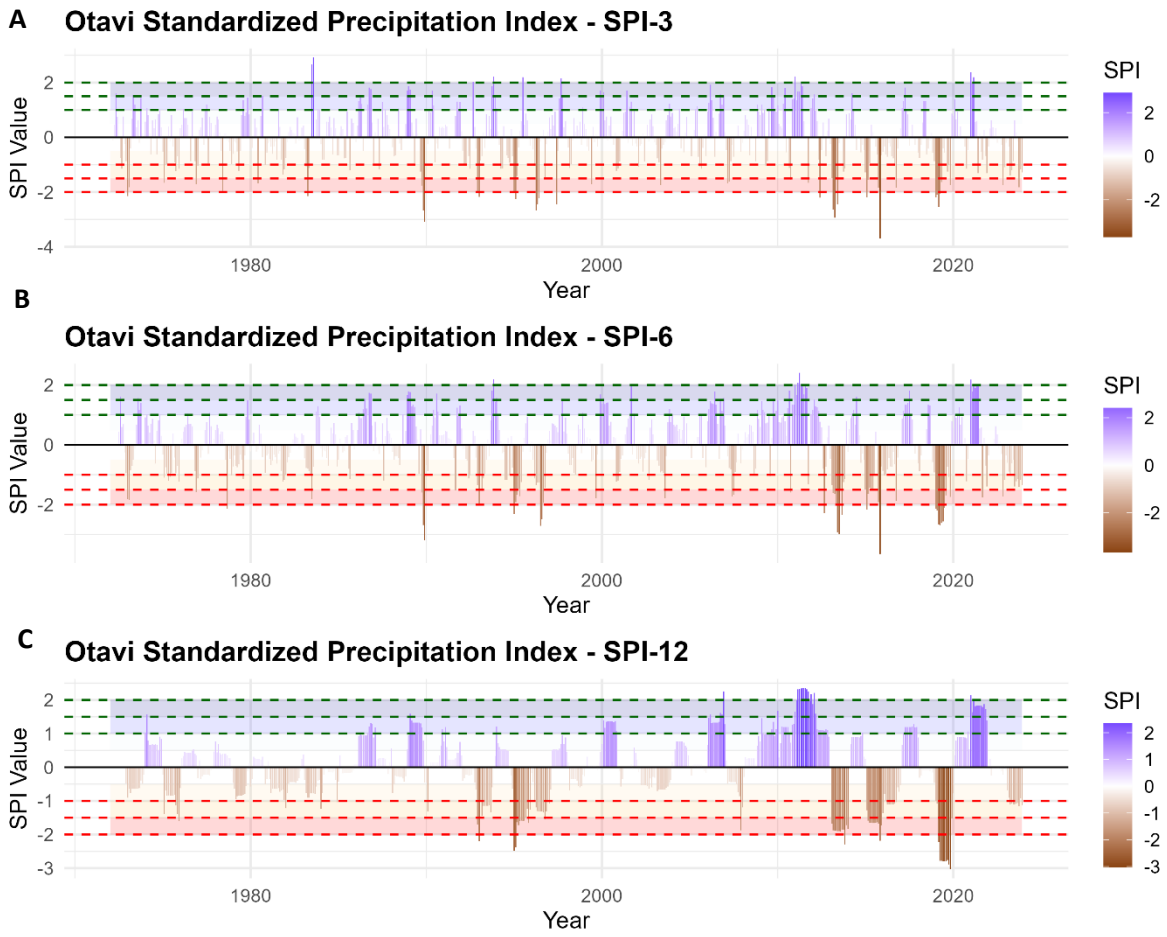


Figure 4-40. Standardised Precipitation Index for Otavi Computed at 3-, 6-, and 12-month time scales

The SPI assessment for Shadikongoro over time, in **Figure 4-41,** indicated a continuous occurrence of droughts. Droughts have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods. The trend of droughts points to a future occurrence of droughts, and calls for smart agricultural practices, especially for Shadikongoro, a significant Agricultural Green Scheme Project in Namibia.

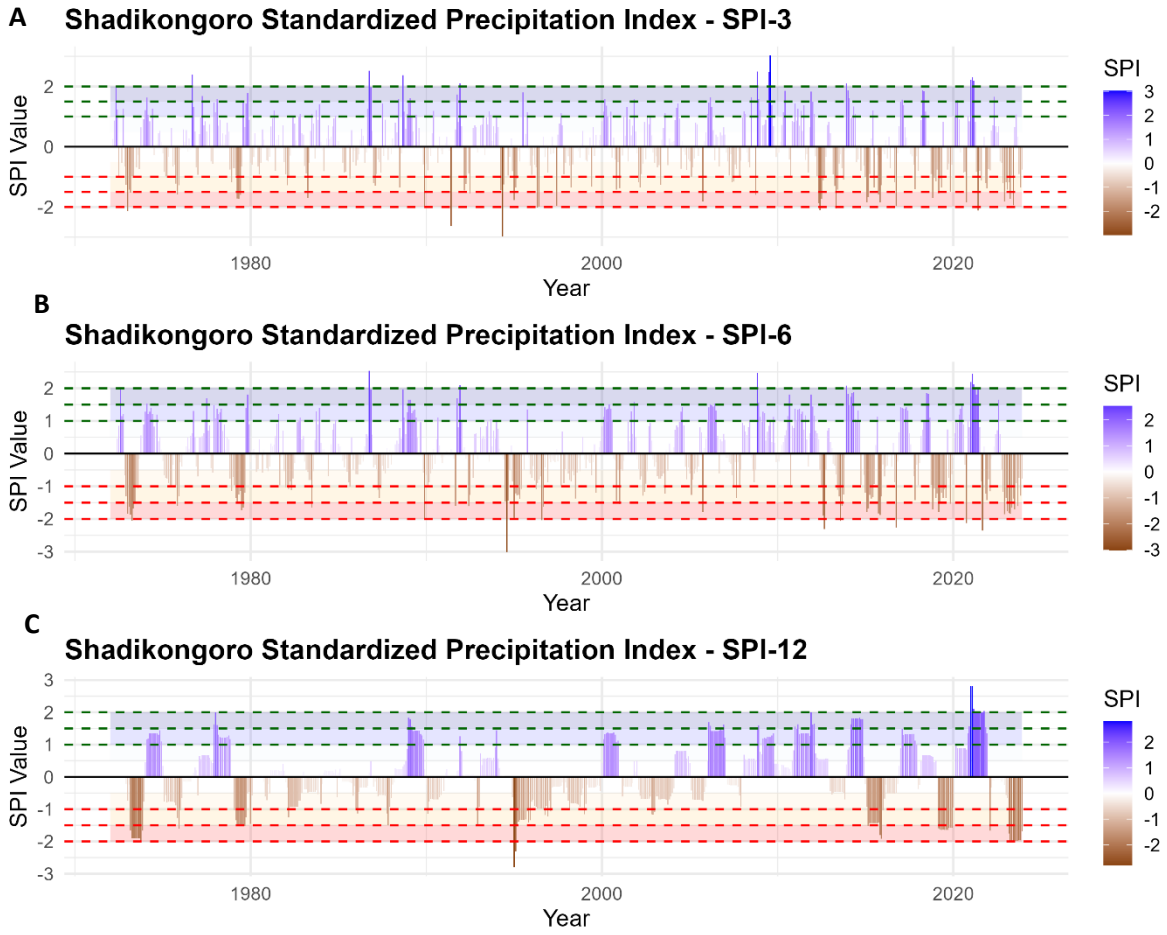


Figure 4-41. Standardised Precipitation Index for Shadikongoro Computed at 3-, 6-, and 12-month time scales

The SPI assessment for Shitemo over time, in **Figure 4-42,** showed a continuous occurrence of droughts. Droughts have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

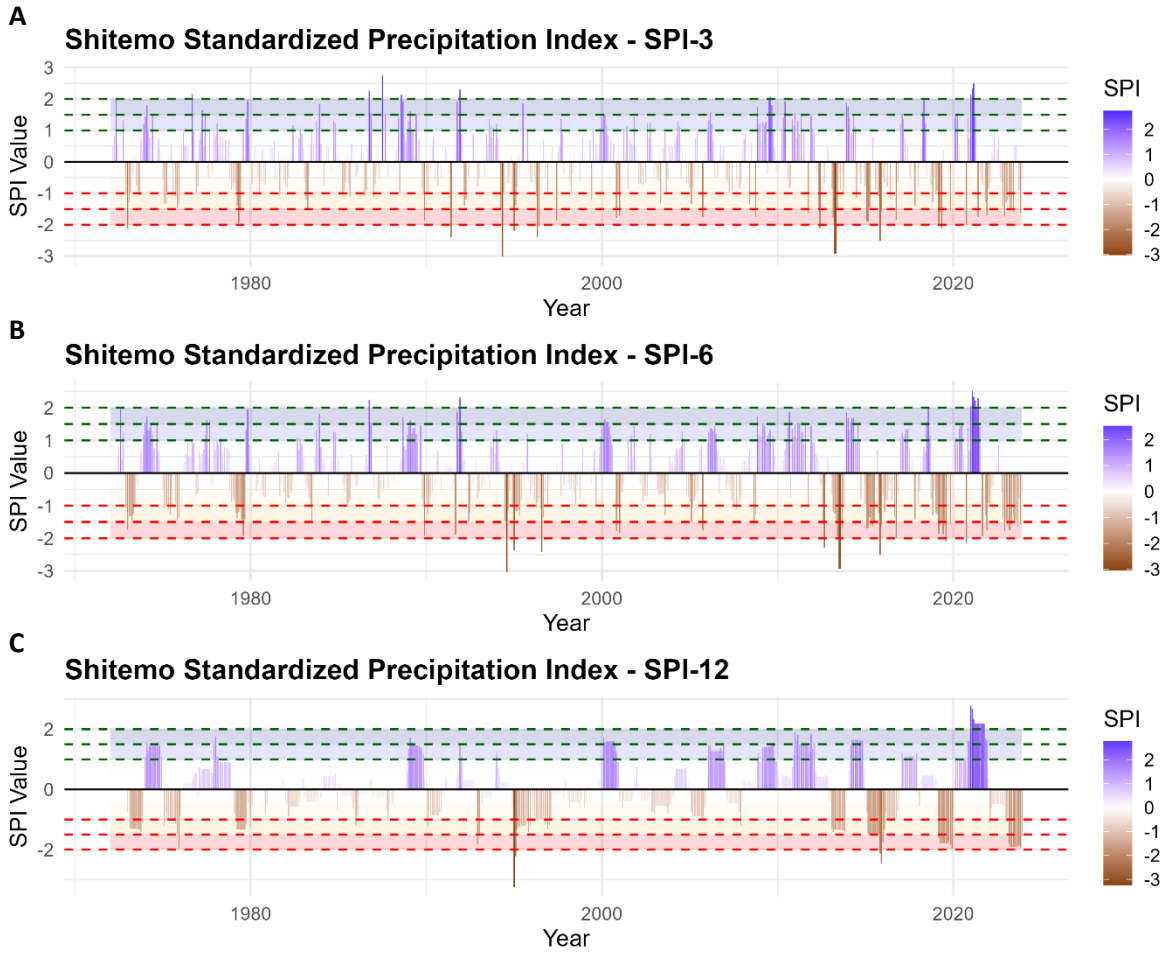


Figure 4-42. Standardised Precipitation Index for Shitemo Computed at 3-, 6-, and 12-month time scales

The SPI assessment for Sikondo over time, in **Figure 4-43,** showed a continuous occurrence of droughts. Droughts have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

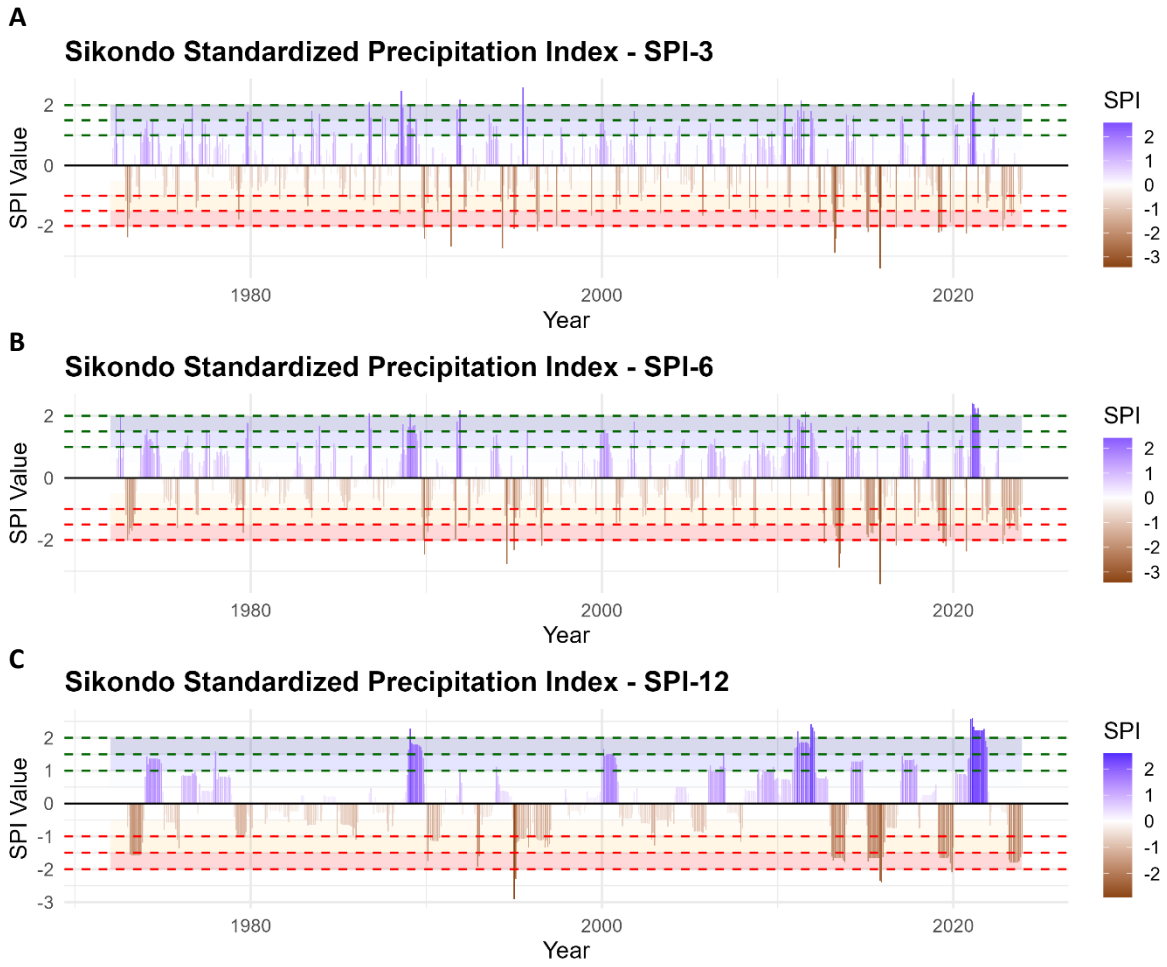


Figure 4-43. Standardised Precipitation Index for Sikondo Computed at 3-, 6-, and 12-month time scales

The SPI assessment for Tsumeb over time, in **Figure 4-44**, showed a continuous occurrence of droughts. Droughts have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

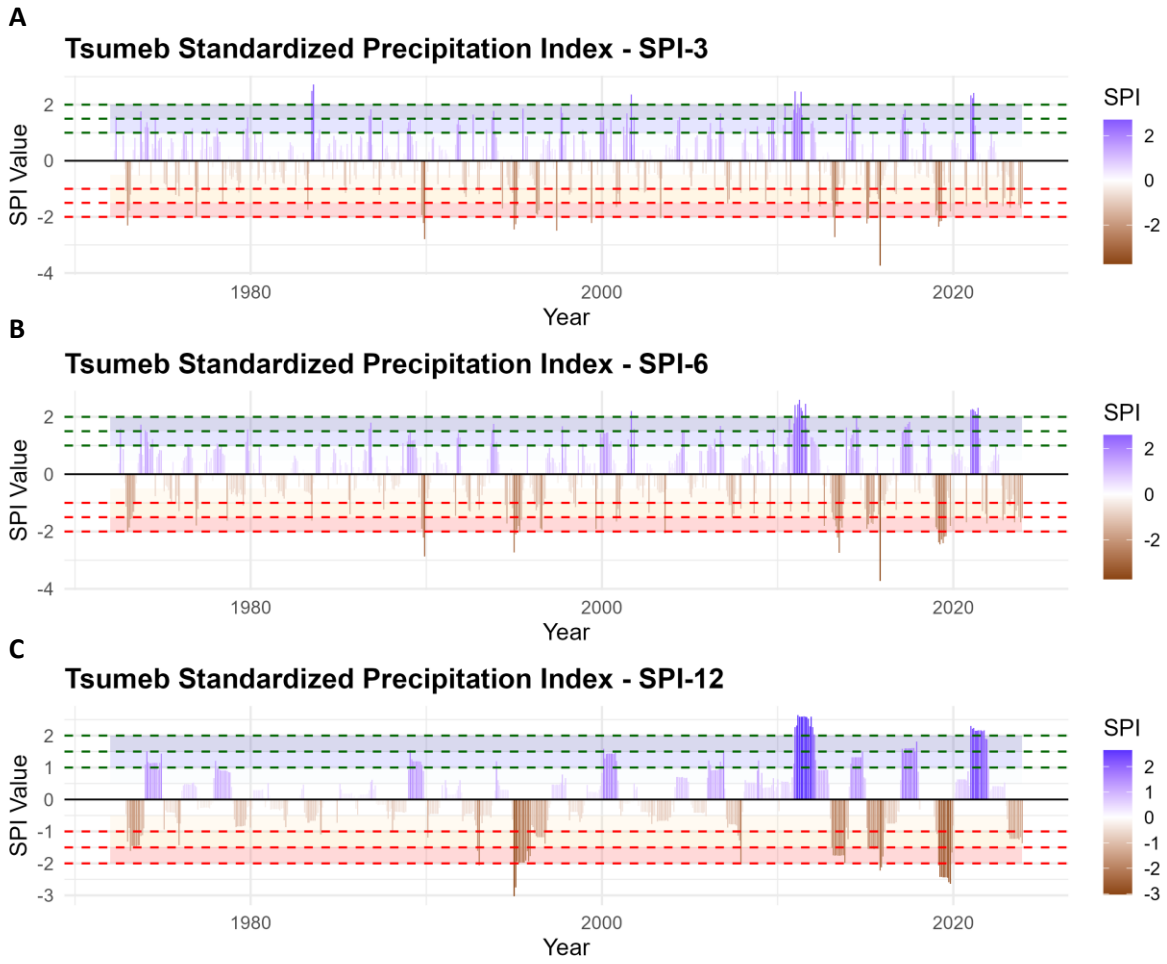


Figure 4-44. Standardised Precipitation Index for Tsumeb Computed at 3-, 6-, and 12-month time scales

Standard Precipitation Evapotranspiration Index (SPEI)

The SPEI for Grootfontein, which incorporates both precipitation and evapotranspiration when assessing for droughts over time, in **Figure 4-45**, established the occurrence of droughts. The periods of drought have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

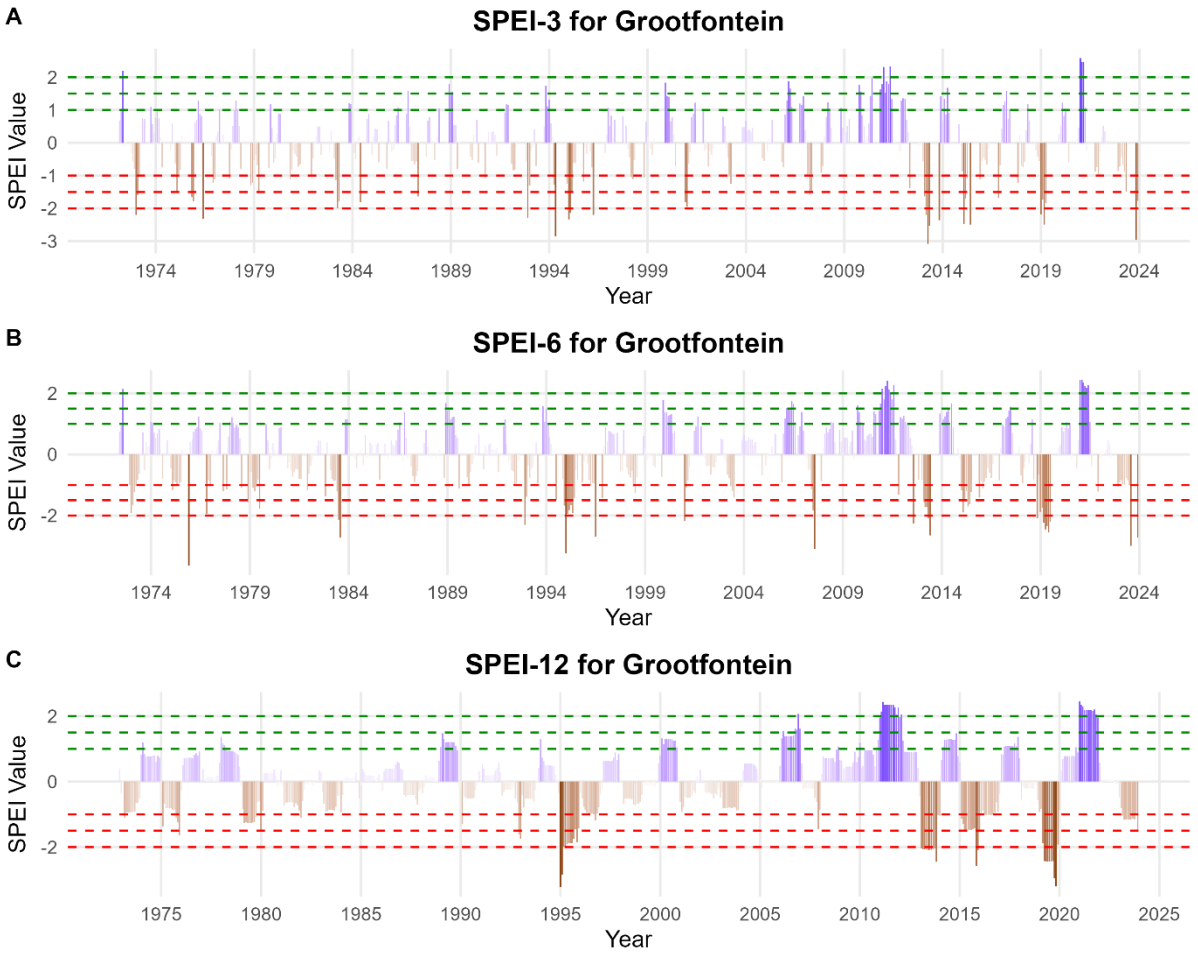


Figure 4-45. Standardised Precipitation Evapotranspiration Index for Grootfontein Computed at 3-, 6-, and 12-month time scales

The SPEI assessment for Ndonga Linena over time, in **Figure 4-46**, affirmed the continuous occurrence of droughts. The periods of drought have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

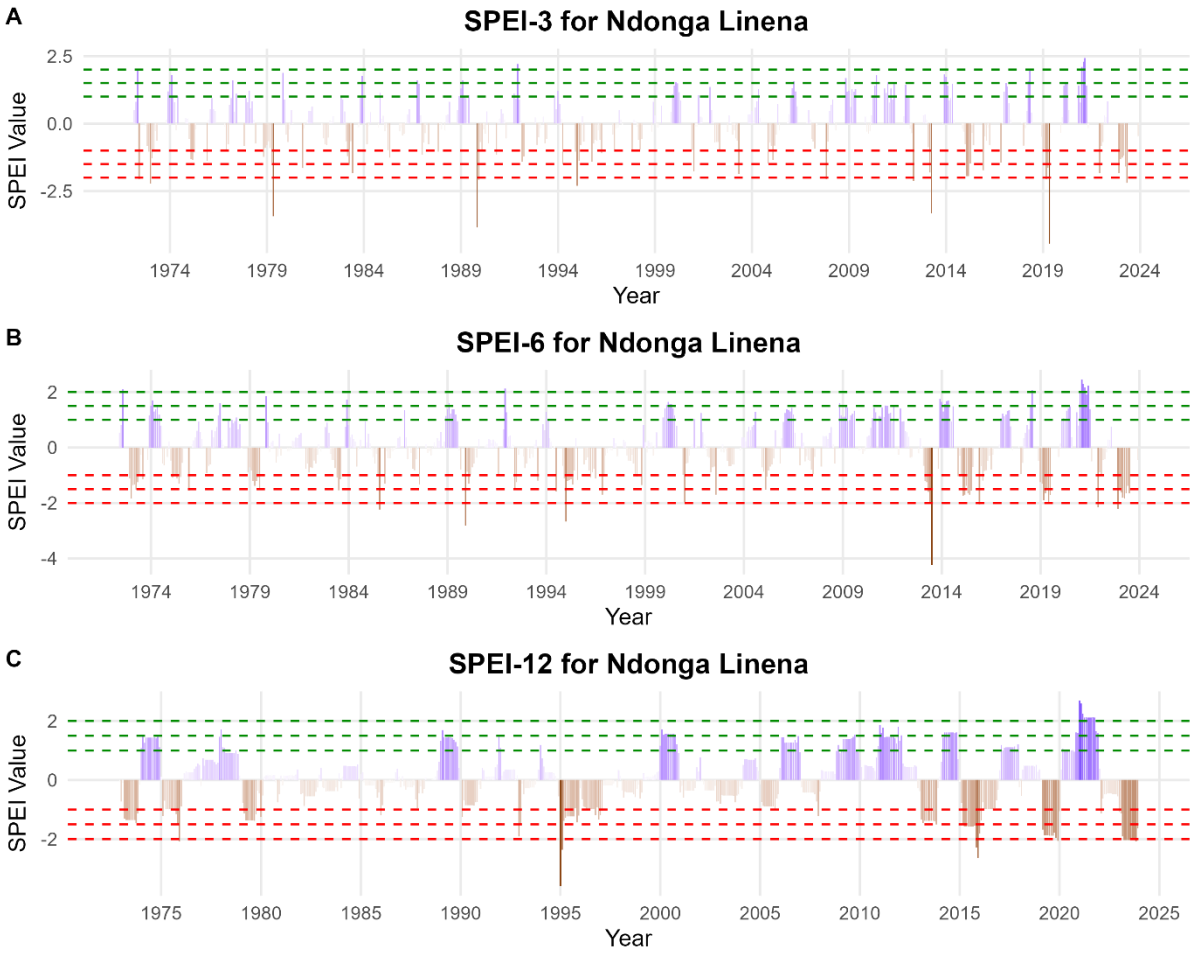


Figure 4-46. Standardised Precipitation Evapotranspiration Index for Ndonga Linena Computed at 3-, 6-, and 12-month time scales

The SPEI assessment for Otavi over time, in **Figure 4-47**, affirmed the continuous occurrence of droughts. The periods of drought have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

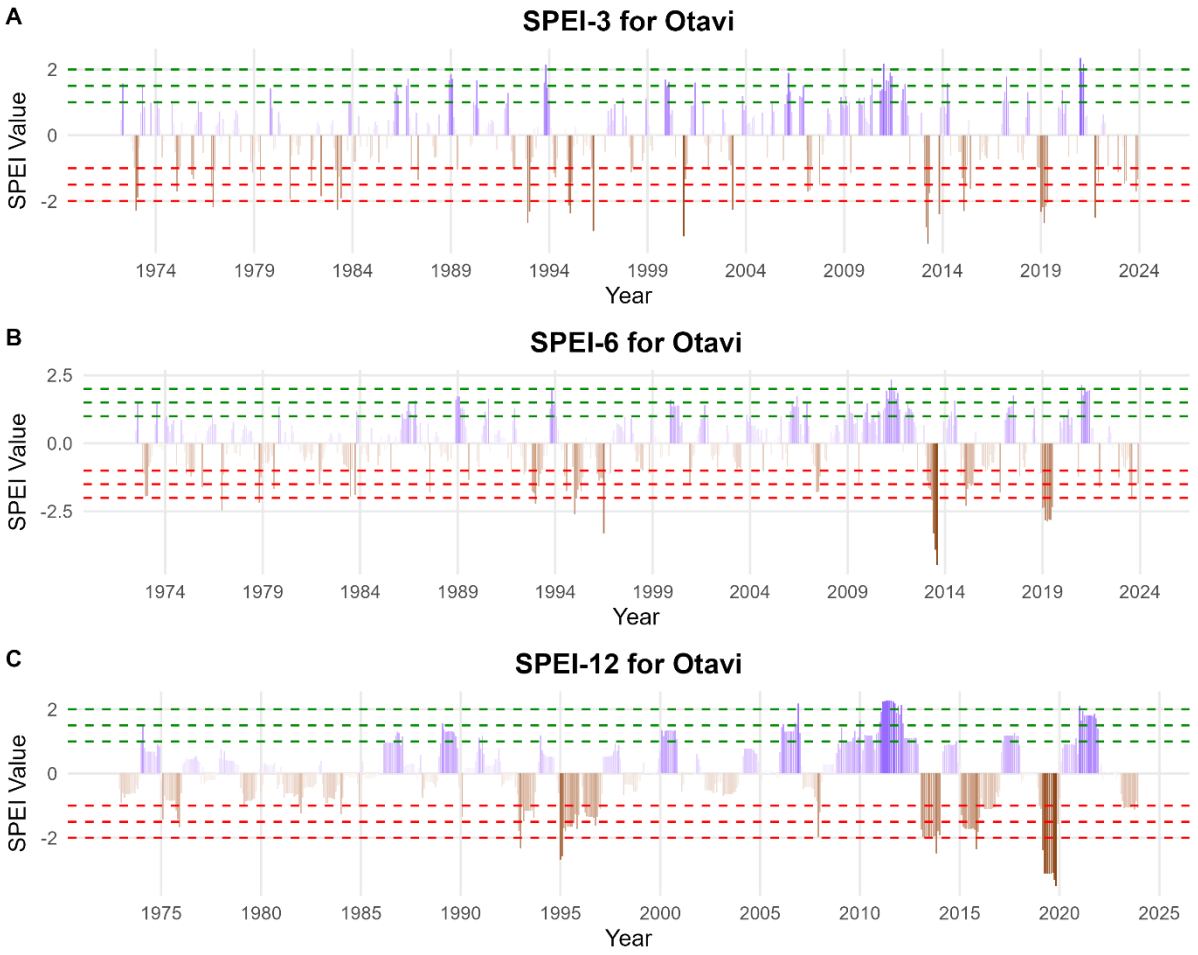


Figure 4-47. Standardised Precipitation Evapotranspiration Index for Otavi Computed at 3-, 6-, and 12-month time scales

The SPEI assessment for Shadikongoro over time, in **Figure 4-48**, affirmed the continuous occurrence of droughts. The periods of drought have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

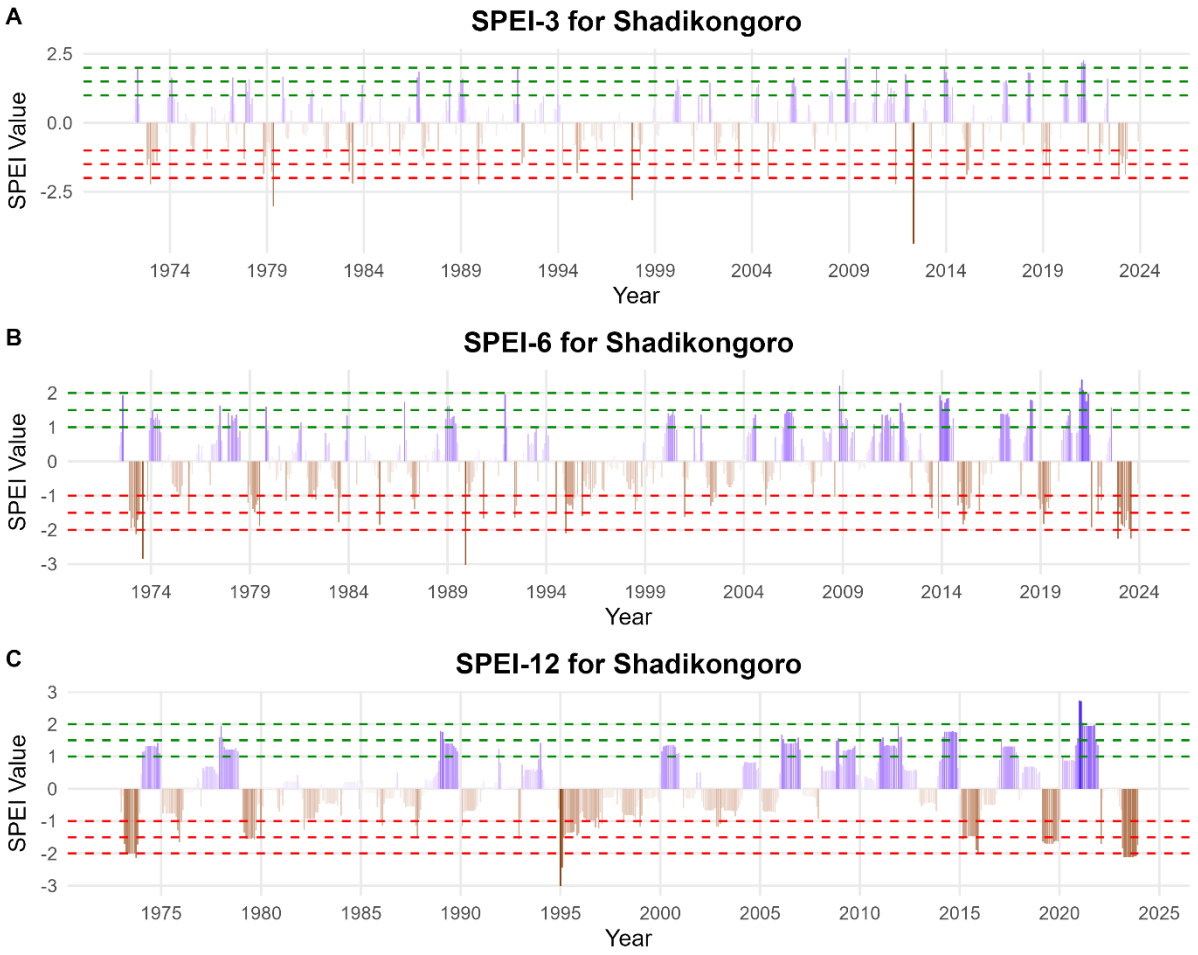


Figure 4-48. Standardised Precipitation Evapotranspiration Index for Shadikongoro Computed at 3-, 6-, and 12-month time scales

The SPEI assessment for Shitemo over time, in **Figure 4-49**, affirmed the continuous occurrence of droughts. The periods of drought have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

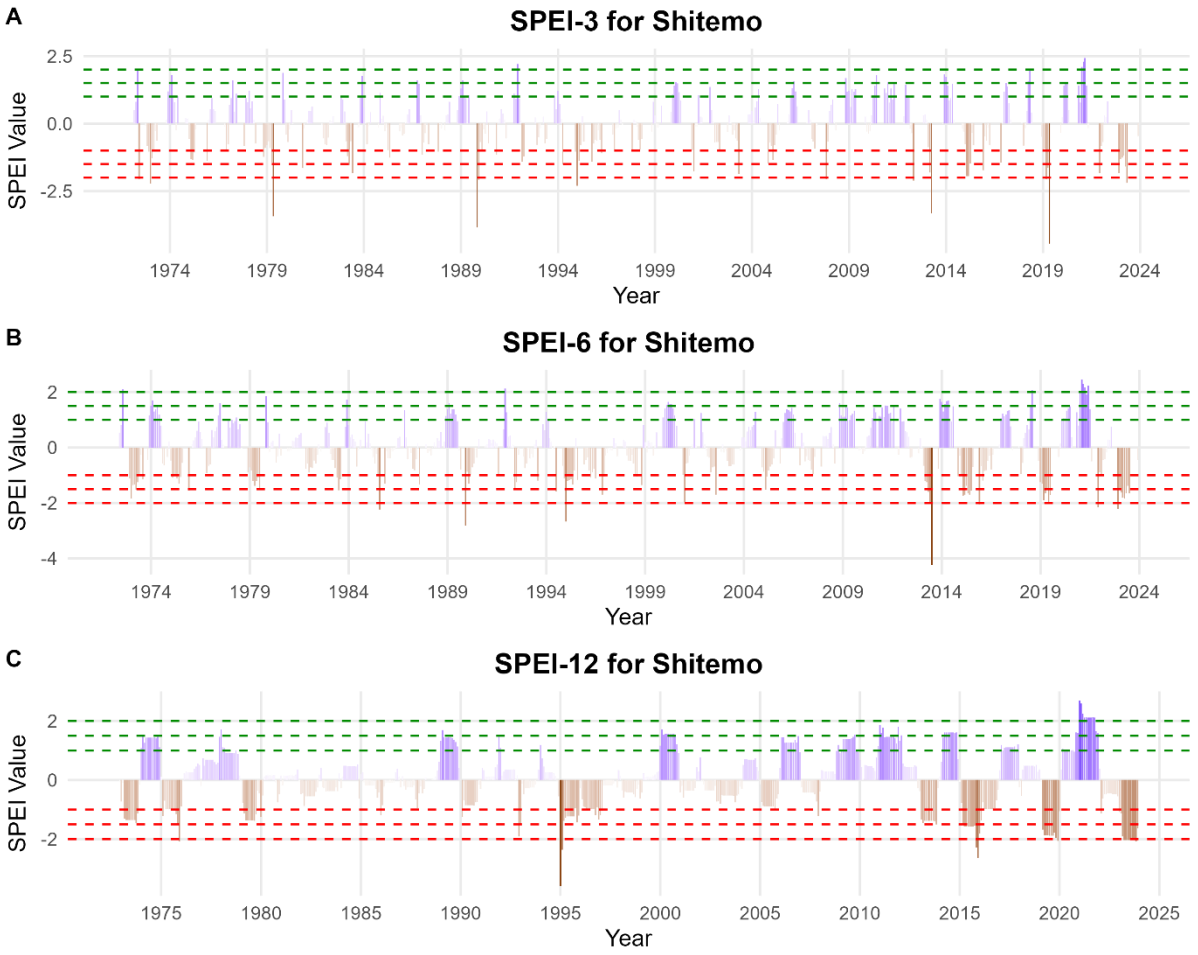


Figure 4-49. Standardised Precipitation Evapotranspiration Index for Shitemo Computed at 3-, 6-, and 12-month time scales

The SPEI assessment for Sikondo over time, in **Figure 4-50,** affirmed the continuous occurrence of droughts. The periods of drought have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

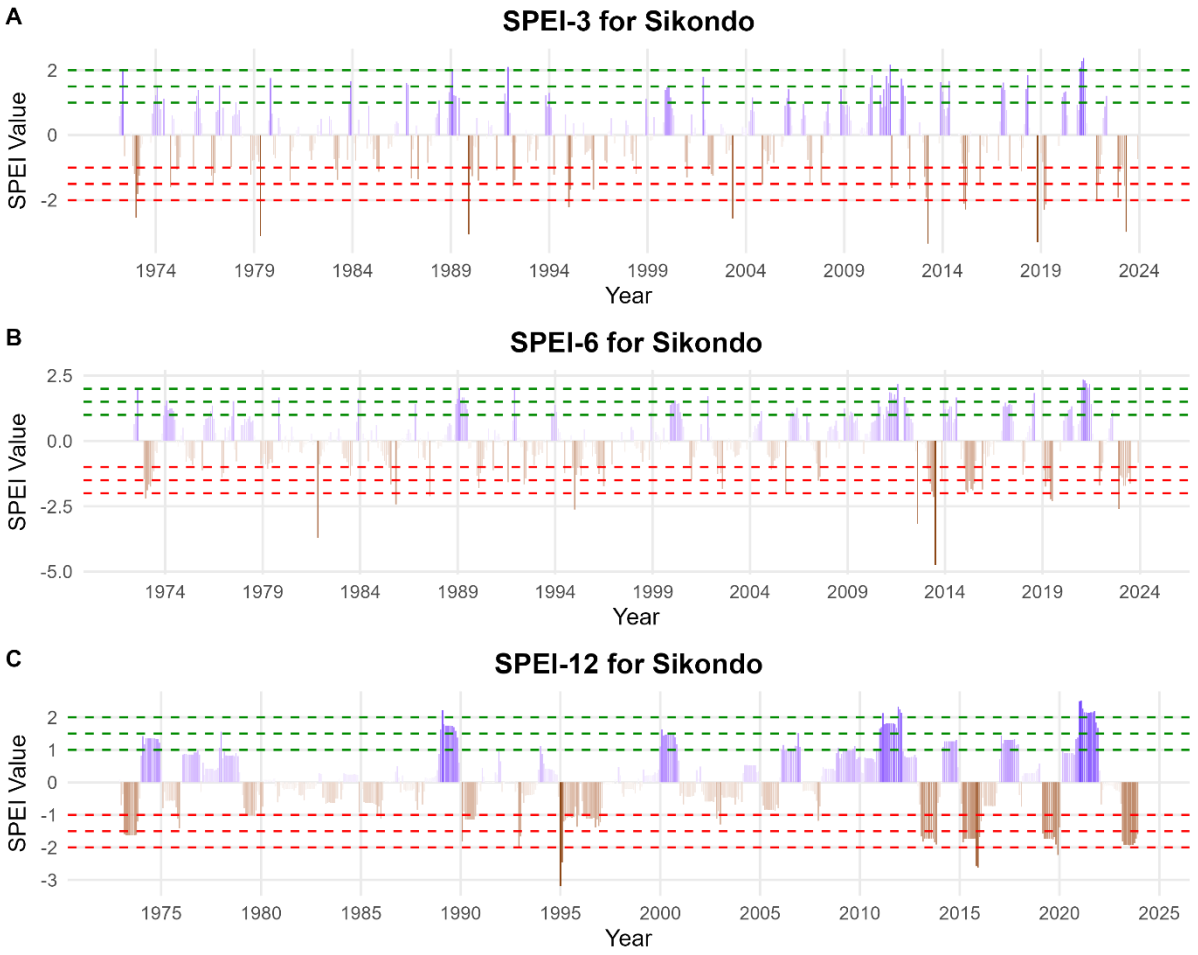


Figure 4-50. Standardised Precipitation Evapotranspiration Index for Sikondo Computed at 3-, 6-, and 12-month time scales

The SPEI assessment for Tsumeb over time, in **Figure 4-51**, affirmed the continuous occurrence of droughts. The periods of drought have been on the increase both in intensity and frequency. Some drought periods lasted longer than others. The SPI-12-month scale showed how more intense and frequent the droughts had been over the longer periods.

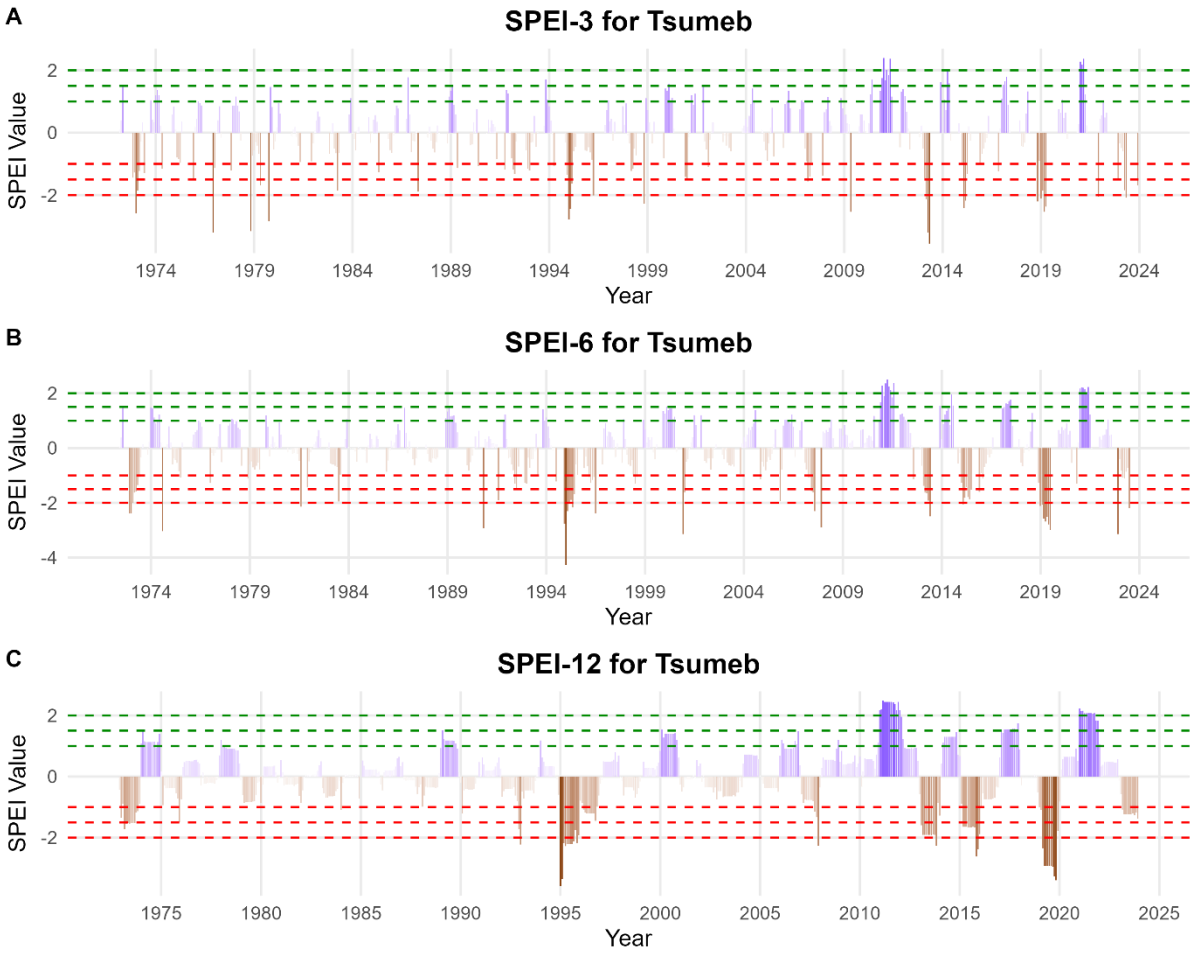


Figure 4-51. Standardised Precipitation Evapotranspiration Index for Tsumeb Computed at 3-, 6-, and 12-month time scales.

4.3.3 Trend analysis for white maize, wheat and pearl millet production 2010 – 2024

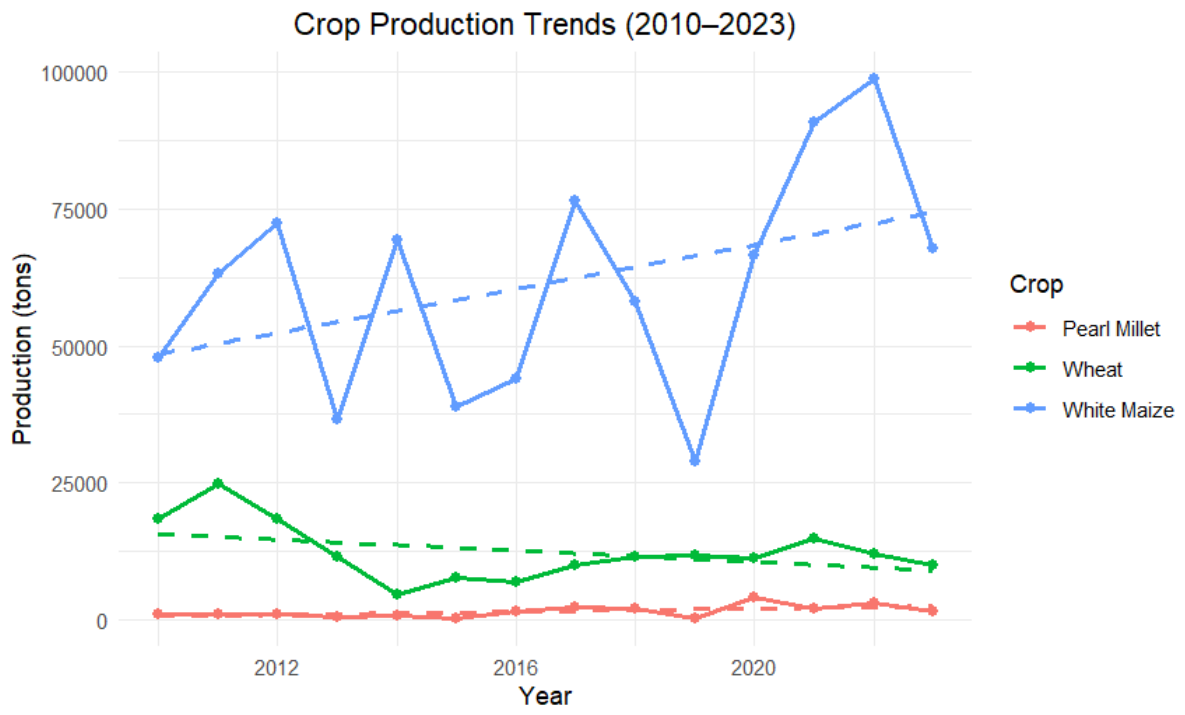


Figure 4-52. Trends in major crops production in Namibia

Wheat and Pearl Millet showed a slightly steady and declining trend in production, while the production of white maize showed a significantly increasing trend over the years. There were sharp declines in the production of all these important crops during the periods 2013/2014, 2015/2016/ and 2019/2020 (**Figure 4-52**). However, the decrease in crop production was more conspicuous for white maize that had a production of more than 72,400 tons in 2012/2013 and declined to less than 29,000 tons in 2019/2020 (**Table 4-38**. Drought Years). During this period (2019/2020), our self-sufficiency decreased to the lowest of 14%, compared to the highest 60% recorded in 2017/2018. Although the production of Pearl Millet has not been very low, with a strong dependence on imports from mainly Angola and Zambia, it also witnessed a significant decline in local production from 1064 tons in 2010/2011 to 111 tons in 2015/2016.

Furthermore, assessing the monetary value of white maize in 2023/2024, over 1.11 billion Namibian Dollars was spent on it, of which 65% was on imports (**Table 4-31).** During this period, Namibia was 28% self-reliant for white maize. This low production is a significant indicator of the trending problem of food insecurity. Namibia is completely dependent on South Africa for the import of white maize **(Table 4-30**), and should there arise a crisis in South Africa, there will be serious problems with food

security. There is a need to balance and enhance local food production to achieve self-sufficiency in major crops production.

Precipitation and crop production trends

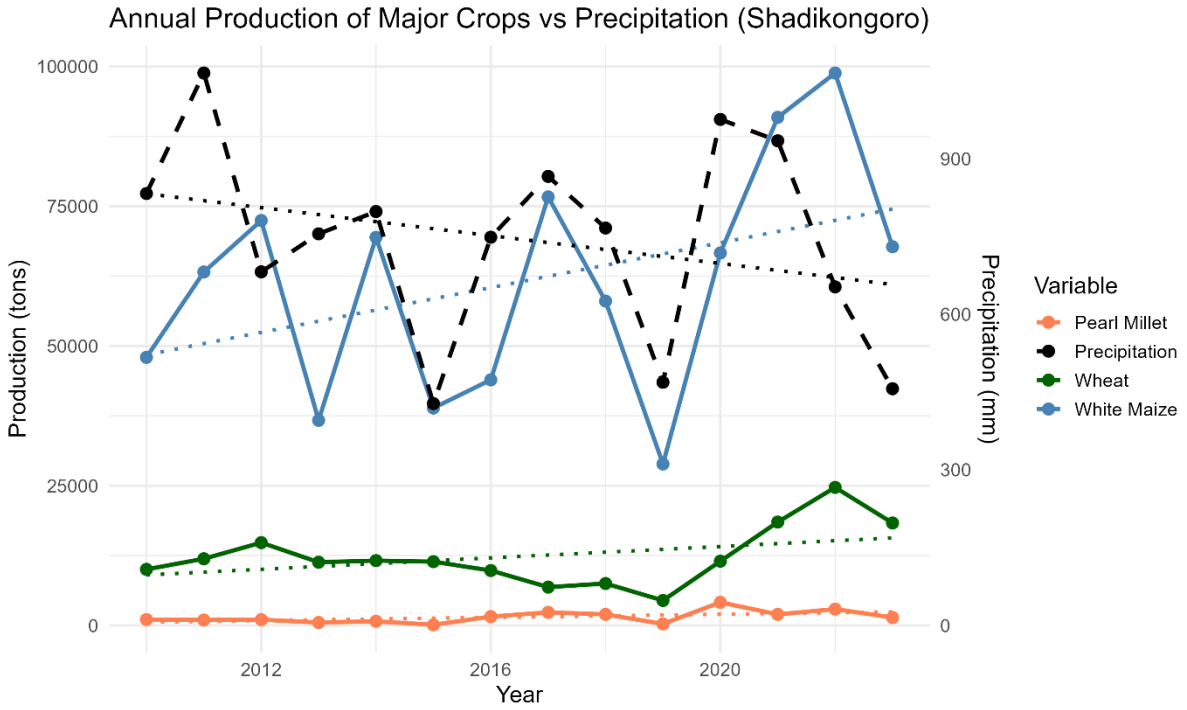


Figure 4-53. Major crops variations with respect to precipitation

Figure 4-53 above relates the trends in precipitation to crop production of the same period. The years 2012, 2015 and 2019 showed a decline in annual precipitation, especially in 2015. During these same periods, there were declines in the production of major crops. For white maize, the lowest production was in 2019. It was indicative from this comparison that annual precipitation impacted crop production. An increase in precipitation would result in increased crop production, while to the contrary, a decrease in precipitation equally resulted in a decrease in crop production. Therefore, climate change is indeed affecting food production and security at large.

Furthermore, the erratic and inconsistent patterns of precipitation also corresponded to the unstable and inconsistent production of major food crops. The production of major crops has been sloping up and down, in its trend against the amount of annual precipitation.

The trends observed in the grain domestic average price per ton showed a clear upward increase across all the grain types (**Table 4-37**). Cost per ton of each of the grain types was almost the same in 2010/2011 and 2011/2012; however, wheat became more costly in 2012/2013, all the way to

2015/2016. Among these major food crops, wheat showed the most dramatic price increase, with average prices rising from N$2700/ton in 2010/2011 to N$8078 in 2022/2023, an increase of 199%. A slight decrease in the price of wheat was observed in 2023/2024 at N$6973, but this still indicated that the average cost price of wheat per ton remained high. This notable spike in the cost of wheat may be linked to the wheat supply disruptions and increased dependence on exports. **Table 4-34** showed that 88% of wheat monetary value was on import, close to N$1 billion, compared to the local wheat monetary value of less than N$130 million, which was just 12% of the sum of the monetary value for wheat. Another factor that might have exacerbated the domestic cost of wheat is that it was imported from Poland, Latvia, Lithuania, and South Africa (**Table 4-33**). The first three countries contributed 92% to the total import of wheat, and these countries are outside the continent of Africa; hence, the transport cost of wheat from these nations to Namibia would take a toll on its market cost in Namibia. Furthermore, the local production of wheat over the years remained significantly low. It was observed that in the periods 2016/2017, 2017/2018, 2019/2020 and 2020/2021, the local production of wheat was well below the average, and the period 2019/2020 was hit the hardest in terms of low production (**Figure 4-57**). This low production of wheat could also be observed from the hectares of land planted over the years (**Table 4-32**). There was a significant decline from 2389 hectares in 2010/2011 to only 1011 hectares in 2019/2020, a decrease of about 58%. This stresses the effects of climate change on the production of wheat. The periods 2013/2014, 2015/2016 and 2019/2020 were declared as drought national emergency years (**Table 4-39**).

The domestic average cost of white maize, per ton, on the other hand, also showed an upward trajectory and was generally more stable. During the periods 2010/2011 to 2014/2015, the average grain domestic cost per ton of white maize was not significantly different, but over the years it ranged from N$2614 in 2010/2011 to the highest in 2022/2023 at N$6639, and slightly declined to N$5704 in 2022/2024 (**Figure 4-55**). The consumption of white maize (**Table 4-29**) showed that it strongly depended on imports. In 2023/2024, for instance, imports contributed 65% with a monetary value of over N$700 million of the total demand for white maize. Interestingly, 100% of the imported grains of white maize were from South Africa (**Table 4-30**). This indicated why the domestic average cost of white maize per ton was fairly stable, though it was also on the increase. The observed trends of the consumption of white maize showed that there were specific periods (2013/2014, 2015/2016 and 2016/2020 in which the local consumption or demand for white maize was high (206,928, 159, 550 and 199, 919 tons respectively) (**Figure 4-54**), with a similar local production of white maize of 36, 694, 38, 900 and 28, 888 tons respectively for these periods (**Table 4-29**). It therefore, implied that the years of low white maize production opened up for more of its import.

Lastly, **Table 4-35** and **Figure 4-58** showed the trends in the grain domestic average price per ton of Pearl Millet, locally known as Mahangu. This is a staple crop in the rural areas of Namibia, and sustains the livelihoods of more than 50% of the population. The trends indicated that the average cost price per ton was moderately stable from 2010/2011 until 2016/2017, after which a significant rise occurred in the price per ton, and eventually culminated in a high price of N$8000 per ton in 2023/2024, and thereby became significantly costlier than white maize and wheat. This was a rise of 200% across the years. The growing demand for pearl millet, relative to the reduced or low local supply, may account for this rise in the tonnage cost of pearl millet. The demand for Pearl Millet attested further to its local consumption in **Table 4-38**, where it showed that 14% was imported in 2023/2024, and that was mainly from Angola, which accounted for 98% and a mere 2% from Zambia. Although the local supply of pearl millet incomparably exceeded that of the imports, its domestic cost remained high because of the low production and limited usefulness at the moment. Unlike white maize and wheat, which are raw materials for a lot of local products, pearl millet is mainly locally used for consumption as porridge or pap and other limited uses. There is a need to expand the usefulness and application of Pearl Millet into further desirable finished products, and thereby increasing its supply and eventually reducing its market cost per ton. The trends in the local production of Pearl Millet showed significant increases in production over the years; however, with a sharp decline in 2015/2016 and 2019/2020. These were periods of national drought emergency (**Table 4-39**), and yet the local consumption demand for pearl millet remained very high. During these periods of drought, only 2% and 8%,

respectively, of the total demand for pearl millet was locally supplied. There is no indication of the hectares on which Pearl Millet was planted over the years, probably because, unlike wheat and white maize, pearl millet is not grown locally by commercial farmers or agricultural schemes but rather by subsistence farmers.

1. White Maize

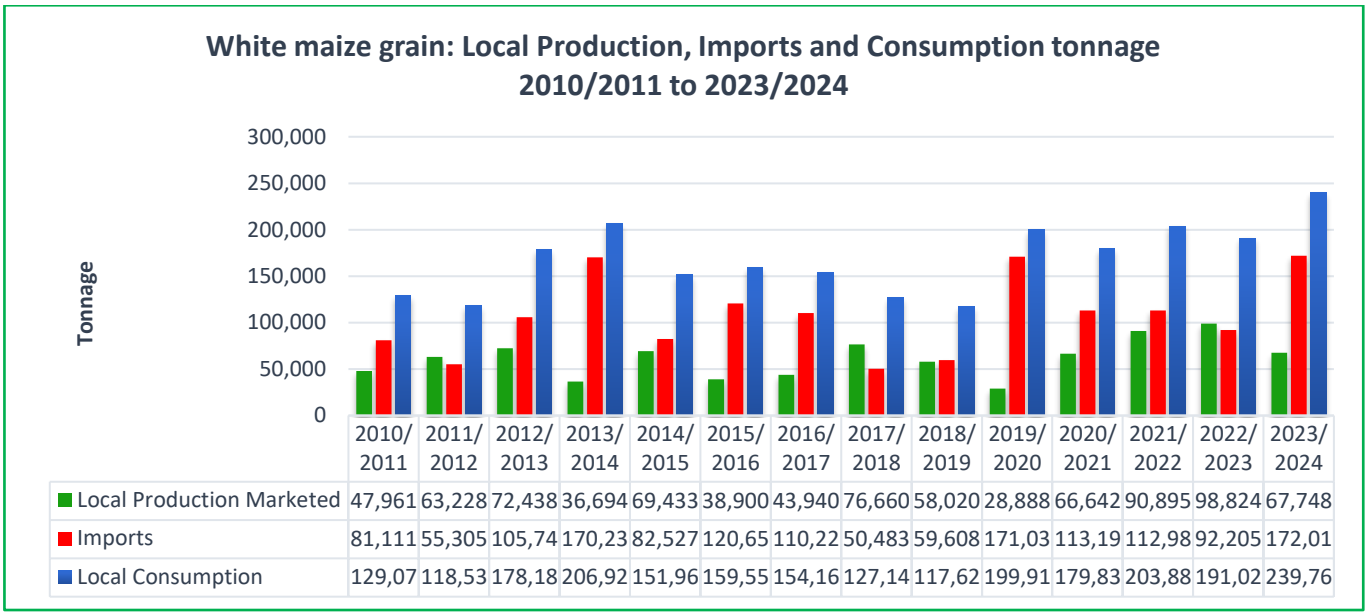
The local production and import of white maize (**Table 4-29**) for the period 2010/2011 to 2023/2024 showed a 38% average self-sufficiency rate. It was only in 2017/2018 that the production of white maize scored a self-sufficiency rate of 60% (the highest). However, it is worth noting that the self-sufficiency rate significantly declined from 52% (2022/2023) to 28% (2023/24).

Table 4-29. White maize consumption of local production relative to imports, and the average domestic price of floor per ton

White maize imports versus local production marketed tonnage for the period 2010/2011 to 2023/2024														
	2010/ 2011	**2011/ 2012**	**2012/ 2013**	**2013/ 2014**	**2014/ 2015**	**2015/ 2016**	**2016/ 2017**	**2017/ 2018**	**2018/ 2019**	**2019/ 2020**	**2020/ 2021**	**2021/ 2022**	**2022/ 2023**	**2023/ 2024**
Local Production Marketed	47,961	63,228	72,438	36,694	69,433	38,900	43,940	76,660	58,020	28,888	66,642	90,895	98,824	67,748
Imports	81,111	55,305	105,742	170,234	82,527	120,650	110,229	50,483	59,608	171,031	113,196	112,985	92,205	172,013
Local Consumption	129,072	118,533	178,180	206,928	151,960	159,550	154,169	127,143	117,628	199,919	179,838	203,880	191,029	239,761
Self-Sufficiency Rate %	37%	53%	41%	18%	46%	24%	29%	60%	49%	14%	37%	45%	52%	28%
White maize domestic average floor price per ton for the period 2010/2011 to 2023/2024														
	2010/ 2011	**2011/ 2012**	**2012/ 2013**	**2013/ 2014**	**2014/ 2015**	**2015/ 2016**	**2016/ 2017**	**2017/ 2018**	**2018/ 2019**	**2019/ 2020**	**2020/ 2021**	**2021/ 2022**	**2022/ 2023**	**2023/ 2024**
Domestic Ave. Floor price N$/Ton	2,614.00	2,831.37	2,998.00	3,169.00	3,302.00	3,948.00	5,304.00	4,860.00	4,822.00	4,824.00	5,008.78	4,711.53	6,639.35	5,704.00

Hectares Planted	20,324	20,979	22,821	15,672	22,220	16,113	17,121	23,665	19,937	8,332	18,694	26,912	31,944	36,082

The local consumption of white maize is shown in **Figure 4-54**, with respect to production and import. The consumption of white maize depends on imports due to lower local production.



	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	2020/2021	2021/2022	2022/2023	2023/2024
Local Production Marketed	47,961	63,228	72,438	36,694	69,433	38,900	43,940	76,660	58,020	28,888	66,642	90,895	98,824	67,748
Imports	81,111	55,305	105,74	170,23	82,527	120,65	110,22	50,483	59,608	171,03	113,19	112,98	92,205	172,01
Local Consumption	129,07	118,53	178,18	206,92	151,96	159,55	154,16	127,14	117,62	199,91	179,83	203,88	191,02	239,76

Figure 4-54. White maize grain consumption tonnage

The average domestic floor price per ton of white maize (**Figure 4-55**) has been on the increase. This may be primarily due to the increased demand for white maize, as shown in **Figure 4-54** previously.

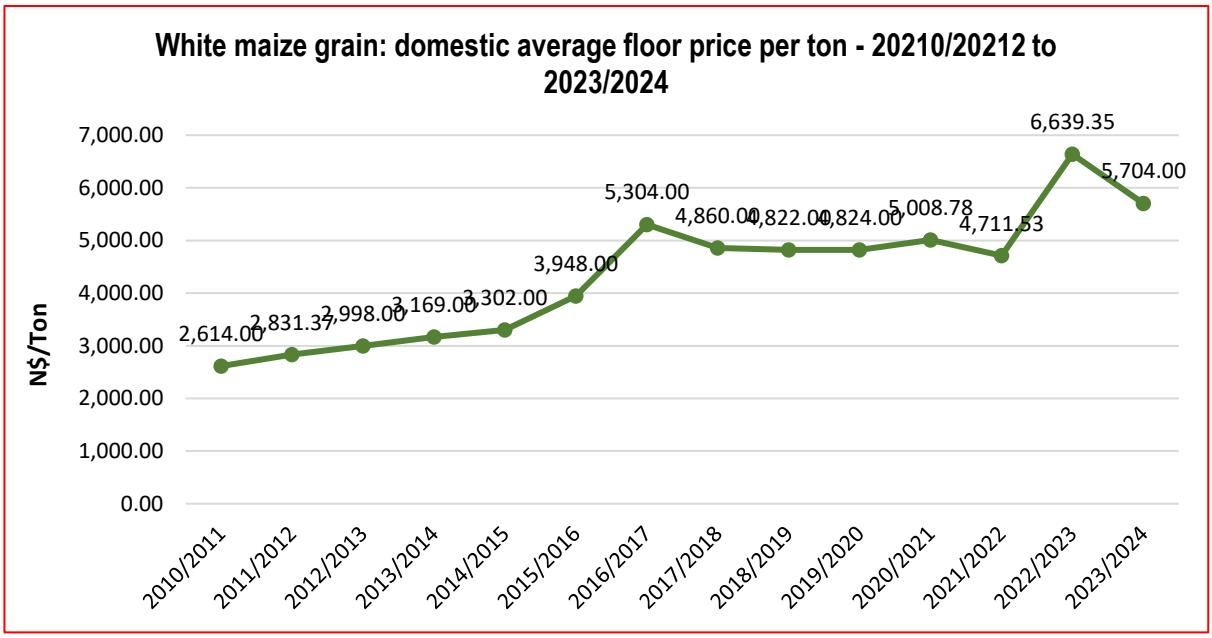


Figure 4-55. White maize grain domestic average floor price per ton

The period 2023/2024 recorded the highest import of white maize over the years, and it was only imported from South Africa (**Table 4-30**). This is a challenge to food security, should there be import challenges.

Table 4-30. Sources of white maize imported in 2023/2024

Sources of imports 2023-2024		
	Tonnage	**Share %**
South Africa	172,013	100%
Zambia	0	0%
Total	**172,013**	**100%**

Furthermore, 65% of the monetary value of the local and imported white maize for the period 2023/2024 was spent on imports (**Table 4-31**). A high cost indeed.

Table 4-31. Monetary value of the local and imported white maize for 2023/2024

White maize monetary value 2023/2024			
	Value N$	**Share %**	**Ave. Price/ton**
Import	723,918,581	65%	4,208.50
Local	386,447,493	35%	5,704.19
Total	**1,110,366,074**	100%	4,956.35

2. Wheat Consumption

Unlike white maize, the consumption of wheat (**Table 4-32**) showed an average self-sufficiency rate of 10%. This indicates a greater margin between local production of wheat and its demand. There is a strong reliance on imported wheat.

Table 4-32. Wheat consumption of local production relative to imports, and the average domestic price of floor per ton

Wheat imports versus local production marketed tonnage for the period 2010/2011 to 2023/2024														
	2010/ 2011	**2011/ 2012**	**2012/ 2013**	**2013/ 2014**	**2014/ 2015**	**2015/ 2016**	**2016/ 2017**	**2017/ 2018**	**2018/ 2019**	**2019/ 2020**	**2020/ 2021**	**2021/ 2022**	**2022/ 2023**	**2023/ 2024**
Local Production Marketed	10,038	11,930	14,819	11,312	11,600	11,411	9,822	6,863	7,508	4,466	11,498	18,498	24,696	18,327
Imports	69,519	84,543	87,726	85,257	103,035	95,190	121,261	104,244	118,698	114,363	125,838	126,441	114,370	172,693
Local Consumption	79,557	96,473	102,545	96,569	114,635	106,601	131,083	111,107	126,206	118,829	137,337	144,939	139,066	191,021
Self-Sufficiency Rate %	13%	12%	14%	12%	10%	11%	7%	6%	6%	4%	8%	13%	18%	10%
Wheat domestic average floor price per ton for the period 2010/2011 to 2023/2024														
	2010/ 2011	**2011/ 2012**	**2012/ 2013**	**2013/ 2014**	**2014/ 2015**	**2015/ 2016**	**2016/ 2017**	**2017/ 2018**	**2018/ 2019**	**2019/ 2020**	**2020/ 2021**	**2021/ 2022**	**2022/ 2023**	**2023/ 2024**
Domestic Ave. Floor price N$/Ton	2,699.74	3,138.49	3,947.95	4,197.02	3,923.11	4,624.84	4,849.59	5,178.13	5,200.33	5,220.47	5,455.56	6,771.10	8,078.13	6,972.82
Hectares Planted	2,389	2,136	2,314	2,198	2,034	2,077	1,832	1,568	1,537	1,011	1,806	3,416	4,254	2,594

The average grain cost of wheat (**Figure 4-56**) has been on the increase over the years, despite a slight decrease in 2023/2024.

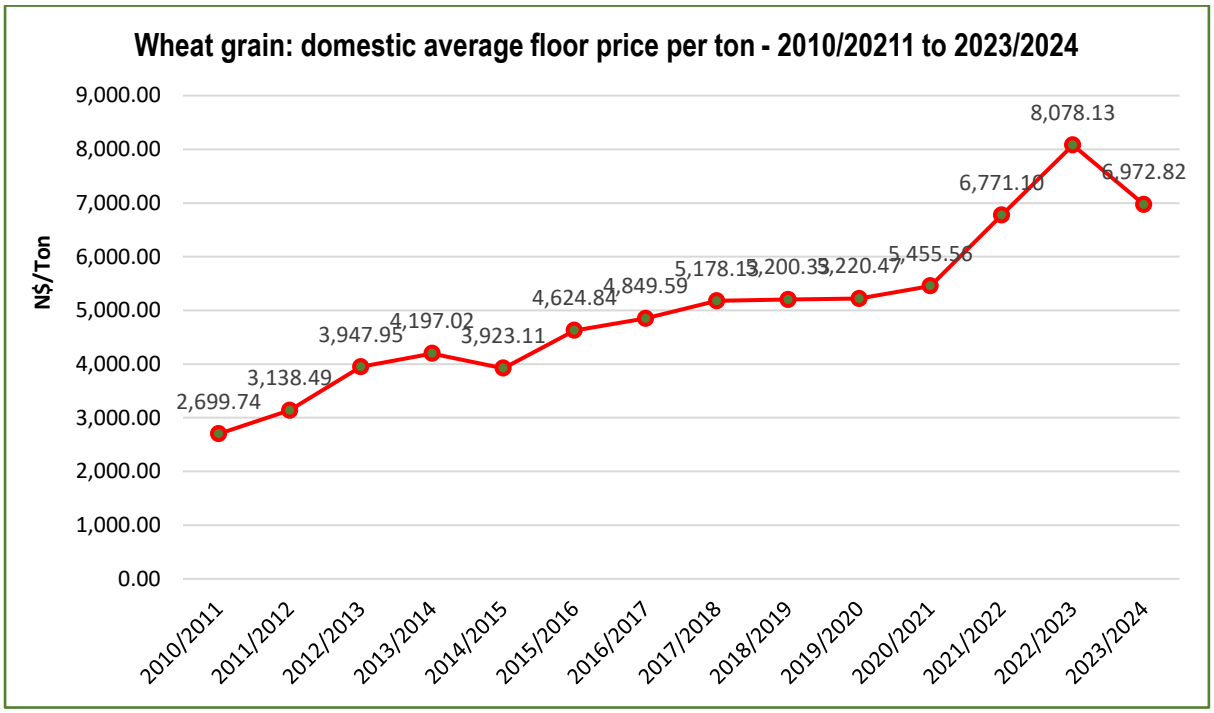
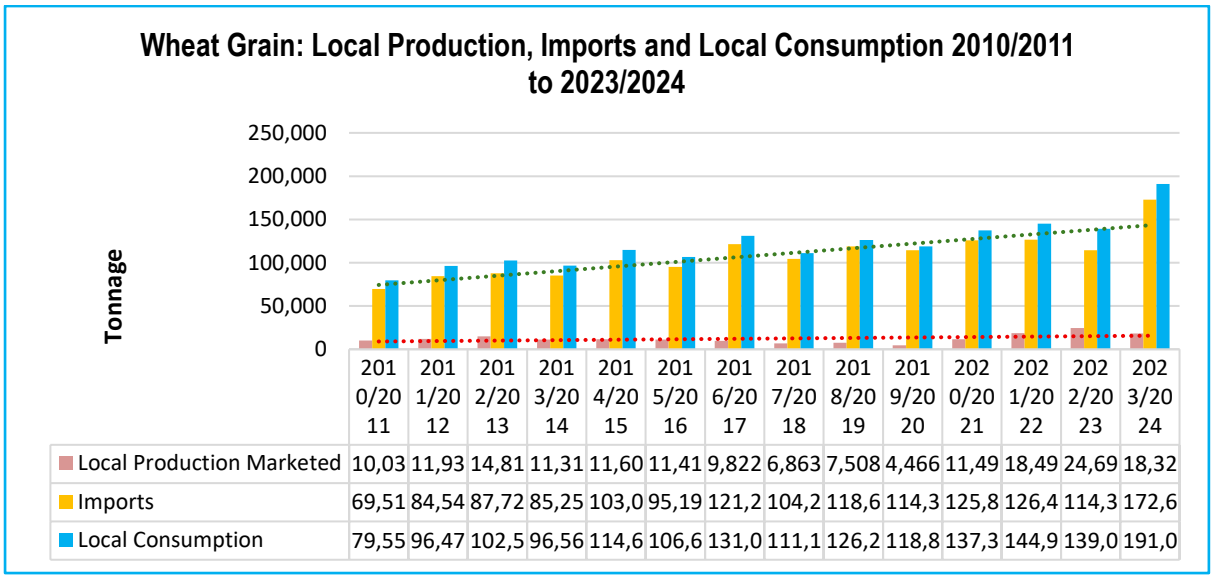


Figure 4-56. Domestic average floor price per ton of wheat grain

The amount of imported wheat (**Figure 4-57**) was almost equal to its local consumption. This showed that the local production of wheat has been significantly low over the year, and that without improvement.



	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	2020/2021	2021/2022	2022/2023	2023/2024
Local Production Marketed	10,03	11,93	14,81	11,31	11,60	11,41	9,822	6,863	7,508	4,466	11,49	18,49	24,69	18,32
Imports	69,51	84,54	87,72	85,25	103,0	95,19	121,2	104,2	118,6	114,3	125,8	126,4	114,3	172,6
Local Consumption	79,55	96,47	102,5	96,56	114,6	106,6	131,0	111,1	126,2	118,8	137,3	144,9	139,0	191,0

Figure 4-57. Wheat grain total consumption of local production and imports

Although white maize was only imported from one country, as aforementioned, in 2023/2024, wheat was imported from four countries (**Table 4-33**). However, the challenging observation was that most

of the imported wheat (87%) was from faraway countries, posing a great challenge on transport costs, and thus affecting food security.

Table 4-33. Sources and quantities of imported wheat grains

Import share per source 2023/2024		
Countries	**Tonnage**	**Share %**
Poland	81,050	47%
Latvia	74,360	43%
South Africa	12,970.14	8%
Lithuanian	4,312	2%
Total	**172,693**	**100%**

Due to the low local production of wheat, the greatest chunk of the wheat monetary value was on imports (88%) (**Table 4-34**).

Table 4-34. The monetary value of local and imported wheat for 2023/2024

Wheat monetary value 2023/2024			
	Value N$	**Share %**	**Ave. Price/ton**
Import	968,654,330	88%	5,609.11
Local	127,793,877	12%	6,972.82
Total	**1,096,448,207**	**100%**	**6,290.96**

3. Pearl millet Consumption

The grain price of pearl millet (**Figure 4-58**) has been on the increase over the year, with a significant increase in the latter years.

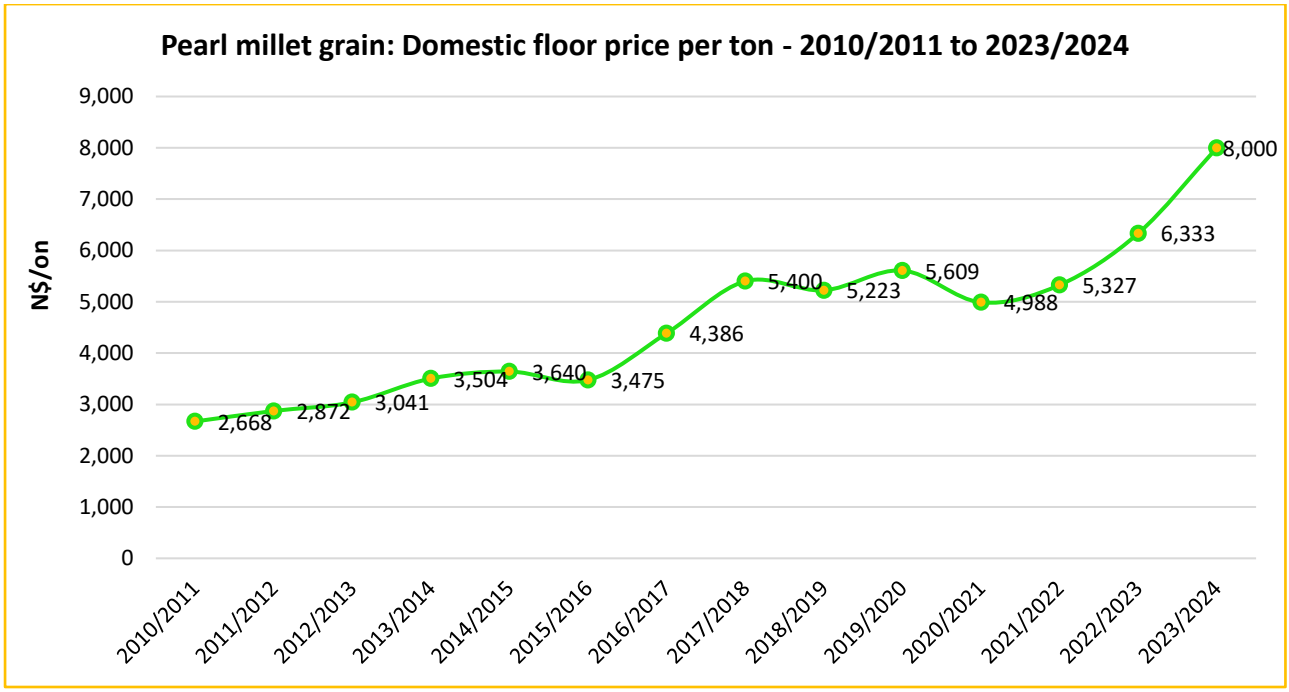


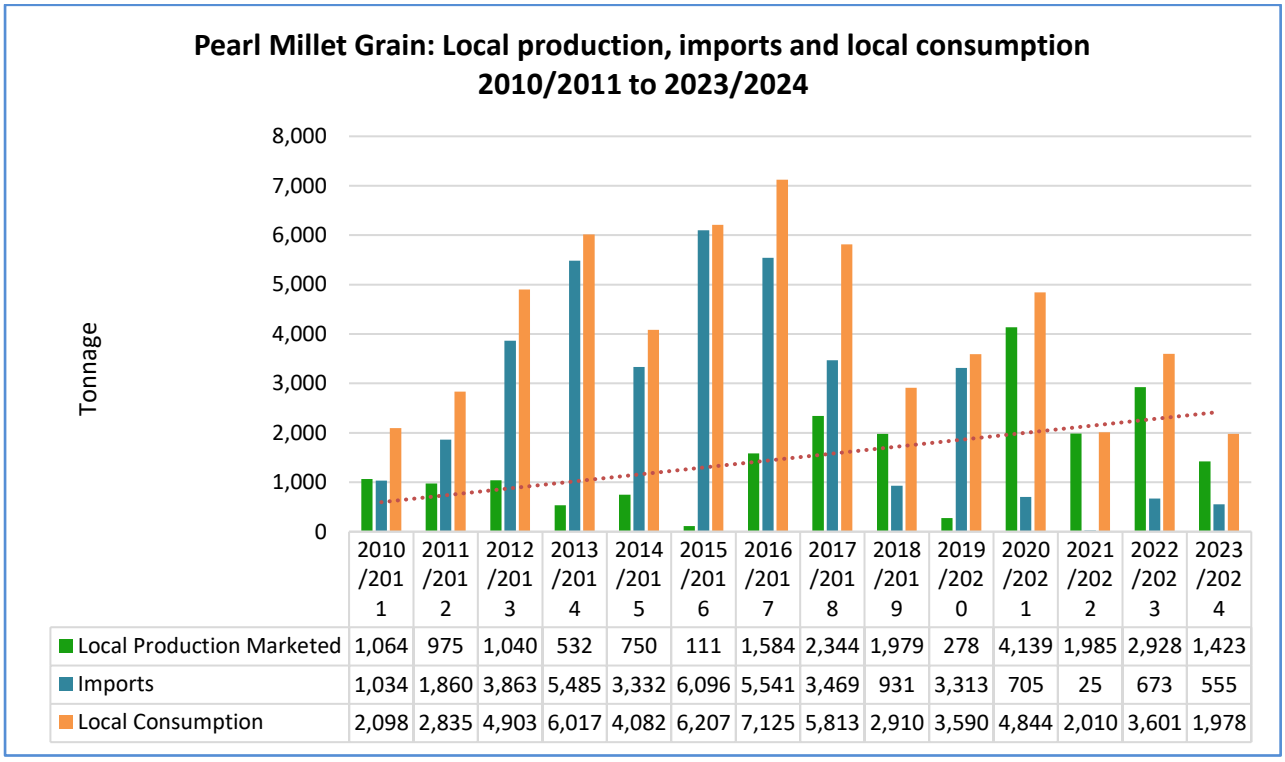
Figure 4-58. The domestic floor price per ton of pearl millet grains

Compared to the other grain food crops mentioned earlier, the monetary value of pearl millet was highest in the local production (**Table 4-35**), with a share of 86% in 2023/2024.

Table 4-35. Monetary value of pearl millet grain for 2023/2024

Pearl millet monetary value 2023/2024			
	Value N$	**Share %**	**Ave. Price/ton**
Import	1,797,117	14%	1,289.18
Local	11,384,000	86%	8,000.00
Total	**13,181,117**	**100%**	**4,644.59**

The local production of pearl millet has been increasing over the year compared to imports (**Figure 4-59**), except in certain periods such as 2015/2016 and 2019/2020. In 2021/2022, the local production of pearl millet recovered so much that the import was about 1% of total local consumption.



	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	2020/2021	2021/2022	2022/2023	2023/2024
Local Production Marketed	1,064	975	1,040	532	750	111	1,584	2,344	1,979	278	4,139	1,985	2,928	1,423
Imports	1,034	1,860	3,863	5,485	3,332	6,096	5,541	3,469	931	3,313	705	25	673	555
Local Consumption	2,098	2,835	4,903	6,017	4,082	6,207	7,125	5,813	2,910	3,590	4,844	2,010	3,601	1,978

Figure 4-59. The consumption of pearl millet grain with respect to local production and imports

The imported pearl millet in 2023/2024 was mainly from Angola and slightly from Zambia (**Table 4-36**). These are neighbouring countries to Namibia; hence, they do not pose a serious threat to food security.

Table 4-36. Sources of imported pearl millet grains for 2023/2024

Source of pearl millet grains	Quantities	
	Tonnage	**Share %**
Angola	1,364	98%
Zambia	30	2%
Total	**1,394**	**100%**

3. The price of the major crops in Namibia

The price of the three grain crops under consideration varied over the years (**Table 4-37**). These variations were mainly due to local production.

Table 4-37. Variation in the grain domestic floor price per ton of the major crops in Namibia over the years

Grain Domestic floor price per ton for the period 2010/2011 to 2023/2024														
	2010/ 2011	**2011/ 2012**	**2012/ 2013**	**2013/ 2014**	**2014/ 2015**	**2015/ 2016**	**2016/ 2017**	**2017/ 2018**	**2018/ 2019**	**2019/ 2020**	**2020/ 2021**	**2021/ 2022**	**2022/ 2023**	**2023/ 2024**
White Maize	2,614	2,831	2,998	3,169	3,302	3,948	5,304	4,860	4,822	4,824	5,009	4,712	6,639	5,704
Wheat	2,700	3,138	3,948	4,197	3,923	4,625	4,850	5,178	5,200	5,220	5,456	6,771	8,078	6,973
Pearl Millet	2,668	2,872	3,041	3,504	3,640	3,475	4,386	5,400	5,223	5,609	4,988	5,327	6,333	8,000

4. The demand for Major Grain Crops in Namibia

The demand for all the major grain crops in Namibia (**Table 4-38**) has been increasing over the years. This may be due to population growth.

Table 4-38. The demand for major grain Crops in Namibia

Grain Domestic floor price per ton for the period 2010/2011 to 2023/2024														
	2010/ 2011	**2011/ 2012**	**2012/ 2013**	**2013/ 2014**	**2014/ 2015**	**2015/ 2016**	**2016/ 2017**	**2017/ 2018**	**2018/ 2019**	**2019/ 2020**	**2020/ 2021**	**2021/ 2022**	**2022/ 2023**	**2023/ 2024**
White Maize	129,072	118,533	178,180	206,928	151,960	159,550	154,169	127,143	117,628	199,919	179,838	203,880	191,029	239,761
Wheat	79,557	96,473	102,545	96,569	114,635	106,601	131,083	111,107	126,206	118,829	137,337	144,939	139,066	191,021
Pearl Millet	2,098	2,835	4,903	6,017	4,082	6,207	7,125	5,813	2,910	3,590	4,844	2,010	3,601	1,978
TOTAL	**210,727**	**217,841**	**285,628**	**309,514**	**270,677**	**272,358**	**292,377**	**244,063**	**246,744**	**322,338**	**322,018**	**350,829**	**333,696**	**432,760**

5. The impacts of drought on the production of major grain crops in Namibia

The lowest production of all the grain crops was observed during the periods of national drought emergency (**Table 4-39**).

Table 4-39. Impact of the years of drought on the production of major crops in Namibia

Grain Domestic floor price per ton for the period 2010/2011 to 2023/2024														
	2010/ 2011	**2011/ 2012**	**2012/ 2013**	**2013/ 2014**	**2014/ 2015**	**2015/ 2016**	**2016/ 2017**	**2017/ 2018**	**2018/ 2019**	**2019/ 2020**	**2020/ 2021**	**2021/ 2022**	**2022/ 2023**	**2023/ 2024**
White Maize (Production)	47,961	63,228	72,438	36,694	69,433	38,900	43,940	76,660	58,020	28,887	66,642	90,895	98,824	67,748
Pearl Millet (Production)	1,064	975	1,040	532	750	111	1,584	2,344	1,979	278	4,139	1,985	2,928	1,423
Wheat (Production)	10,038	11,930	14,819	11,312	11,600	11,411	9,822	6,863	7,508	4,466	11,498	18,498	24,696	18,327
Drought declared a national emergency				Declared		Declared				Declared				

6. All Grains Imports and Local Production

A summarised reflection of all the major grain crops with respect to their production and imports is shown in **Table 4-40**.

Table 4-40. Trends on the import and local production of the major grains in Namibia

Grain Trend: Imports and local production - 2010/2011 to 2023/2024									
	White Maize Tonnage			Wheat Tonnage			Pearl Millet Tonnage		
Years	Import	Local Purchase	Local Share%	Import	Local Purchase	Local Share%	Import	Local Purchase	Local Share%
2023/2024	172,013	67,748	28%	172,693	18,327	10%	555	1,423	72%
2022/2023	92205	98,824	52%	114,370	24,696	18%	673	2,928	81%
2021/2022	112,985	90,895	45%	126,441	18,498	13%	25	1,985	99%
2020/2021	113,196	66,642	37%	125,838	11,498	8%	705	4,139	85%
2019/2020	171,031	28,888	14%	114,363	4,466	4%	3,313	278	8%
2018/2019	59,608	58,020	49%	118,698	7,508	6%	931	1,979	68%
2017/2018	50,483	76,660	60%	104,244	6,863	6%	3,469	2,344	40%
2016/2017	110,229	43,940	29%	121,261	9,822	7%	5,541	1,584	22%
2015/2016	120,650	38,900	24%	95,190	11,411	11%	6,096	111	2%
2014/2015	82,527	69,433	46%	103,035	11,600	10%	3,332	750	18%
2013/2014	170,234	36,694	18%	85,257	11,312	12%	5,485	532	9%
2012/2013	105,742	72,438	41%	87,726	14,819	14%	3,863	1,040	21%
2011/2012	55,305	63,228	53%	84,543	11,930	12%	1,860	975	34%
2010/2011	81,111	47,961	37%	69,519	10,038	13%	1,034	1,064	51%
Annual Average	**102,758**	**57,808**	**38%**	**103,010**	**10,814**	**10%**	**2,971**	**1,398**	**38%**

The production of white maize witnessed a strong reliance on imports over the period 2010/2011 to 2023/2024, as indicated in **Table 4-40**. The imports accounted for an average of 102,758 tons per annum, which significantly surpassed the local production of 57,808 tons. The local production of maize varied widely from a very low of 14% in 2019/2020 (which was a drought year, leading to the Covid-19 pandemic) to a highest of 60% in 2017/2018. Although the local production of white maize was highest in 2019/2020 with a tonnage of 98,824, a significant decline was observed in 2023/2024 with a production of 67,748 tons. The local production of white maize persistently fluctuated through the period of study, which may likely be due to climatic factors that impact production yields. While the local production of wheat showed that it was the most import-dependent grain in Namibia, with an average import volume of about 103,010 tons, with a meager average local share of only 10%. Interestingly, the local production of wheat never exceeded 25,000 tons, with a local share ranging from 4% to 18%. Although there were some small improvements in the recent years, 2021/22 to 2023/2023, the gap between the local production and import of wheat has been wide, and the local production has not made significant strides, implying that Namibia is still very far from becoming self-sufficient in this respect. This is suggestive of the urgent need for substantial policy intervention for the governing authorities and calls for investments that would reduce the margin between locally produced and imported wheat, which would result in improved local production of wheat. Pearl millet, on the other hand, showed distinct trends compared to white maize and wheat. This can be attributed to the fact that pearl millet, locally known as Mahangu, is majorly produced by subsistence farmers and that for personal consumption, who only depend on rain-fed agriculture, unlike white maize and wheat, which are produced by commercial farmers who use surface and ground water sources for irrigation. Pearl millet has become increasingly reliant on local production, with imports averaging only 2,971 tons per annum compared to the local production of 1,398 tons per annum. The local share of pearl millet production reached a peak of 99% in 2021/2022 and remained above 70% in the subsequent years. This trend analysis of the locally produced grain crops compared to the imports showed that the grain sector of Namibia remains heavily dependent on imports, particularly for white maize and wheat. While pearl millet showed promising local production dominance, white maize exhibited unstable but improving local share in some years. The production of wheat was stagnant and heavily depended on imports. Thus, there is a need to strengthen its local production through investment into irrigation, extension services, and climate-resilient varieties. Access to the market could also help improve Namibia's grain self-sufficiency and food security in the long term.

Trends in the sums of the Local Production and Imported Grains for 2010/11 – 2023/24

The share of locally produced grains in Namibia ranged from 10% to 38%, with an average share of about 26% (**Table 4-41**). Hence, Namibia is about 74% dependent on imports for the supply of the major grain crops. The local production of grains is still lagging behind, despite the good quality of both surface water and groundwater, suitable for irrigation purposes, as pointed out in **objective 1**. It is therefore, imperative to consider scaling up the local production of these indispensable major crops, which is vital to sustain livelihoods and achieve significant economic stability.

Table 4-41. The variation in the share of the local production of major grain crops compared to that which was imported

Period	Local Tonnage	Import Tonnage	Local Share %
2010/2011	59,063	151,664	28%
2011/2012	76,133	141,708	35%
2012/2013	88,297	197,331	31%
2013/2014	48,538	260,976	16%
2014/2015	81,783	188,894	30%
2015/2016	50,422	221,936	19%
2016/2017	55,346	237,031	19%
2017/2018	85,868	158,195	35%
2018/2019	67,507	179,237	27%
2019/2020	33,632	288,706	10%
2020/2021	82,279	239,739	26%
2021/2022	111,378	239,451	32%
2022/2023	126,448	207,248	38%
2023/2024	87,498	345,262	20%

4.3.4 The Multivariable Analysis of the Microbial and Physicochemical Characteristics of the Water Used for Irrigation

The Principal Component Analysis (PCA) of the physico-chemical variables of the irrigation water in **Figure 4-60** showed that 73.4% of the total variance among the parameters was explained by Principal Component 1 (PC1), while 11.2% was explained by PC2, thus, together giving about 84.6% of the variability. The high PC1 was indicative of a mineralisation and ionic strength gradient. The strong positive loading of the TDS, Na^+, K^+, EC, Cl^-, SO_4^{2-}, Ca^{2+} and total alkalinity suggested that these water parameters were increasing together. These parameters were mainly positive to the right along the PC1 axis; hence, they had high salinity and total dissolved solids, which is characteristic of evaporated and mineralised water.

The Principal Component 2 axis was mainly characterised by DO, pH and turbidity. These parameters create a distinction between aerated, clear water having high dissolved oxygen and pH, to turbid water with low dissolved oxygen.

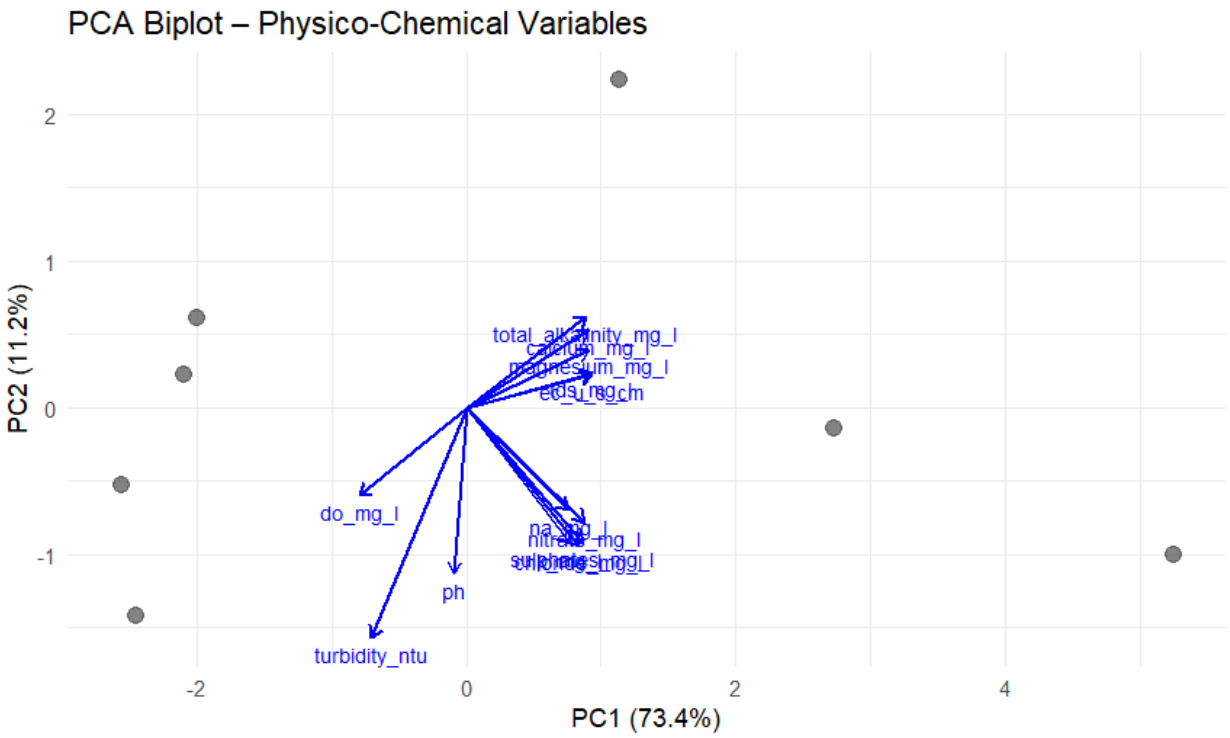


Figure 4-60. The Principal Component Analysis Biplot of the physico-chemical and climatic variables.

The Spearman correlation of the climatic and physico-chemical variables (**Figure 4.60**) showed strong positive correlations (> 0.8) among EC, TDS, Na^+, Cl^-, SO_4^{2-}, Mg^{2+}, Ca^{2+}, and total alkalinity. These findings

are in harmony with the results of the Principal Component Analysis. This strong correlation relationship is suggestive of the potential salinisation process and rock-water interactions that are characteristic of groundwater and some surface water sources. The ionic parameters showed moderate positive correlation with nitrate (≈ 0.5-0.7), which could potentially be indicative of the nutrient enrichment that is associated with anthropogenic activities such as farming and agricultural green scheme projects. However, a weak negative correlation occurred on precipitation versus EC, TDS and Na+. This could be due to the dilution effects during periods of high rainfall, which reduces solute concentrations. On the contrary, during periods of low rainfall, there would be a low dilution effect, thereby increasing solute/salinity concentration.

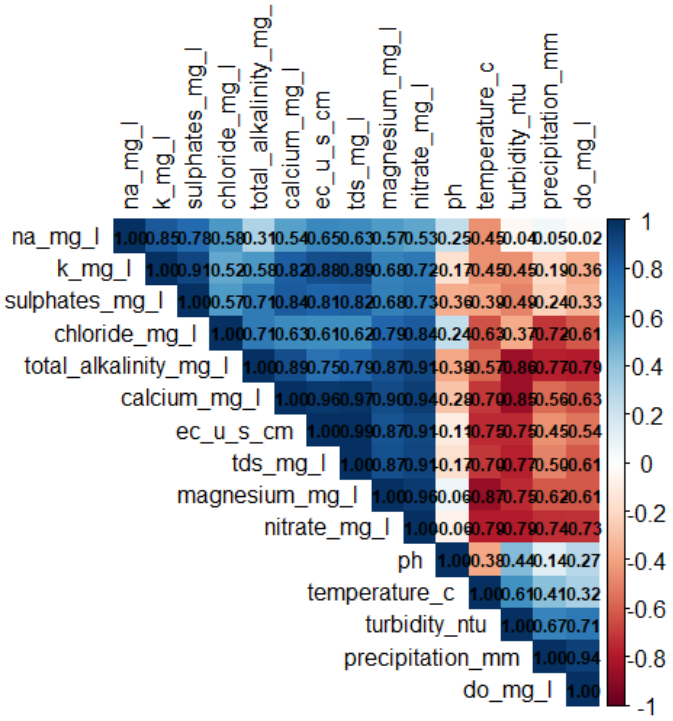


Figure 4-61. The Spearman correlation analysis of the physico-chemical and climatic variation to establish the interconnectedness of the climatic and physico-chemical characteristics of the water

Focusing on Shadikongoro, Ndonga Linena and Shitemo Agricultural Green Schemes, the correlation analysis of the physico-chemical and microbial variables with respect to climatic parameters of precipitation and temperature in **Figure 4.62**, gave an additional attestation to the impacts of climate change on the availability of water for irrigation purposes. A strong negative correlation was observed on pH versus temperature, EC and TDS (≈ -1). As the temperature, EC and TDS increase, the pH, on the

contrary, decreases. This was indicative that climate change, which is causing warmer temperatures, and thereby resulting in higher ionic concentrations in water bodies due to high evaporations, is linked to the acidic conditions of the water. The acidic condition of the water is not favourable for irrigation without water treatment, hence affecting food security. Furthermore, a strong negative correlation was also observed for total coliforms versus temperature and EC (≈ -1). Again, climate change comes into view. Microbial contamination is expected to decline as the temperature and EC rise. This may be due to the unfavourable survival conditions for microorganisms under higher temperatures. The correlation of precipitation versus TDS, temperature and EC was strongly positive (≈ 0.87). This was indicative that increasing rainfall would result in increased TDS (due to surface runoffs, floods, and soil erosion), temperature and EC in water bodies. The correlation of *E.coli* with physico-chemical and climatic variables such as TDS, EC and temperature, was weak to moderate (≈ -0.5). This implies that the concentration of the water may decline slightly under high saline and warmer climatic conditions. However, the dilution effects associated with heavy rainfall may also result in lower *E.coli* concentrations in the water.

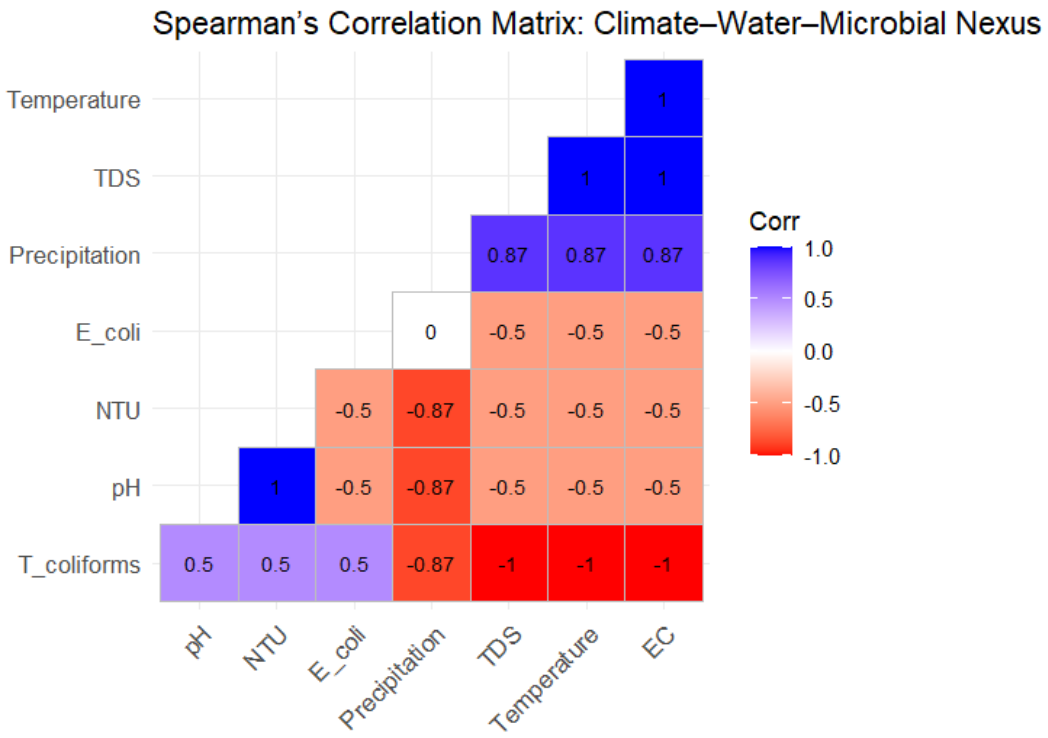


Figure 4-62. The Spearman correlation analysis of the microbial, physico-chemical and climatic variables

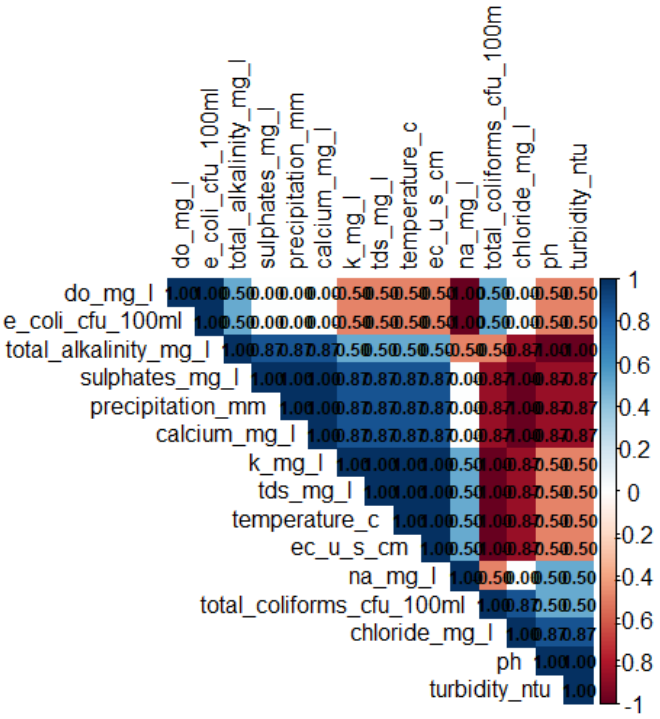


Figure 4-63. Impact of climate change on the physico-chemical and microbial quality of the water

Lastly, the climatic components of precipitation and temperature (**Figure 4.63**) had an impact on the physico-chemical and microbial quality of the water. This finding established and affirmed the interconnectedness of the climate-water-microbial system, which speaks to the water-food-climate nexus.

Chapter 5: Comprehensive Discussion

The analysed results of each specific objective are discussed to make an application of the research findings. These were compared with the findings and recommendations of similar studies.

5.1 Objective 1

Water is an indispensable commodity of human life, which is the currency that drives human activities and sustenance of livelihoods. Historically, ancient civilisations were constructed on the banks of large rivers that met the demand of both water supply (for drinking) and agricultural activities (food production) (Anuja et al., 2024). This study characterised the physico-chemical properties of the water used for irrigation and application of irrigation water indices as the first of its kind in the study locations, with its relevance to the agricultural production of horticultural crops. This was important to establish the suitability of the water for that purpose in harmony with the United Nations' Sustainable Development Goals (SDGs) 3 and 6, for the promotion of human rights and access to clean water in the fight against hunger and food security (SDG 1). Furthermore, this would contribute by influencing decision-makers to avert the use of contaminated water without treatment, affecting both human health and crop productivity (Atangana, 2023). The findings of this study indicated that pH values ranged from 6.90 to 8.00, with a mean of 7.47. This collectively attests to waters with high alkalinity (pH >6.5), which implied that these waters are suitable for irrigation purposes (Elsayed et al., 2020; Ayers and Westcott, 1985). The values of the electrical conductivity (EC) ranged from 15.05 to 1,339.67 µS/cm, with a mean of 518.11 µS/cm. This indicated that the waters were at suitable levels for use in agricultural purposes (Gapparov and Isakova, 2023; Cormier et al., 2018; McCleskey et al., 2011). The lower electrical conductivity values were mainly from the surface water samples, while the higher EC values were recorded on groundwater samples. Generally, the lower EC values speak to the fast soil-water ion exchange, insoluble geologic rocks and mineral form, and little solute dissolution. It is significant to point out that EC, which indicates the risk of salinity, is the most important water quality indicator for crop productivity (Salifu et al., 2017). Based on the classifications of Wilcox (1955), 86.2% of the samples were safe and 13.8% were tolerable for use in irrigation purposes. These results may be an affirmation of the satisfactory crop productivity in the study area and a motivation for increased cultivation. On the contrary, water with elevated levels of electrical conductivity affects the ability of the crops to compete for ions in the soil, hence causing physiological drought and subsequently resulting in crop yield reduction. This further implies that though the field may appear to have plenty of moisture, the high EC will make the crops wilt because of the

inability of their roots to absorb water. As pointed out by Almeida et al. (2008), irrigation water characterized by excessive salinity retards crop yields by restricting crops from utilising the available water in the soil. This would be a set for agricultural activities that are geared towards achieving food security. Moreover, the classification of the TDS quality of the irrigation was found to belong to the "none" and "slight to moderate" groupings. Therefore, the water is suitable for irrigation purposes based on the TDS concentrations. The application of the USSL and Wilcox diagrams alongside the water quality indices was employed by Yu et al. (2020) to quantify the differences in water quality. The findings were similar to those of this study; the USSL and Wilcox diagrams showed that the water was fit for irrigation purposes. It is important to note that groundwater quality varies from place to place due to aquifer differences, though it may be the same basin. This was shown by Shuai et al (2021) when assessing shallow groundwater for hydrochemical characteristics and quality. It was noted that part of the basin had groundwater that was of the freshwater type (TDS, lower than 1000 mg/l), and part of the basin was saline with TDS levels higher than 1000 mg/l. In Namibia, similar findings were noted on the Groot Aub groundwater quality (Mutilifa et al., 2024). Such were the findings of this study, in which the water was generally of the freshwater type and was suitable for irrigation purposes.

Furthermore, the application of water quality indices (WQIs) showed that the Na% of the water under study varied from 0.6 to 50.2, with a mean value of 27.75. The findings showed that 83% of the samples were either good or excellent for irrigation, whereas the remaining 17% were in the category of being permissible for irrigation suitability. The Wilcox Diagrams further indicated that all the samples (100%) were excellent-to-good in terms of their suitability for irrigation. Hence, both the groundwater and surface water in the area of study were suitable for irrigation. Sodium Adsorption Ratio (SAR) showed 62% and 3% were excellent and good for irrigation, respectively, while 34% of the water samples were classified as poor (SAR > 26). Since SAR affects the soil, irrigation water with high salt levels is of special concern and symbolises the sodium hazard. Residual Sodium Carbonate (RSC), the classifications of the water quality indices for irrigation water indicated that 48% of the water samples were of water that can be used safely, and 52% of the water samples were of water that was not suitable for irrigation purposes. All the water samples (100%) were classified as of excellent quality for irrigation purposes by the permeability index, and thereby indicative that the irrigation water would not affect the permeability properties of the soil. The MAR value of the irrigation water ranged from 56.87 to 77.41, with a mean of 66.64. All the water samples (100%) were not suitable for irrigation purposes (MAR>50) with respect to this water quality index. The karst that characterises the groundwater sources with elevated magnesium ions, agricultural

activities, and domestic waste discharges may account for the unsuitable categorisation of the waters for irrigation. All the samples in this study were classified as suitable for irrigation purposes according to Kelly's Index and Potential Salinity Indices of water quality. These findings align with the proposal (Almeida et al, 2008) to profile irrigation water quality using existing water quality indices (WQIs) and to apply this approach to arid and semi-arid regions, including Namibia. Amwele et al (2021) also found similar results when the water quality indices were assessed for the sustainability of groundwater for irrigation purposes in the semi-arid parts of Namibia. Their findings were, on the contrary, that most of the groundwater was unsuitable for irrigation, except in some regions where it was found to be slightly to moderately suitable for irrigation purposes.

Lastly, the multi-mixed model profile that was performed to establish seasonal and source of water variations and thereby relate them to the suitability of the water for irrigation of horticultural crops showed that the use of groundwater for irrigation varies around low, moderate and permissible suitability for the parameters potassium, EC and TDS during both seasons, except for sodium, which faired as ideal. Nonetheless, during the wet season, the suitability of the groundwater for irrigation is much better than during the dry season. In comparison, surface water showed excellent and ideal suitability for irrigation for parameters TDS, EC and Na. Only potassium (K) was less suitable during the dry season and moderately suitable during the wet season. The use of surface water for irrigation is most appropriate during the wet season, and based on the irrigation water suitability matrix, surface water should be the source of choice for the irrigation of horticultural crops, especially during the wet season. Hence, in meeting both national and international goals for sustainable development and poverty eradication while protecting the environmental health and that of the consumers, it is evident that the promotion of increased cultivation of horticultural crops should be made through greens scheme projects and farms that mainly depend on surface water sources for irrigation, while those that rely on groundwater should do so with the exercise of caution by monitoring certain parameters. It is conclusive from the performed multi-mixed model profiling of the irrigation water sources and season that the surface water is most suitable for irrigation across both seasons (dry and wet) and is highly recommended for the irrigation of sensitive and high-value horticultural crops. At the same time, the use of groundwater for irrigation is acceptable, though it may require the monitoring of the soil's electrical conductivity. The overall recommendation would be for salt-tolerant cultivars for irrigation during the wet season with groundwater.

5.2 Objective 2

This study provided the first in-depth characterisation of microbial diversity, community structure, and foodborne pathogen risks in irrigation water and sediment samples from agricultural regions in Namibia using full-length 16S rRNA gene sequencing. The results revealed distinct microbial profiles between water and sediment environments, reflecting environmental conditions, land use practices, and contamination pathways. These findings highlighted the potential for irrigation water to act as a transmission route for foodborne pathogens and stress the importance of integrating microbial monitoring into agricultural water management.

Alpha diversity indices (Chao1, Shannon) showed that irrigation water from government-managed green schemes, particularly in Kavango-East, had higher microbial richness and evenness than those from smallholder farms. Sediment samples generally showed greater community evenness than water samples, likely due to their more stable environmental conditions and complex microhabitats. These observations are consistent with Abia et al. (2018), who found higher microbial stability in riverbed sediments than in the overlying water columns in South African aquatic systems.

Taxonomically, *Pseudomonadota* (formerly Proteobacteria) dominated many water samples, with relative abundance peaking at 93% in groundwater from Grootfontein. This phylum includes metabolically versatile genera like *Pseudomonas* and *Acinetobacter*, which are known to thrive in nutrient-rich environments and may carry virulence or antimicrobial resistance traits (Luczkiewicz et al., 2015). In addition, *Pseudomonadota* contains classes *Gammaproteobacteria*, *Alphaproteobacteria*, and *Epsilonproteobacteria,* which harbours food-borne pathogens like *E. coli*, *Shigella,* and *Pseudomonas* (Scallan et al. 2011). In contrast, sediment samples were enriched with Actinomycetota and Bacillota, especially in Shadikongoro and Ndonga Linena, indicating niche partitioning and environmental filtering. Similar microbial shifts between water and sediment have been observed in irrigation canals and rivers in China (Zhang et al., 2021) and North America (Falardeau et al., 2017), confirming the global relevance of habitat-type in structuring microbial communities.

The presence of *Clostridium* in high abundance in Otavi_L and *Escherichia coli* in Shadikongoro_L and Grootfontein_L reflects recent or ongoing faecal contamination, likely from livestock runoff or untreated human waste. These genera include well-known human pathogens such as *C. perfringens* and *E. coli* O157:H7 linked to foodborne outbreaks (Brandl, 2006; Berger et al., 2010). The occurrence of *Klebsiella* and *Aeromonas*, though at lower levels, also poses a health concern as both are opportunistic pathogens

capable of surviving in aquatic environments and entering the food chain via irrigation (Benjamin et al., 2013; Olaimat and Holley, 2012).

Notably, sediment samples exhibited minimal presence of these pathogens, supporting findings by Jenkins et al. (2015) that sediment can act as a reservoir for microbial communities but may not always support active pathogen proliferation. This further suggests that the water column poses a more immediate risk of transferring pathogens to crops, particularly leafy greens and other minimally processed produce, as previously reported in the U.S., Spain, and Israel (Steele & Odumeru, 2004; Uyttendaele et al., 2015).

The Redundancy Analysis (RDA) revealed that environmental factors, particularly electrical conductivity, TDS, nitrate, calcium, and sulphates, significantly shaped microbial community composition. The first two RDA axes accounted for 65% of the variation, indicating strong environmental control. For instance, *Pseudomonas* and *Tepidibacter* were positively correlated with high nitrate levels, suggesting a link between nutrient enrichment and the proliferation of potentially pathogenic bacteria. Similar associations were observed in studies from Canada and Brazil, where nitrate-rich irrigation waters favoured the growth of fast-growing opportunists like *Pseudomonas* spp. (Falardeau et al., 2017; Santos et al., 2024).

The Mantel test further supported these findings, showing significant correlations between microbial composition and water chemistry parameters such as temperature, conductivity, and trace metals. These relationships are critical, as environmental conditions not only influence microbial diversity but may also affect the survival and virulence of foodborne pathogens (Franz and van Bruggen, 2008; Gu et al., 2013). Comparable studies from Israel and California have shown that water quality parameters, particularly turbidity, dissolved oxygen, and nitrate, are strong predictors of *E. coli* and *Salmonella* presence in irrigation water (Hintz et al., 2010; Jenkins et al., 2015). Our results confirm these associations in a sub-Saharan African context and underscore the need for environmental monitoring as part of integrated food safety systems. The detection of potential pathogens, even in relatively low abundance, has significant implications for food safety in Namibia, particularly as irrigation becomes increasingly necessary due to arid conditions and climate variability. Fresh produce that is contaminated with microbes can pose a threat to public health (Garcia et al., 2015). This aligns with Garcia et al (2015), who emphasized that detecting fecal indicator microorganisms is essential for assessing the microbial quality of water to prevent contamination with harmful microbes. This helps protect against health risks linked to freshwater produce irrigated with untreated water.

Given the widespread use of untreated or minimally treated water in many parts of Namibia and the limited enforcement of water quality guidelines, this study provided crucial evidence of the necessity for the development of microbial water standards tailored to the region.

5.3 Objective 3

As Benjamin Franklin rightly stated, “When a well is dry, we know the worth of water”. Water is the currency that drives livelihood and sustainable development. A community without water has no means of life. Climate change affects water and consequently affects food production. Inadvertently, water and food security are inseparable. Water insecurity leads to food insecurity. Due to the limited surface and groundwater resources, precipitation has been the primary source of water for irrigation by practitioners of rainfall-fed agriculture. Climate Change will affect agriculture and food production as a result of the changes in the spatial and temporal distribution of rainfall and water availability. The assessment of the precipitation trends from 1972 to 2023 showed the impacts of climate change on precipitation and major food crop production in Namibia. This study made a first-time analysis of the spatial and temporal variations and trends of precipitation using the rainfall seasonal index (RSI), Standardised Precipitation Index (SPI), Standardised Precipitation Evapotranspiration Index (SPEI), and Precipitation Concentration Index (PCI), for seven locations from four regions in Namibia. This study covered a significant gap in water and food security studies as it pertained to varying climatic conditions.

Among the three major food crops, the production of Pearl Millet (Mahangu) was seriously affected by the drought conditions as a result of climate change, because its cultivators rely entirely on rainfed agriculture. The local commercial farmers who use surface and ground water sources for irrigation do not grow Pearl Millet, although it is a staple food crop in Namibia. Thus, severe drought events due to limited precipitation hamper the production of Pearl Millet severely, and negatively impact the living conditions of subsistence farmers’ food security. Several studies have equally highlighted that insufficient rainfall and heightened climate vulnerability pose a threat to agricultural activities, especially small farmers who depend on rainfed production.

Both the Standardised Precipitation Index (SPI) and Standardised Precipitation Evapotranspiration Index (SPEI) were used to characterise the rainfall over the period under study; however, the SPEI was used to characterise the drought severity, intensity, frequency and duration. The SPEI was most preferred because it incorporates both precipitation and evapotranspiration, unlike the SPI, which only focuses on precipitation. Hence, the SPEI gave a comprehensive picture of the availability of water, which is relevant for agricultural food production. Although the trend analyses were generally not statistically significant in

the long term, the seasonal trends analyzed using the modified Mann-Kendal test showed that during the winter, Grootfontein, Otavi, Tsumeb and Sikondo had statistically significant trends of precipitation. Furthermore, the Hirsch-Slack test for the seasonal Mann-Kendall test showed significant trends for Grootfontein, Ndonga Linena, Shadikongoro, Shitemo and Sikondo. Similarly, the Z-statistics and Mann-Kendall S statistic, collectively showed strong decreasing trends in the precipitation, such as was observed for Grootfontein (Z = -2.664, S = -1128, and p-value = 0.0077). The SPEI assessment for drought at a 12-month time scale indicated that Grootfontein, Ndonga Linena, Otavi, Shadikongoro, Shitemo, Sikondo, and Tsumeb had severe drought frequencies of 16, 18, 16, 19, 18, 18 and 14, respectively. The droughts with higher severities occurred in 1992, 1995, 1996, 2013, 2015, 2019 and 2023. These findings agreed with the Namibia Drought Assessment Report (IFRC, 2022) which indicated Namibia experienced persistent drought conditions in over 7 years, to which the Namibian government declared national emergencies in 1992/1993, 1995/1996 and 2018/2019 due to extreme drought events and by the end of 2019, which was hit the hardest, agricultural production were at its lowest. It is important to point out that the impacts of these droughts were more realised and experienced by the rural population because they highly depend on rainfed agricultural practices.

Furthermore, the spatial analysis of SPI and SPEI indices expressed important patterns in the occurrence of droughts across the study locations. These indices were effective in capturing droughts induced by climatic events, with SPI focusing only on precipitation, and SPEI capturing both precipitation and evapotranspiration (Chisadza et al., 2024). Although SPIs were computed in this study, the drought severity analyses, along with the other drought characteristics across the locations, were computed using the SPEI at 3-, 6-, and 12-month time scales. The SPI was excluded from this purpose because it would have probably underrepresented the severity of the drought in Namibia, where temperature-induced evapotranspiration plays a significant role. The analyses of the individual location at different time scales gave comprehensive insight into localized drought trends. The SPI-3 and SPI-6 gave indications of the occurrence of short-term and medium-term wet and dry conditions, but the SPI-12 presented clearer distinctions of the wet and dry conditions. All the locations had periods of wet and dry conditions, but interestingly, there seemed to be an alternating trend between these conditions. Good wet conditions (SPI values > 0) were generally followed by severe dry (drought) conditions. Overall, though drought conditions in severity were experienced in the 1970s and 1990s, the intensity, severity and duration of the droughts showed increasing trends across the years.

Implications of the drought on food production

White maize, wheat and pearl millet (Mahangu) are controlled crops in Namibia, and are significant for food security (NSA, 2021). The trend analyses of the production of white maize, wheat, and Pearl Millet for 2010 – 2024 (the only available data) showed that wheat and Pearl Millet had slightly steady, though declining trends of production, while white maize showed significantly increasing trends over the years. However, there were sharp declines in the production of all these staple crops in 2013/2014, 2015/2016 and 2019/2020. These were periods of national drought emergencies. The decline in production during these difficult periods was a lot conspicuous for white maize, which had production of more than 72,400 tons in 2012/2013 and declined to less than 29,000 tons in 2019/2020. During this period (2019/2020), the self-sufficiency in terms of local production fell to its lowest level of 14% compared to the highest self-sufficiency record of 60% in 2017/2018.

The precipitation trends as related to the variations in crop production for the same period (2010-2024) showed that the production of the major crops declined during the years in which there was a reduction in annual precipitation. White maize, for instance, is mainly produced by commercial farmers who depend primarily on groundwater in the Tsumeb-Otavi-Grootfontein maize triangle, except for a few who also utilise rainfed irrigation practices to grow white maize. The lower production of white maize during the periods of lower precipitation is indicative that there was a decline in both surface and groundwater sources. This can be established in that agricultural green schemes such as Shadikongoro, Ndonga Linena and Sikondo depend on surface water for irrigation purposes. Moreover, the erratic and inconsistent patterns of precipitation also correspond to the unstable and inconsistent production of the major food crops, thereby threatening food security. The production of the major food crops showed a sloping up and down trend with respect to annual rainfall.

In addition, it is significant to point out that the impacts of climate change on food security were shown by the observed trends of the grain domestic average price per ton. The grain domestic average price per ton indicated a clear upward increase in all three grain crops. Although the cost per ton of each type of grain was almost the same in 2010/2011 and 2012/2013, the price of wheat became more costly than the other grain-crops from 2012/2013 through to 2015/2015. The low local production of the major crops led to a corresponding strong dependence on imports to augment the demand for these staple food crops, which have been on the rise due to population growth, among other factors. The cost of imports has also subsequently impacted negatively the domestic prices of the grain crops and thereby aggravated food insecurity due to increased costs of food.

The Water-Food-Climate Nexus

Climate change and water quality are connected (Fant et al., 2017), particularly through the biochemical reactions in water bodies that are impacted by the variabilities in climate. There is a connection between microorganisms and the physico-chemical characteristics of the water with respect to climate change. Physico-chemical parameters serve as nutrients for microorganisms in water. Climate change is causing water temperatures to rise, and consequently, the thermophiles would thrive better in warmer waters. The findings, similarly, showed that water quality will most likely worsen as a result of climate change. A holistic Water-Food-Climate (WFC) Nexus (**Figure 5-1**) was achieved through the integration of the climate-food (**Objective 3**) component with the microbial and physico-chemical findings from Objectives 1 and 2. The WFC Nexus is a significant and integral framework that brings together water availability, food production, and climate change.

Furthermore, the microbiological and physico-chemical quality of the water constitutes an important biophysical indicator that connects climate change (the environmental conditions) to agricultural productivity (food) through the water systems. About 60% of the population of the Southern African Development Community (SADC) lives in rural areas and depends on rainfed agriculture (Kabeya et al., 2022). Ensuring water and food security is central on the development agenda on improving livelihoods and building resilience for the SADC (Kabeya et al., 2022). The increasing demands for water due to population growth, increasing urbanisation and increasing economic growth are a continuous challenge. These challenges are further exacerbated by climate change due to the strong dependence on climate-sensitive agriculture, which relies heavily on water resources (Kusangaya et al., 2014).

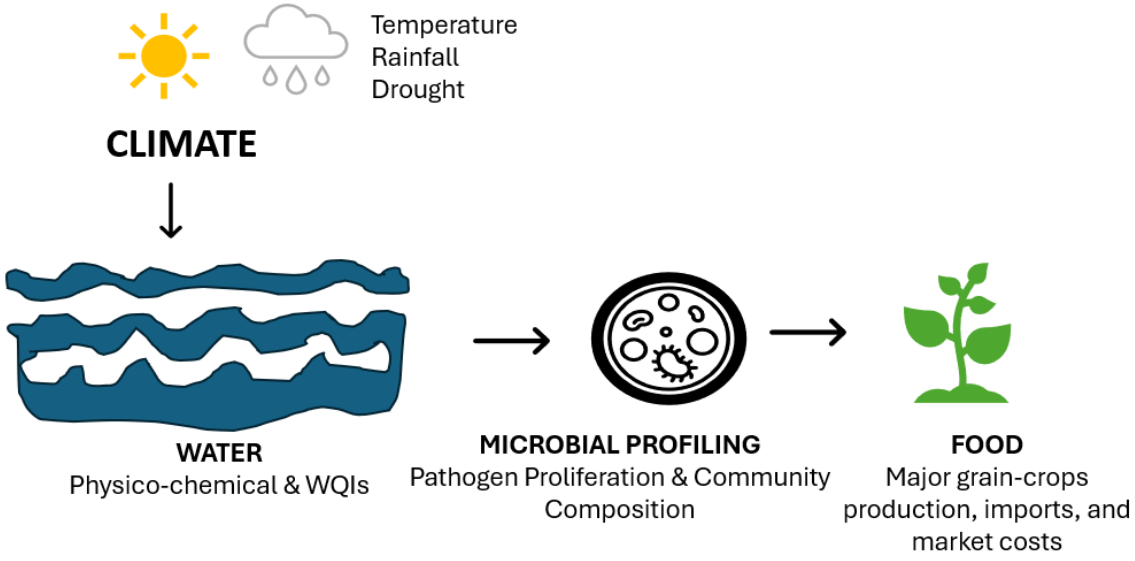


Figure 5-1. A holistic Water-Food-Climate nexus

The interlinkages in the WFC Nexus

(a) Water to Food linkage: the erratic rainfall patterns have consequently resulted in fluctuations in the production of grain crops and a strong reliance on imports. This has, in turn, affected the market prices of the grain crops. The decline in rainfall limits irrigation and crop yield, and thereby threatens food security. The mission to achieve zero hunger without compromising health through the right to access clean water (SDGs 3 and 6) remains a daunting task. The challenges of limited water on food production can be attested by the sharp declines in the production of all the staple crops in 2013/2014, 2015/2016 and 2019/2020. These were periods of national drought emergencies. The decline in production during these difficult periods was more conspicuous for white maize, which had production of more than 72,400 tons in 2012/2013 and declined to less than 29,000 tons in 2019/2020. During this period (2019/2020), the self-sufficiency in terms of local production fell to its lowest level of 14% compared to the highest self-sufficiency record of 60% in 2017/2018.

(b) Climate to water: the rising temperatures with declining rainfall, and increased evaporations reduces the amount of water available for irrigation. The assessment of using SPI and SPEI, especially the latter, which captured both precipitation and evapotranspiration, showed an increase in severe drought events between 1972 and 2023. These droughts increased in frequency and intensity, and in the duration they lasted.

(c) Climate to food: the negative impacts of climate on food production and security were observed with respect to precipitation. Low production grain productions were recorded during the periods of low precipitation. These low productions corresponded to a strong dependence on imports to augment the high demand for the major stable crops.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

The findings of **objective 1** on the characterisation of the physico-chemical properties of the water used for irrigation of horticultural crops indicated that the water was generally suitable for irrigation purposes. This encourages the need to scale up the food crops in the pursuit of increasing self-sufficiency and boosting food security from the local perspective. It is also imperative that commercial farmers consider the need to commercialise the production of pearl millet (Mahangu), a significant and indispensable staple crop to more than 50% of the Namibian population. **Objectives 2** significantly exhumed the presence of different microbial communities in both the water and sediments used for agricultural activities. This study provides the first comprehensive analysis of microbial diversity, community composition, and the presence of potential foodborne pathogens in irrigation water and sediments across key agricultural regions in Namibia, such as *Escherichia coli*, *Clostridium*, *Klebsiella*, and *Aeromonas*, indicating faecal contamination and underscoring the risk of pathogen transmission to fresh produce. Using full-length 16S rRNA gene sequencing, we identified distinct bacterial communities shaped by sample type and environmental factors such as nitrate, electrical conductivity, and total dissolved solids. Sediment samples exhibited more stable and diverse microbial communities but generally showed lower prevalence of foodborne pathogens, suggesting that the water column is a more immediate vehicle for contamination. The strong influence of environmental parameters on microbial community structure, as revealed by redundancy and correlation analyses, highlights the need for regular water quality monitoring as part of a proactive food safety strategy. These findings demonstrate that irrigation water in Namibia, particularly in regions with intensive agricultural activity and limited water treatment, can serve as a conduit for human pathogens and potentially antibiotic-resistant organisms. As such, the implementation of Good Agricultural Practices (GAPs), microbial risk assessments, and region-specific water quality guidelines is critical to safeguarding public health and promoting sustainable agricultural development in arid and semi-arid regions.

Among the microbial communities is the presence of microorganisms that could be pathogenic and could potentially result in food and water-borne diseases. This calls for caution through policies and regulations to ensure that the monitoring of water for its quality does not only stop at the physico-chemical

characteristics but also at the microbial quality of both the water and sediments to safeguard the health of the consumers.

The outcomes of **objective 3** stressed the impacts of climate change on water and food security. The erratic and irregular rainfall patterns over the years have revealed the threat climate change poses to water security, and which has inadvertently affected food security due to severe drought conditions that have reduced the agricultural productivity of major crops. It is thus important to plan for maximum crop production during the good wet season to help mitigate food insecurity and ensure the continued sustenance of the local communities during the periods of drought that have proved to follow seasons of good rainfall. This would lessen dependence on imports and the stress of the market cost of food to the consumers. Furthermore, priority should be given to the production of drought-tolerant crops to sustain livelihoods during periods of drought, as their water requirements are minimal and would not place pressure on the utilisation of much ground or surface water. The climatic trends clearly indicate that climate change is here to stay, and periods of drought should be expected frequently. Hence, agricultural planning for effective crop production in difficult times and preparedness is required at all levels, individual families, local farmers, commercial farmers, government and non-governmental organisations.

6.2 Recommendations

Based on the findings of this study, the following recommendations were made:

1) Due to the presence of potential pathogenic microorganisms in water, there is a need for further assessment of the water and sediment microbial community composition by employing whole genome sequence technologies that cater for viruses and fungal microorganisms, unlike the 16S rRNA gene, which was limited to the bacterial community composition.
2) It is recommended to test the microbial quality of vegetables, especially salad and root vegetables, as they often exhibit high levels of microbial contamination and are frequently consumed raw.
3) Since the presence of faecal indicator organisms in the irrigation water was confirmed by the detection of *Escherichia coli* in Shadikongoro and Ndonga Linena, it is recommended that a study be conducted to include the types of diseases that are associated with water-borne and food-borne pathogens.
4) The water of both surface and groundwater was generally suitable for the irrigation of horticultural crops. This study recommends that water be continuously monitored and protected from anything that can alter its quality, from suitability for irrigation usage.

5) The findings of this study have established the Water-Food-Climate Nexus. However, the correlation in terms of cause and effect was not well pronounced. There is, therefore, a need to characterise and establish the link between microorganisms and physico-chemical characteristics of water, and connect it to climate change.
6) The impacts of climate change on the water sources and food security were found to be a reality in the study area. However, it was noted that the land used for the cultivation of food crops was less than available, hence low crop production and strong dependence on imports. There is a need to scale up agricultural production in the presence of good water quality. Especially, at the agricultural green projects that source water from the Kavango River, and the commercial farmers in the Karst area (Tsumeb-Grootfontein-Otavi), where there is adequate groundwater.
7) Lastly, pearl millet (Mahangu), though a staple food crop in Namibia, among the three major food crops that can grow both during the rainy season and dry season, has been lowly produced, and that is mainly by the subsistence farmers who depend on rain-fed agriculture, and thus grow it only during the rainy season. The commercial farms that both depend on rain and other water sources for irrigation do not cultivate Mahangu (pearl millet), but rather white maize and wheat. Hence, depending on imports to augment the local demand for Pearl Millet. Furthermore, the cost of Mahangu flour (e.g., Meme Mahangu) is very high compared to that of White Maize on the market. There is a need for the local commercial farmers to grow Mahangu, and that on large scales, like they do for white maize and wheat in the fight for food security. This would reduce the costs for importing Pearl Millet, especially on transportation, which affects the market price.

   Generally, during the drought years, outbreaks of locusts and floods, the subsistence farmers suffer a lack in the production of Pearl Millet, which shifts to maize flour produced from white maize. The demand for white maize becomes high, and thereby increasing the market price of maize floor per ton, because consumers of Mahangu have no option. However, in normal years, the market price of the pearl millet is higher than that of white maize (reference 2023/2024 from the records above). This is because the former is the main option for consumption by more than 50% of the population, who generally depend on rain-fed agriculture but mostly do not produce enough to meet yearly demands. Climate change, therefore, not only affected the production of major food crops but also the cost of living because the market cost of these staple food crops was equally affected.

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Appendices

Appendix 1 Ethical Clearance

NAMIBIA UNIVERSITY OF SCIENCE AND TECHNOLOGY
Faculty of Health, Natural Resources and Applied Sciences
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DECISION/FEEDBACK ON RESEARCH PROPOSAL ETHICAL CLEARANCE

Dear ~~Prof/Dr~~/Mr~~/Ms/Other(s)~~: Petrus Tuhafeni Paulus

Student No (if applicable):

Research Topic:	Microbial Quality and Physico-chemical Profiling of Water Used for Irrigation in Namibia
Supervisor (if applicable):	Prof Percy Chimwamurombe
Co-supervisor(s): if applicable	Dr. Norman Muzhinji, Prof Collins Ateba and Prof Christian Borgemeister
Qualification registered for (if applicable):	PhD in Natural Resources Sciences

Re: Ethical screening application No: FHNRAS:31/2023

The Research Ethics Screening Committee has reviewed your application for the above-mentioned research project. Based on the recommendation of the expert reviewer, the research as set out in the application is hereby:

(Indicate with an X)

Approved: i.e. may proceed with the project	X	
Approved provisionally: i.e. may proceed but subject to compliance with recommendation(s) listed below		
Not approved: Not to proceed with the project until compliance with recommendation(s) listed below and resubmit ethics application for consideration		
IS MINISTRY OF HEALTH & SOCIAL SERVICES (MoHSS) APPROVAL REQUIRED?	YES:	NO: X

It is important to note that as a researcher, you are expected to maintain ethical integrity of your research, strictly adhere to the ethical policy of NUST, and remain within the scope of your research proposal and supporting evidence as submitted to the REC. Should any aspect of your research change from the information as presented, which could have an impact or effect on any research participants/subjects/environment, you are to report this immediately to your supervisor or REC as applicable in writing. Failure to do so may result in withdrawal of approval. Kindly consult your supervisor or HoD if you need further clarification.

We wish you success in your research endeavour and are of the belief that it will have positive impact on your career as well as the development of NUST and the society in general.

Ethical issues that require compliance/ must be addressed: None		
No.	**Ethical issues**	**Comment/recommendation**
1.		
2.		

NB: May attach additional page as required

Reviewrs name:..... Signature: Date:

Full Name: Dr Larai Aku-Akai Signature: Date: **11 April 2023**

Chair: Ethics Screening Committee

Appendix 2 **Certificate in Microbiology**

NAMIBIA UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Universität Bremen

[NUST, Universität Bremen]

Certificate of Completion

is hereby granted to

PETRUS PAULUS

to certify that the Microbiology Course was completed to satisfaction

[SUSTAIN]

Granted: August 1, 2023

Prof. Dr. Percy Chimwamurombe

Dr Abhijit Sarkar

Appendix 3 **Climate-Smart Agriculture in South Africa**

Appendix 4 Certificate on Data and Bioinformatics



UNIVERSITY OF THE FREE STATE
UNIVERSITEIT VAN DIE VRYSTAAT
YUNIVESITHI YA FREISTATA

UFS UV

CERTIFICATE OF PARTICIPATION*

This is to certify that

Petrus Tuhafeni Paulus

Has attended on 03 - 07 July 2023

Training on Data and Bioinformatics, organized by the University of the Free State – Next Generation Sequencing (UFS-NGS) Unit

Brief description of content:
Analysis of whole genome NGS data, 16S metagenomics and viral metagenomics data using Linux command lines
https://ufs-ngs.org.za/more-information/

Prof. M.M. Nyaga
Head of UFS-NGS Unit

UFS-NGS

DIPLOMICS

*Not credit-bearing towards a UFS qualification

Appendix 5 **Training Certificate on Vitek 2 Compact**

Training Certificate

BIOMÉRIEUX



awarded to

Petrus Tuhafeni Paulus

For participation in the training course

Vitek® 2 Compact
17-20 July 2023- Namibia University of Science & Technology

Yatisha Jairam
Trainer

Signature

Appendix 6 Course Certificate on Whole Genome Sequencing of Bacterial Genomes – Tools and Applications



Appendix 7 Contacts

(a) Mr. Romanus Mangundu 0816807149, Sikondo Green Scheme Irrigation Project
(b) Mr. Joseph Mutero, 0813317885, Shadikongoro Green Scheme Irrigation Project, Project Manager
(c) Ndonga Linena, 0816877280, Project Manager, Ndonga Linena Green Scheme Irrigation Project
(d) Shitemo, 0817207389, Shitemo Green Scheme Irrigation Project
(e) Steven S K, Basin Officer, Rundu

Appendix 8 Onsite Physico-chemical characteristics of irrigation water

In situ analyses of physico-chemical parameters:

SIK – MFS 1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.75	6.75	6.75	**6.75**
ORP	mV	21.50	20.70	20.50	**20.90**
Conductivity	µS/cm	46.20	46.20	46.30	**46.23**
TDS	mg/l	23.20	23.20	23.30	**23.23**
Temperature	^{o}C	22.70	22.70	22.70	**22.70**
Salinity	ppt	21.90	21.90	21.90	**21.90**

SIK – MSF 2

(a) Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.41	6.41	6.42	**6.41**
ORP	mV	38.60	38.90	38.60	**38.70**
Conductivity	µS/cm	46.60	46.61	46.64	**46.62**
TDS	mg/l	23.44	23.47	23.48	**23.46**
Temperature	^{o}C	22.90	23.00	23.00	**22.97**
Salinity	ppt	22.19	22.20	22.21	**22.20**

(b) Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.90	6.91	6.91	6.91
ORP	mV	11.7	11.35	11.33	11.46
Conductivity	µS/cm	47.00	44.00	40.00	43.67
TDS	mg/l	22.00	22.00	22.00	22.00
Temperature	°C	23.31	23.31	23.31	23.31
Salinity	ppt	-	-	-	-

SIK – CSF

(a) Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.15	6.17	6.18	**6.17**
ORP	mV	47.80	47.50	47.20	**47.50**
Conductivity	µS/cm	45.33	45.38	45.40	**45.37**
TDS	mg/l	22.90	22.91	22.93	**22.91**
Temperature	°C	22.50	22.50	22.50	**22.50**
Salinity	ppt	21.62	21.64	21.64	**21.63**

(a) Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.73	6.75	6.74	6.74
ORP	mV	103.30	103.20	103.10	103.2
Conductivity	µS/cm	44.00	44.00	44.00	44.00
TDS	mg/l	22.00	22.00	22.00	22.00
Temperature	°C	22.87	22.87	22.87	22.87
Salinity	ppt	-	-	-	-

SIK – PS 1

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.91	6.93	6.94	**6.93**
ORP	mV	110.60	110.30	110.00	**110.30**
Conductivity	µS/cm	42.00	41.00	41.00	**41.33**
TDS	mg/l	21.00	21.00	21.00	**21.00**
Temperature	°C	23.71	23.71	23.71	**23.71**
Salinity	ppt	-	-	-	**-**

SIK – PS 2

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.88	6.89	6.90	**6.89**
ORP	mV	108.50	108.20	108.00	**108.23**
Conductivity	µS/cm	39.00	39.00	40.00	**39.33**
TDS	mg/l	19.00	20.00	20.00	**19.67**
Temperature	°C	21.51	21.54	21.54	**21.53**
Salinity	ppt	-	-	-	-

SIK – MR

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.93	6.96	6.98	**6.96**
ORP	mV	109.90	109.00	109.20	**109.37**
Conductivity	µS/cm	43.00	44.00	43.00	**43.33**
TDS	mg/l	22.00	22.00	22.00	**22.00**
Temperature	°C	23.22	23.24	23.22	**23.23**
Salinity	ppt	-	-	-	-

SHA – PP A

In situ data not well taken with instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.76	-	-	-
ORP	mV	18.8	-	-	-
Conductivity	µS/cm	-	-	-	-
TDS	mg/l	-	-	-	-
Temperature	°C	22.4	-	-	-
Salinity	ppt	17.28	-	-	-

SHA – PP B

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.52	6.50	6.47	**6.50**
ORP	mV	31.60	31.10	31.00	**31.27**
Conductivity	µS/cm	16.89	16.78	16.77	**16.77**
TDS	mg/l	16.62	16.63	16.64	**16.63**
Temperature	°C	22.40	22.40	22.40	**22.40**
Salinity	ppt	15.79	15.80	15.81	**15.80**

SHA – PP C

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.72	6.70	6.67	**6.70**
ORP	mV	48.90	48.70	50.00	**49.20**
Conductivity	µS/cm	15.08	15.05	15.03	**15.05**
TDS	mg/l	15.88	15.89	15.90	**15.89**
Temperature	°C	21.80	21.80	21.80	**21.80**
Salinity	ppt	14.99	14.99	14.99	**14.99**

SHA – SS 1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.42	6.42	6.40	**6.41**
ORP	mV	39.30	40.20	40.20	**39.90**
Conductivity	µS/cm	30.50	30.50	30.40	**30.47**
TDS	mg/l	15.26	15.26	15.25	**15.26**
Temperature	°C	24.70	24.70	24.70	**24.70**
Salinity	ppt	14.38	14.38	14.38	**14.38**

SHA – SS 2

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.46	6.47	6.49	**6.47**
ORP	mV	35.80	35.80	35.70	**35.77**
Conductivity	µS/cm	30.52	30.51	30.45	**30.49**
TDS	mg/l	15.20	15.19	15.19	**15.19**
Temperature	°C	26.00	26.00	26.00	**26.00**
Salinity	ppt	14.33	14.33	14.34	**14.33**

SHA – SS 3

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.02	6.02	6.01	**6.02**
ORP	mV	59.50	59.80	59.20	**59.50**
Conductivity	µS/cm	31.93	31.92	31.85	**31.90**
TDS	mg/l	15.91	15.91	15.92	**15.91**
Temperature	°C	30.60	30.50	30.50	**30.53**
Salinity	ppt	14.97	14.96	14.95	**14.96**

SHA – SS 4

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	7.10	6.86	6.82	**6.93**
ORP	mV	25.80	25.80	25.90	**25.83**
Conductivity	µS/cm	33.90	33.83	33.79	**33.84**
TDS	mg/l	16.76	16.75	16.79	**16.77**
Temperature	°C	37.00	37.00	37.00	**37.00**
Salinity	ppt	15.82	15.82	15.82	**15.82**

SHA – SS 5

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.21	6.22	6.22	**6.22**
ORP	mV	49.10	48.90	48.80	**48.93**
Conductivity	µS/cm	15.18	15.16	15.15	**15.16**
TDS	mg/l	16.04	16.03	16.03	**16.03**
Temperature	°C	23.30	23.30	23.30	**23.30**
Salinity	ppt	15.12	15.13	15.13	**15.13**

TSU – MAN 1

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.59	6.61	6.62	**6.61**
ORP	mV	147.60	146.90	145.70	**146.73**
Conductivity	µS/cm	1144.00	1166.00	1120.00	**1143.33**
TDS	mg/l	615.00	610.00	602.00	**609.00**
Temperature	°C	25.76	25.76	25.76	**25.76**

Salinity	ppt	-	-	-	-

TSU – MAN 2

Instrument 2

Parameter	**Unit**	**Reading 1**	**Reading 2**	**Reading 3**	**Average**
pH	pH	6.78	6.79	6.80	**6.79**
ORP	mV	106.80	106.60	106.40	**106.60**
Conductivity	µS/cm	950.00	784.00	1026.00	**920.00**
TDS	mg/l	448.00	414.00	410.00	**424.00**
Temperature	°C	26.23	26.23	26.23	**26.23**
Salinity	ppt	-	-	-	-

TSU – MAN 3

Instrument 2

Parameter	**Unit**	**Reading 1**	**Reading 2**	**Reading 3**	**Average**
pH	pH	6.88	6.89	6.89	**6.89**
ORP	mV	110.00	109.70	109.30	**109.67**
Conductivity	µS/cm	1234.00	1233.00	1237.00	**1234.67**
TDS	mg/l	621.00	619.00	620.00	**620.00**
Temperature	°C	32.72	32.69	32.69	**32.70**
Salinity	ppt	-	-	-	-

TSU – UIT

Instrument 2

Parameter	**Unit**	**Reading 1**	**Reading 2**	**Reading 3**	**Average**
pH	pH	6.93	6.95	6.97	**6.94**
ORP	mV	131.00	130.50	129.50	**130.33**
Conductivity	µS/cm	1349.00	1323.00	1347.00	**1339.67**
TDS	mg/l	684.00	687.00	643.00	**671.33**
Temperature	°C	29.21	29.22	29.22	**29.22**
Salinity	ppt	-	-	-	**-**

TSU – MUR 1

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.77	6.84	6.88	**6.83**
ORP	mV	134.90	133.00	132.30	**133.40**
Conductivity	µS/cm	811.00	833.00	830.00	**824.67**
TDS	mg/l	413.00	415.00	420.00	**416.00**
Temperature	°C	24.04	24.04	24.04	**24.04**
Salinity	ppt	-	-	-	**-**

TSU – MUR 2

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.78	6.78	6.77	**6.78**
ORP	mV	129.20	128.80	128.50	**128.83**
Conductivity	µS/cm	758.00	760.00	759.00	**759.00**
TDS	mg/l	383.00	379.00	381.00	**381.00**
Temperature	°C	31.61	31.61	31.61	**31.61**
Salinity	ppt	-	-	-	**-**

TSU – KEYB 1

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.81	6.80	6.80	**6.80**
ORP	mV	106.90	106.40	106.10	**106.47**
Conductivity	µS/cm	865.00	948.00	948.00	**920.33**
TDS	mg/l	478.00	480.00	480.00	**479.33**
Temperature	°C	27.29	27.29	27.30	**27.29**
Salinity	ppt	-	-	-	**-**

TSU – KEYB 2

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.76	6.77	6.77	**6.77**
ORP	mV	104.80	104.00	104.00	**104.27**
Conductivity	µS/cm	1209.00	1206.00	1208.00	**1207.67**
TDS	mg/l	601.00	604.00	605.00	**603.33**
Temperature	°C	26.66	26.66	26.65	**26.66**
Salinity	ppt	-	-	-	**-**

TSU – KEYB 3

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.82	6.81	6.81	**6.81**
ORP	mV	105.70	105.30	104.20	**105.07**
Conductivity	µS/cm	870.00	868.00	869.00	**869.00**
TDS	mg/l	524.00	510.00	534.00	**522.67**
Temperature	°C	26.92	26.92	26.93	**26.92**
Salinity	ppt	-	-	-	**-**

TSU – COR Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.70	6.71	6.73	**6.71**
ORP	mV	116.10	114.20	113.50	**114.60**
Conductivity	µS/cm	655.00	658.00	659.00	**657.33**
TDS	mg/l	343.00	347.00	341.00	**343.67**
Temperature	°C	27.02	27.01	27.01	**27.01**

Salinity	ppt	-	-	-	**-**

GRO – HAR 1

Instrument 1

Parameter	**Unit**	**Reading 1**	**Reading 2**	**Reading 3**	**Average**
pH	pH	6.33	6.34	6.34	**6.34**
ORP	mV	45.30	45.70	45.50	**45.50**
Conductivity	µS/cm	833.30	833.70	833.70	**833.57**
TDS	mg/l	417.00	417.00	417.00	**417.00**
Temperature	°C	24.10	24.10	24.10	**24.10**
Salinity	ppt	411.70	411.80	411.80	**411.77**

Instrument 2

Parameter	**Unit**	**Reading 1**	**Reading 2**	**Reading 3**	**Average**
pH	pH	6.92	6.90	6.87	**6.90**
ORP	mV	145.60	145.20	144.60	**145.13**
Conductivity	µS/cm	590.00	600.00	606.00	**598.67**
TDS	mg/l	398.00	400.00	401.00	**399.67**
Temperature	°C	24.09	24.09	24.09	**24.09**
Salinity	ppt	-	-	-	-

GRO – HAR 2

Instrument 1

Parameter	**Unit**	**Reading 1**	**Reading 2**	**Reading 3**	**Average**
pH	pH	6.50	6.50	6.49	**6.50**
ORP	mV	39.70	39.80	39.80	**39.77**
Conductivity	µS/cm	710.80	710.70	711.10	**710.87**
TDS	mg/l	356.00	356.10	356.10	**356.07**
Temperature	°C	27.80	27.80	27.80	**27.80**
Salinity	ppt	350.80	351.60	351.30	**351.23**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.99	7.04	7.05	7.03
ORP	mV	137.00	136.30	136.00	136.43
Conductivity	µS/cm	558	534.00	534.00	542.00
TDS	mg/l	267.00	269.00	267.00	267.67
Temperature	°C	27.60	27.60	27.59	27.60
Salinity	ppt	-	-	-	-

GRO – DER 1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.13	6.13	6.14	**6.13**
ORP	mV	55.80	55.70	55.60	**55.70**
Conductivity	µS/cm	796.50	769.90	797.30	**787.90**
TDS	mg/l	399.00	399.00	399.10	**399.03**
Temperature	°C	31.20	31.20	31.20	**31.20**
Salinity	ppt	393.80	393.70	393.90	**393.80**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.88	6.85	6.83	**6.85**
ORP	mV	149.30	149.00	148.50	**148.93**
Conductivity	µS/cm	771.00	775.00	786.00	**777.33**
TDS	mg/l	366.00	380.00	373.00	**373.00**
Temperature	°C	30.80	30.81	30.82	**30.81**
Salinity	ppt	-	-	-	**-**

GRO – DER 2

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.81	6.20	6.21	**6.41**
ORP	mV	46.70	46.50	46.40	**46.53**
Conductivity	µS/cm	840.20	839.90	839.50	**839.87**
TDS	mg/l	420.10	420.20	420.30	**420.20**
Temperature	^{o}C	24.70	24.70	24.70	**24.70**
Salinity	ppt	415.30	415.30	415.30	**415.30**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.90	6.89	6.88	**6.89**
ORP	mV	152.60	152.60	152.60	**152.60**
Conductivity	µS/cm	857.00	856.00	854.00	**855.67**
TDS	mg/l	424.00	424.00	423.00	**423.67**
Temperature	^{o}C	24.64	24.58	24.62	**24.61**
Salinity	ppt	-	-	-	**-**

GRO – RIET 1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.15	6.16	6.17	**6.16**
ORP	mV	48.20	48.00	47.00	**47.73**
Conductivity	µS/cm	733.20	733.60	733.20	**733.33**
TDS	mg/l	366.70	366.70	366.90	**366.77**
Temperature	^{o}C	27.80	27.80	27.80	**27.80**
Salinity	ppt	362.10	362.20	362.10	**362.13**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	7.06	7.09	7.11	**7.09**

ORP	mV	140.00	138.10	137.30	**138.47**
Conductivity	µS/cm	717.00	716.00	714.00	**715.67**
TDS	mg/l	357.00	356.00	356.00	**356.33**
Temperature	°C	27.79	27.78	27.78	**27.78**
Salinity	ppt	-	-	-	**-**

GRO – RIET 2

Instrument 1

Parameter	**Unit**	**Reading 1**	**Reading 2**	**Reading 3**	**Average**
pH	pH	6.23	6.40	6.53	**6.39**
ORP	mV	35.70	34.60	34.40	**34.90**
Conductivity	µS/cm	807.80	809.00	809.40	**808.73**
TDS	mg/l	405.40	405.40	405.40	**405.40**
Temperature	°C	27.00	27.00	27.00	**27.00**
Salinity	ppt (mg/l)	400.20	400.40	400.40	**400.33**

Instrument 2

Parameter	**Unit**	**Reading 1**	**Reading 2**	**Reading 3**	**Average**
pH	pH	7.13	7.15	7.16	**7.15**
ORP	mV	137.40	137.30	137.00	**137.23**
Conductivity	µS/cm	785.00	789.00	791.00	**788.33**
TDS	mg/l	397.00	401.00	399.00	**399.00**
Temperature	°C	27.09	27.11	27.02	**27.07**
Salinity	ppt	-	-	-	**-**

Dry Season Sampling

Water samples were collected on 04 to 11 February 2024 for physico-chemical and microbiological quality analysis.

In situ analyses of physico-chemical parameters:

SHA – Pump A

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.52	6.27	6.13	**6.31**
Turbidity	NTU	*	*	*	*
Conductivity	µS/cm	47	51	52	**50**
TDS	mg/l	24	24	24	**24**
Temperature	°C	28.60	28.54	28.51	**28.55**
Salinity	ppt	*	*	*	*
DO	mg/l	*	*	*	*

* Not measured

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	-
Turbidity	mV	-	-	-	-
Conductivity	µS/cm	-	-	-	-
TDS	mg/l	-	-	-	-
Temperature	°C	28.5	28.5	28.5	**28.5**
Salinity	PSU	-	-	-	-
DO	mg/l	6.05	5.84	5.81	**5.90**

SHA – Pump B

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	5.90	5.59	5.57	**5.69**
Turbidity	NTU	*	*	*	*
Conductivity	µS/cm	49	50	50	**49.67**
TDS	mg/l	25	25	25	**25**
Temperature	°C	29.07	29.05	29.02	**29.05**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	*	*	*	*

*Not measured

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	-
Turbidity	mV	-	-	-	-
Conductivity	µS/cm	-	-	-	-
TDS	mg/l	-	-	-	-
Temperature	°C	30.3	29.3	29.2	**29.6**
Salinity	PSU	-	-	-	-
DO	mg/l	5.80	5.86	5.77	**5.81**

SHA – Pump C

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	5.98	5.70	5.64	**5.77**
Turbidity	NTU	11.7	12.5	13.0	**12.4**
Conductivity	µS/cm	32	32	33	**32.33**
TDS	mg/l	23	16	17	**18.67**
Temperature	^{o}C	28.99	28.99	28.94	**28.97**
Salinity	PSU	0.02	0.01	0.01	**0.01**
DO	mg/l	0.42	3.75	3.55	**2.57**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	30.3	29.4	29.2	**29.63**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.81	6.00	6.00	**5.94**

SHA – SS 1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.34	5.85	5.66	**5.95**
Turbidity	NTU	1.8	4.7	6.4	**4.3**
Conductivity	µS/cm	47	47	52	**48.67**
TDS	mg/l	24	24	21	**23**
Temperature	^{o}C	30.16	30.17	30.14	**30.16**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	0.67	0.48	0.53	**0.56**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	31.1	30.5	30.3	**30.63**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.31	5.01	4.93	**5.08**

SHA – SS 2

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.00	5.49	5.48	**5.66**
Turbidity	NTU	15.8	12.4	18.6	**15.6**
Conductivity	µS/cm	67	56	55	**59.33**
TDS	mg/l	30	28	26	**28**
Temperature	^{o}C	30.19	30.14	30.14	**30.16**
Salinity	PSU	0.03	0.02	0.02	**0.02**
DO	mg/l	4.15	0.78	0.82	**1.92**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	30.2	30.3	30.3	**30.27**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.58	4.79	4.70	**5.02**

SHA – SS 3

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.03	5.83	5.79	**5.88**
Turbidity	NTU	5.5	18.4	13.6	**12.5**
Conductivity	µS/cm	52	51	51	**51.33**
TDS	mg/l	26	26	26	**26**
Temperature	^{o}C	29.65	29.63	29.65	**29.64**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	4.03	5.53	3.33	**4.30**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	32.5	30.3	30.0	**30.93**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.90	5.86	5.75	**5.84**

SHA – SS 4

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	5.91	5.81	5.65	**5.79**
Turbidity	NTU	19.9	19.9	20.0	**19.9**
Conductivity	µS/cm	49	51	51	**50.33**
TDS	mg/l	25	25	25	**25**
Temperature	°C	31.85	31.86	31.80	**31.84**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	4.79	4.28	4.04	**4.37**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	°C	32.5	32.2	32.1	**32.27**
Salinity	PSU	-	-	-	**-**
DO	mg/l	6.22	6.24	6.18	**6.21**

SHA – SS 5

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	5.69	5.67	5.67	**5.68**
Turbidity	NTU	19.2	19.3	19.3	**19.3**
Conductivity	µS/cm	52	51	51	**51.33**
TDS	mg/l	26	25	26	**25.67**
Temperature	°C	29.78	29.81	29.78	**29.79**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	4.28	4.00	3.72	**4.00**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	°C	31.7	30.5	30.1	**30.77**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.90	6.32	6.34	**6.19**

SHA – SS 6

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	5.82	5.80	5.84	**5.82**
Turbidity	NTU	20.0	19.0	19.6	**19.53**
Conductivity	µS/cm	51	51	51	**51**
TDS	mg/l	25	25	25	**25**
Temperature	°C	31.15	31.02	30.99	**31.05**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	4.07	3.88	3.73	**3.89**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	°C	31.3	31.1	31.1	**31.17**
Salinity	PSU	-	-	-	**-**
DO	mg/l	6.44	6.15	5.98	**6.19**

NDO – Pump A

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.38	6.25	6.26	**6.30**
Turbidity	NTU	15.5	18.6	15.6	**16.57**
Conductivity	µS/cm	47	47	47	**47**
TDS	mg/l	23	22	24	**23**
Temperature	^{o}C	28.97	28.95	28.95	**28.96**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	4.09	3.91	3.84	**3.95**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	28.3	28.6	28.8	**28.57**
Salinity	PSU	-	-	-	**-**
DO	mg/l	6.26	5.26	5.48	**5.67**

NDO – Pump B

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.07	6.00	5.98	**6.02**
Turbidity	NTU	18.0	18.1	15.9	**17.33**
Conductivity	µS/cm	42	48	48	**46**
TDS	mg/l	24	24	24	**24**
Temperature	^{o}C	29.20	29.20	29.21	**29.20**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	4.31	3.98	3.79	**4.03**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	31.2	30.0	29.6	**30.27**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.48	5.32	5.33	**5.38**

SHI – Pump A

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	7.51	6.45	6.36	**6.77**
Turbidity	NTU	14.3	16.0	16.4	**15.57**
Conductivity	µS/cm	37	45	45	**42.33**
TDS	mg/l	22	22	23	**22.33**
Temperature	^{o}C	28.43	28.40	28.39	**28.41**
Salinity	PSU	0.00	0.02	0.02	**0.01**
DO	mg/l	4.36	3.77	3.54	**3.89**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	°C	27.3	28.1	28.4	**27.93**
Salinity	PSU	-	-	-	**-**
DO	mg/l	6.20	5.65	5.48	**5.78**

SHI – Pump B

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.56	6.28	6.25	**6.36**
Turbidity	NTU	16.3	16.5	16.4	**16.4**
Conductivity	µS/cm	51	46	46	**47.67**
TDS	mg/l	22	23	22	**22.33**
Temperature	°C	28.60	28.56	28.48	**28.55**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	3.54	3.52	3.59	**3.55**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	°C	28.2	28.3	28.3	**28.27**
Salinity	PSU	-	-	-	**-**
DO	mg/l	6.42	5.77	5.55	**5.91**

SHI – Pump C

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.34	6.17	6.12	**6.21**
Turbidity	NTU	16.3	16.7	18.2	**17.07**
Conductivity	µS/cm	45	40	46	**43.67**
TDS	mg/l	21	23	21	**21.67**
Temperature	^{o}C	28.00	28.44	28.41	**28.28**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	3.66	3.37	3.35	**3.56**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	28.2	28.3	28.3	**28.27**
Salinity	PSU	-	-	-	**-**
DO	mg/l	7.04	5.89	5.53	**6.15**

SHI – P 1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.31	6.29	6.29	**6.30**
Turbidity	NTU	15.4	15.7	16.6	**15.9**
Conductivity	µS/cm	46	47	47	**46.67**
TDS	mg/l	23	23	23	**23**
Temperature	^{o}C	28.52	28.49	28.46	**28.49**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	4.28	4.01	3.89	**4.06**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	28.4	28.4	28.4	**28.4**
Salinity	PSU	-	-	-	**-**
DO	mg/l	6.17	6.12	6.11	**6.13**

SHI – P 2

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.34	6.33	6.37	**6.35**
Turbidity	NTU	15.9	15.5	16.4	**15.93**
Conductivity	µS/cm	47	47	47	**47**
TDS	mg/l	23	23	23	**23**
Temperature	^{o}C	28.85	28.82	28.79	**28.82**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	3.72	3.50	3.43	**3.55**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	29.7	29.2	29.0	**29.3**
Salinity	PSU	-	-	-	**-**
DO	mg/l	6.12	6.07	6.06	**6.08**

SIK – RIVER

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.24	6.23	6.13	**6.20**
Turbidity	NTU	12.4	15.5	15.9	**14.6**
Conductivity	µS/cm	43	43	43	**43**
TDS	mg/l	22	21	21	**21.33**
Temperature	^{o}C	29.76	29.95	30.00	**29.90**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	4.84	3.98	3.78	**4.20**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	31.7	30.8	30.4	**30.97**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.36	5.19	5.15	**5.23**

SIK – Booster Pump 1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.32	6.14	6.08	**6.18**
Turbidity	NTU	15.2	13.6	16.6	**15.13**
Conductivity	µS/cm	42	42	42	**42**
TDS	mg/l	21	31 (21)	21	**21**
Temperature	^{o}C	28.74	28.72	28.70	**28.72**
Salinity	PSU	0.03	0.02	0.02	**0.02**
DO	mg/l	4.33	3.88	3.37	**3.86**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	34.4	30.9	29.7	**31.67**
Salinity	PSU	-	-	-	**-**
DO	mg/l	4.98	4.22	4.26	**4.49**

SIK – P1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.30	6.07	6.01	**6.13**
Turbidity	NTU	15.8	18.2	16.7	**16.9**
Conductivity	µS/cm	41	42	42	**41.67**
TDS	mg/l	21	21	21	**21**
Temperature	^{o}C	29.31	29.37	29.51	**29.40**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	3.69	3.44	3.28	**3.47**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	31.9	30.5	30.1	**30.83**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.13	4.88	4.76	**4.92**

SIK – P2

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.47	6.10	6.12	**6.23**
Turbidity	NTU	18.6	16.3	16.9	**17.27**
Conductivity	µS/cm	42	43	43	**42.67**
TDS	mg/l	21	21	21	**21**
Temperature	^{o}C	29.44	29.61	29.60	**29.55**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	3.88	3.51	3.24	**3.54**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	30.6	30.2	30.0	**30.27**
Salinity	PSU	-	-	-	**-**
DO	mg/l	4.59	4.65	4.67	**4.64**

SIK – MS 1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.42	6.21	6.25	**6.29**
Turbidity	NTU	15.8	16.2	18.4	**12.75**
Conductivity	µS/cm	49	49	49	**49**
TDS	mg/l	24	24	24	**24**
Temperature	^{o}C	34.38	34.30	34.29	**34.32**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	3.54	3.33	3.17	**3.35**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	°C	35.9	35.0	34.6	**35.17**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.31	5.14	5.08	**5.18**

SIK – MS P1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.50	6.19	6.09	**6.26**
Turbidity	NTU	17.0	17.4	16.2	**16.87**
Conductivity	µS/cm	42	43	43	**42.67**
TDS	mg/l	21	21	21	**21**
Temperature	°C	29.16	29.34	29.43	**29.31**
Salinity	PSU	0.02	0.02	0.02	**0.02**
DO	mg/l	3.00	2.83	2.81	**2.88**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	°C	32.4	31.0	30.4	**31.27**
Salinity	PSU	-	-	-	**-**
DO	mg/l	4.65	4.36	4.21	**4.41**

GRO – Roux B1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.28	6.28	6.25	**6.27**
Turbidity	NTU	11.1	15.5	12.2	**12.93**
Conductivity	µS/cm	680	812	821	**771**
TDS	mg/l	406	411	410	**409**
Temperature	°C	25.08	25.11	25.11	**25.10**
Salinity	PSU	0.40	0.40	0.40	**0.40**
DO	mg/l	7.00	6.57	6.39	**6.65**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	°C	29.1	26.5	25.8	**27.13**
Salinity	PSU	-	-	-	**-**
DO	mg/l	4.93	4.58	4.55	**4.69**

GRO – DER B1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.30	6.24	6.23	**6.26**
Turbidity	NTU	12.4	12.7	12.9	**12.67**
Conductivity	µS/cm	909	903	895	**902.33**
TDS	mg/l	456	456	454	**455.33**
Temperature	°C	24.94	24.97	25.02	**24.98**
Salinity	PSU	0.45	0.45	0.45	**0.45**
DO	mg/l	6.04	5.92	5.90	**5.95**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	28.6	26.9	26.2	**27.23**
Salinity	PSU	-	-	-	**-**
DO	mg/l	4.27	3.82	3.69	**3.93**

GRO – DER B2

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.33	6.12	6.11	**6.19**
Turbidity	NTU	12.8	12.9	13.1	**12.93**
Conductivity	µS/cm	889	884	889	**887.33**
TDS	mg/l	444	444	444	**444**
Temperature	^{o}C	30.16	30.14	30.13	**30.14**
Salinity	PSU	0.43	0.43	0.43	**0.43**
DO	mg/l	5.46	5.41	5.31	**5.39**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	30.1	30.1	30.9	**30.37**
Salinity	PSU	-	-	-	**-**
DO	mg/l	4.54	2.79	1.97	**3.10**

GRO – Zam

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.46	6.31	6.32	**6.36**
Turbidity	NTU	13.3	14.9	13.6	**13.93**
Conductivity	µS/cm	854	852	852	**852.67**
TDS	mg/l	426	420	426	**424**
Temperature	^{o}C	25.91	25.91	25.94	**25.92**
Salinity	PSU	0.40	0.42	0.42	**0.41**
DO	mg/l	5.56	5.35	5.47	**3.79**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	29.6	27.8	26.9	**28.1**
Salinity	PSU	-	-	-	**-**
DO	mg/l	4.27	4.01	3.89	**4.06**

OTA – P 17

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.44	6.45	6.44	**6.44**
Turbidity	NTU	13.4	14.9	13.4	**13.9**
Conductivity	µS/cm	1163	1160	1159	**1160.67**
TDS	mg/l	580	580	578	**579.33**
Temperature	^{o}C	25.59	25.61	25.64	**25.61**
Salinity	PSU	0.57	0.57	0.57	**0.57**
DO	mg/l	5.59	5.55	5.60	**5.58**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	32.3	28.3	27.0	**29.2**
Salinity	PSU	-	-	-	**-**
DO	mg/l	4.97	5.26	5.40	**5.21**

OTA – P 19

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.37	6.26	6.24	**6.29**
Turbidity	NTU	13.4	19.5	13.5	**15.43**
Conductivity	µS/cm	1197	1197	1197	**1197**
TDS	mg/l	599	599	598	**598.67**
Temperature	^{o}C	25.28	25.32	25.33	**25.31**
Salinity	PSU	0.59	0.59	0.59	**0.59**
DO	mg/l	5.50	5.47	5.64	**5.54**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	28.3	26.8	26.0	**27.03**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.01	4.39	4.27	**4.56**

TSU – BOS

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.31	6.15	6.15	**6.20**
Turbidity	NTU	12.8	12.3	15.8	**13.63**
Conductivity	µS/cm	971	970	970	**970.33**
TDS	mg/l	484	485	485	**484.67**
Temperature	^{o}C	26.67	26.69	26.70	**26.69**
Salinity	PSU	0.47	0.48	0.48	**0.48**
DO	mg/l	5.87	5.70	5.62	**5.73**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	28.6	27.5	27.0	**27.7**
Salinity	PSU	-	-	-	**-**
DO	mg/l	5.21	3.63	3.38	**4.07**

TSU – KEY B1

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.26	6.15	6.14	**6.18**
Turbidity	NTU	12.8	13.3	13.5	**13.2**
Conductivity	µS/cm	1088	1083	1083	**1084.67**
TDS	mg/l	542	542	542	**542**
Temperature	^{o}C	27.02	27.12	27.18	**27.11**
Salinity	PSU	0.53	0.53	0.53	**0.53**
DO	mg/l	5.94	5.66	5.47	**5.69**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	31.1	28.8	28.0	**29.3**
Salinity	PSU	-	-	-	**-**
DO	mg/l	3.84	3.32	3.24	**3.47**

TSU – KEY B2

Instrument 1

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.19	6.05	6.01	**6.08**
Turbidity	NTU	15.9	13.4	13.5	**14.27**
Conductivity	µS/cm	1254	1253	1252	**1253**
TDS	mg/l	627	624	626	**625.67**
Temperature	^{o}C	26.93	27.3	27.05	**27.09**
Salinity	PSU	0.61	0.62	0.62	**0.62**
DO	mg/l	5.63	5.60	5.49	**5.57**

Instrument 2

Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	30.5	28.6	27.8	**28.97**
Salinity	PSU	-	-	-	**-**
DO	mg/l	4.05	2.66	2.27	**2.99**

TSU – TULI

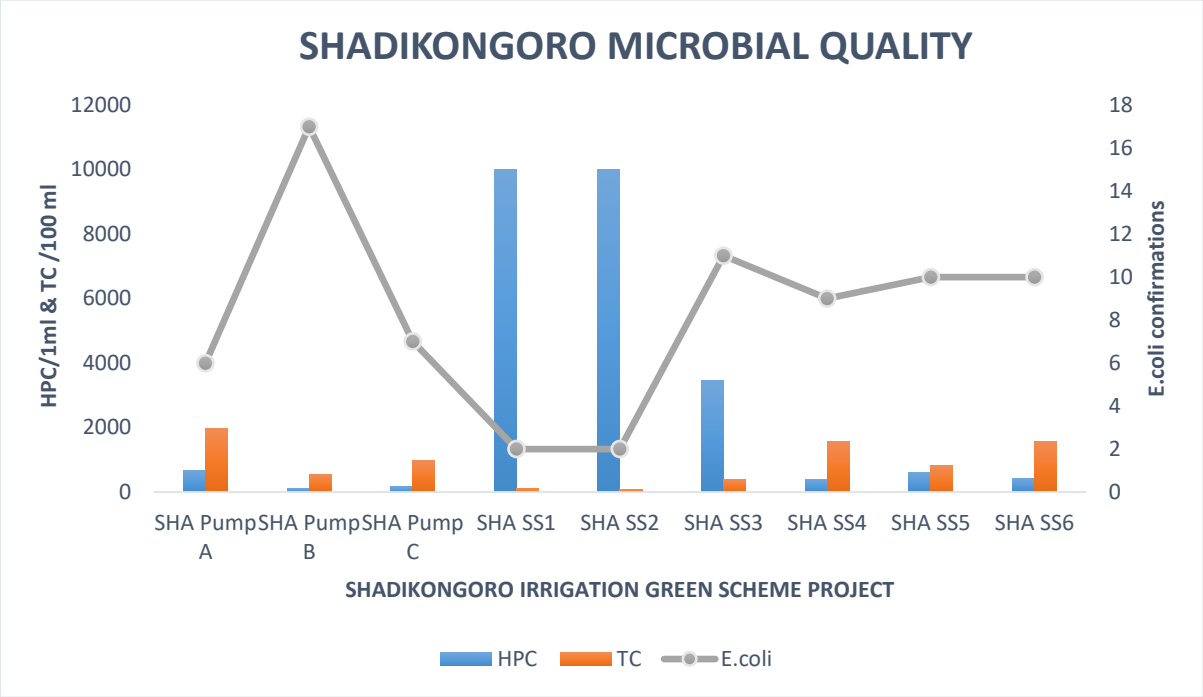
Instrument 1

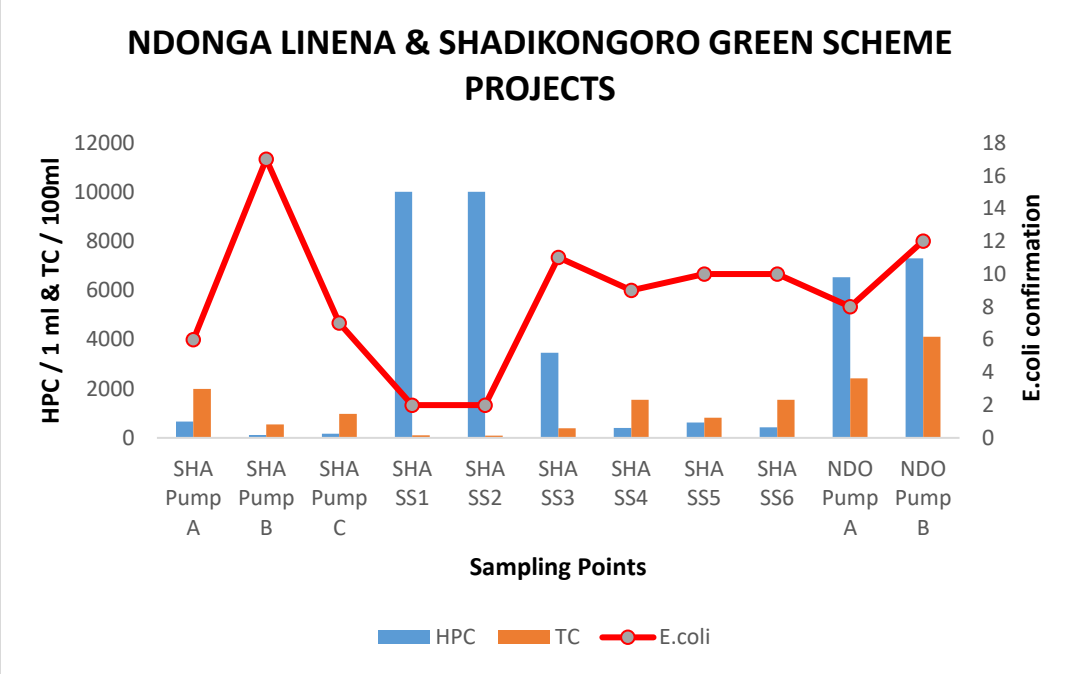
Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	6.26	6.13	6.13	**6.17**
Turbidity	NTU	13.5	13.7	13.7	**13.63**
Conductivity	µS/cm	1904	1906	1903	**1904.33**
TDS	mg/l	954	952	952	**952.67**
Temperature	^{o}C	27.91	27.98	28.02	**27.97**
Salinity	PSU	0.96	0.96	0.96	**0.96**
DO	mg/l	5.52	5.32	5.31	**5.38**

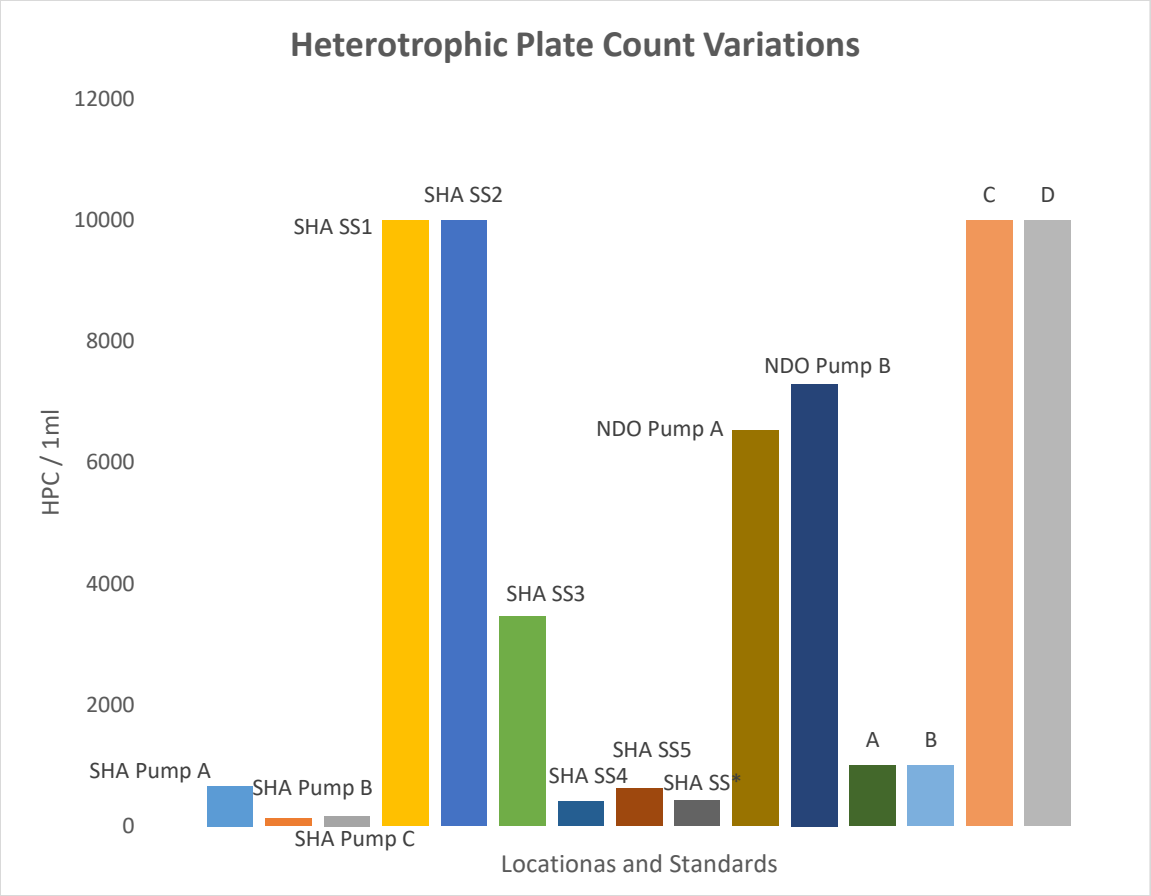
Instrument 2

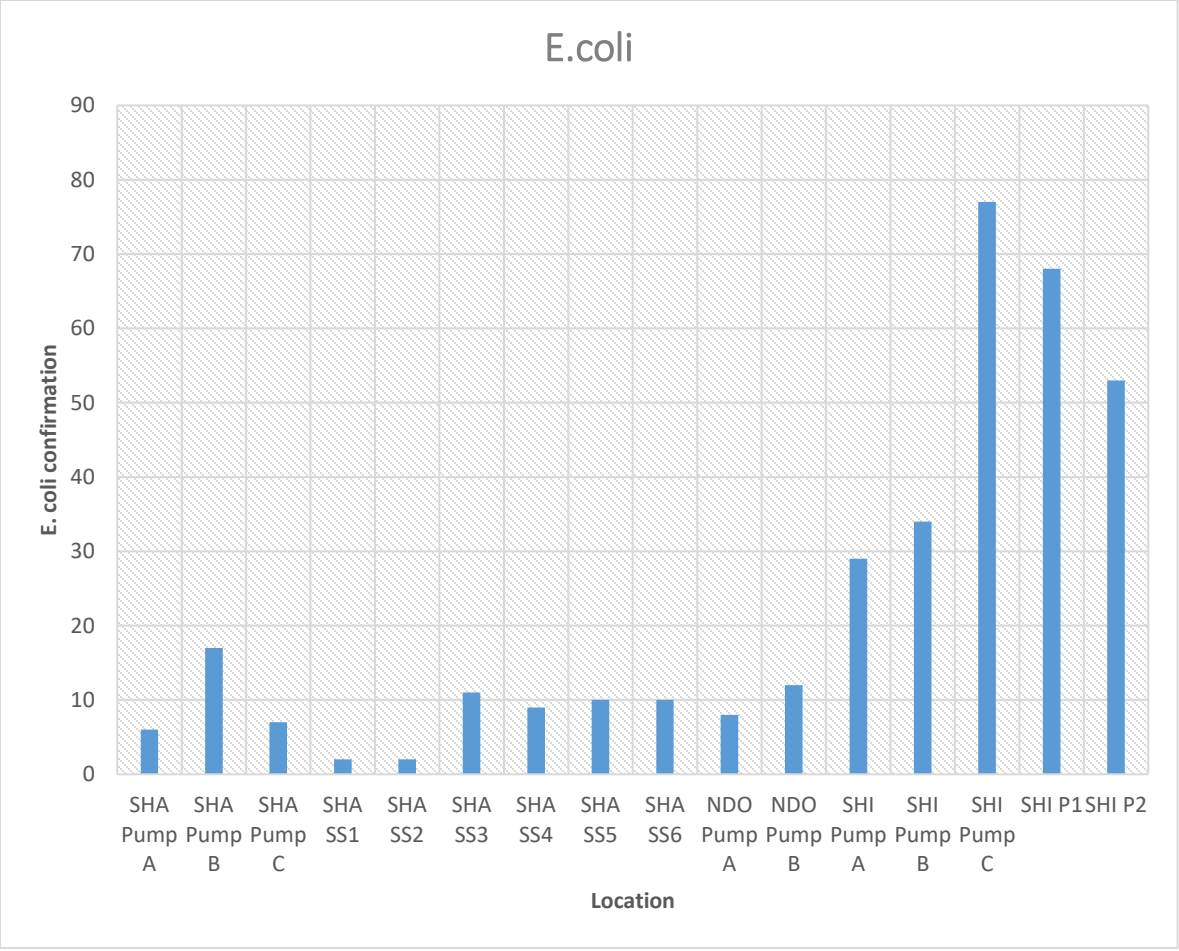
Parameter	Unit	Reading 1	Reading 2	Reading 3	Average
pH	pH	-	-	-	**-**
Turbidity	mV	-	-	-	**-**
Conductivity	µS/cm	-	-	-	**-**
TDS	mg/l	-	-	-	**-**
Temperature	^{o}C	29.6	28.9	28.5	**29**
Salinity	PSU	-	-	-	**-**
DO	mg/l	3.88	3.30	3.20	**3.46**

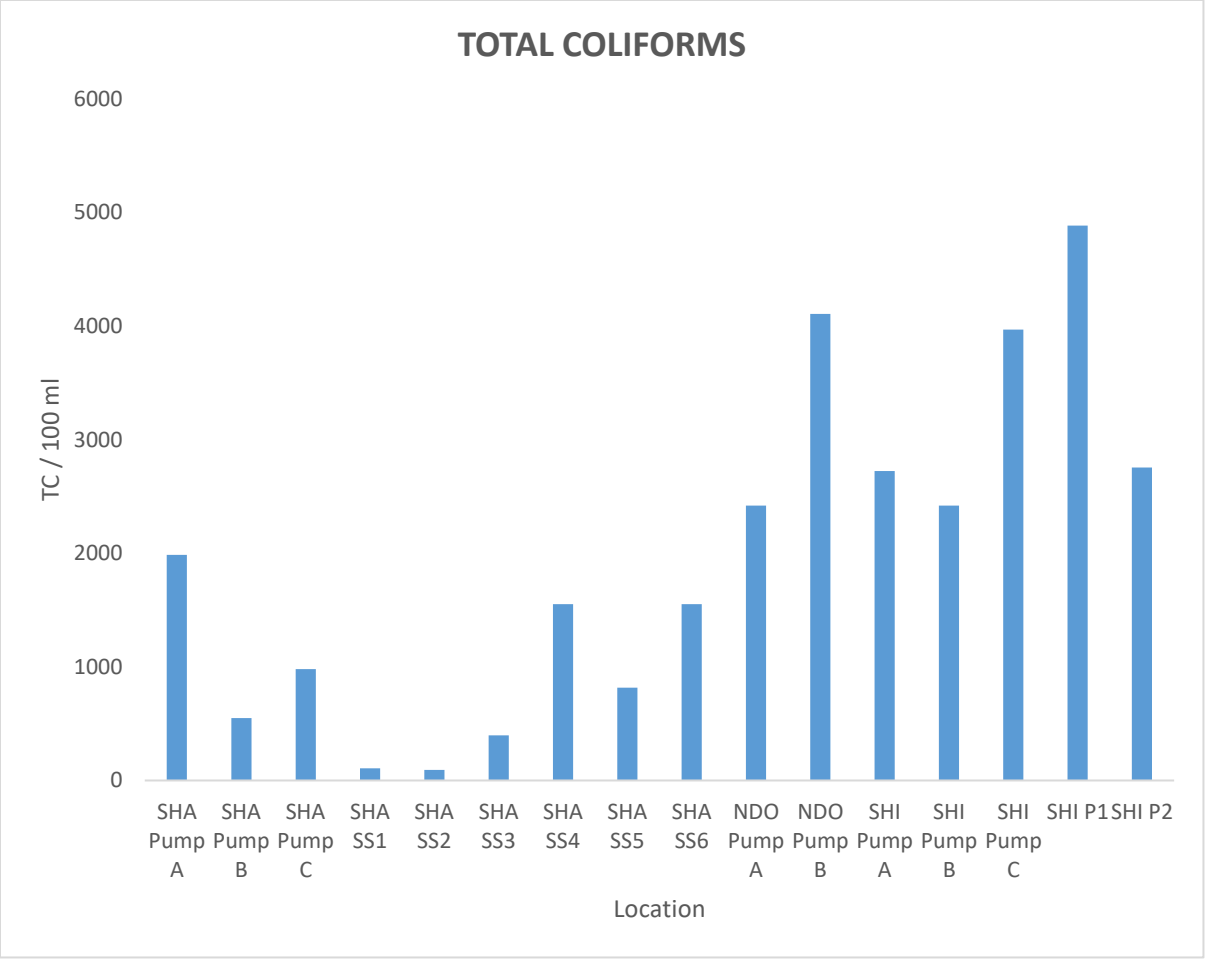
Appendix 9 **Microbiological quality of the water used for irrigation**






Heterotrophic Plate Count Variations
12000
10000
8000
6000
4000
2000
0
HPC / 1ml
SHA Pump A
SHA Pump B
SHA Pump C
SHA SS1
SHA SS2
SHA SS3
SHA SS4
SHA SS5
SHA SS*
NDO Pump A
NDO Pump B
A
B
C
D
Locationas and Standards


E.coli
E. coli confirmation
90
80
70
60
50
40
30
20
10
0
SHA Pump A
SHA Pump B
SHA Pump C
SHA SS1
SHA SS2
SHA SS3
SHA SS4
SHA SS5
SHA SS6
NDO Pump A
NDO Pump B
SHI Pump A
SHI Pump B
SHI Pump C
SHI P1
SHI P2
Location


TOTAL COLIFORMS
6000
5000
4000
3000
2000
1000
0
TC / 100 ml
SHA Pump A
SHA Pump B
SHA Pump C
SHA SS1
SHA SS2
SHA SS3
SHA SS4
SHA SS5
SHA SS6
NDO Pump A
NDO Pump B
SHI Pump A
SHI Pump B
SHI Pump C
SHI P1
SHI P2
Location

Appendix 10 Sequencing Project Summary

Sample Name	Barcode	Barcode Quality	HiFi Reads	HiFi Read Length (mean, bp)	HiFi Read Quality (median, QV)	HiFi Yield (bp)	Run
PP-GRO-L-16S	KXBC_Fwd_10--KXBC_Rev_18	99.71685156	9465	1486	Q34	14072185	250304/2
PP-HDO-L-16S	KXBC_Fwd_10--KXBC_Rev_19	99.57877523	8867	1488	Q30	13200702	250304/2
PP-SHA-L-16S	KXBC_Fwd_10--KXBC_Rev_20	99.68885819	34743	1485	Q53	51601313	250304/2
PP-SHI-L-16S	KXBC_Fwd_11--KXBC_Rev_13	99.3630665	27758	1487	Q55	41282714	250304/2
PP-SIK-L-16S	KXBC_Fwd_11--KXBC_Rev_14	99.67750969	23210	1481	Q57	34379320	250304/2
PP-OTA-L-16S	KXBC_Fwd_11--KXBC_Rev_15	99.60356897	31998	1483	Q57	47473216	250304/2
PP-TSU-L-16S	KXBC_Fwd_11--KXBC_Rev_16	99.71176552	7199	1491	Q32	10736653	250304/2
PP-GRO-4-16S	KXBC_Fwd_11--KXBC_Rev_17	99.71460877	22110	1498	Q55	33132989	250304/2
PP-NDO-1-16S	KXBC_Fwd_11--KXBC_Rev_18	99.71386279	38845	1491	Q55	57941995	250304/2
PP-SHA-3-16S	KXBC_Fwd_11--KXBC_Rev_19	99.53883011	5009	1492	Q28	7475802	250304/2
PP-SHI-5-16S	KXBC_Fwd_11--KXBC_Rev_20	99.696965	32290	1493	Q54	48240847	250304/2
PP-TSU-2-16S	KXBC_Fwd_12--KXBC_Rev_14	99.73051749	19556	1494	Q55	29234046	250304/2
PP-SIK-7-16S	KXBC_Fwd_12--KXBC_Rev_15	99.65082777	21866	1496	Q51	32712940	250304/2

Appendix 11 The Physicochemical characteristics of the sediments

Sample	Date	pH	Nitrate (mg/L)	Nitrite (mg/L)	Ammonium (mg/L)	Moisture content (%)	Soil density	Phosphorus (mg/100g)	Potassium (mg/L)	Sedimentation
SHA-PC	23/09/2024	5	10	0	10	33.75	1.464	0	3.1	Sand
SHA-PB	23/09/2024	4	10	0	10	19.05	1.466	1	2	Sand
SHA-SS3A	23/09/2024	4	10	0	10	10.05	1.424	1	8	Sandly loam
SHA-Pump A	23/09/2024	4	10	0	10	42.5	1.142	0	1	Sand
SHA-33B	23/09/2024	6	10	0	0	10.35	1.409	2	11	Sandy loam
SHA-SS2A	23/09/2024	4	10	0	10	8.4	1.293	4	8	Slightly loamy
Ndonga Pump 2 (Phase2)	23/09/2024	5.5	10	0	10	47	1.326	3	1	Sand
SHI-Pump C	23/09/2024	5.5	10	0	10	16.4	1.476	1	2	Slightly loamy
Ndonga Linena SSF 1B	23/09/2024	6	10	0	10	6.7	1.335	1	2	Loamy sand
SHA-SS1A	23/09/2024	4	10	0	10	10.6	1.045	6	6	Sandy Loam
SHA-SS2B	23/09/2024	6	10	0	25	0.086	1.262	3	10	Loamy sand
Ndonga Linena SSF 1A	23/09/2024	4	10	0	0	6.2	1.419	1	8	Sand
SHA-SS1B	23/09/2024	6.5	10	0	10	12.95	1.169	8	8	Slightly loamy
Ndonga Lwena Pump 1 (Phase 1)	23/09/2024	5.5	10	0	10	21	1.306	1	10	Loamy sand
SHI-Pump B	23/09/2024	6.5	10	0	10	31.8	1.233	1	10	Sand
SHI-Pump A	23/09/2024	6	10	0	10	22.2	1.323	1	4	Sand
SIK-CSF 2b	24/09/2024	4	10	0	10	11.7	1.383	4	10	Slightly loamy
SIK-MSF 1B	24/09/2024	6	10	0	10	0.1	1.435	8	15	Sand
SIK-CSF1	24/09/2024	5	10	0	10	0.35	1.47	6	15	Slightly loamy
SIK-MSF 1A	24/09/2024	5	10	0	10	9.3	1.128	8	15	Slightly loamy
SIK-CSF 1	24/09/2024	5	10	0	10	0.75	1.474	3	8	Sand
SIK-MSF2B	24/09/2024	5.5	10	0	10	8.8	1.18	8	15	Slightly loamy
SIK-CSF 2a	24/09/2024	4	10	0	10	9.8	1.283	4	15	Slightly loamy
SIK RIVER	24/09/2024	6.5	10	0	10	15.35	1.327	1	4	Sand
SIK-MSF 2A	24/09/2024	5	10	0	10	0.1085	1.306	6	8	Sand

TSU-KEY 1B	25/09/2024	6.5	50	0	10	7	1.165	-	-	Sandy loam
TSU-TUCL 1B	25/09/2024	7.5	100	0	10	18.5	1.174	-	-	Slightly loamy
TSU-COR 2A	25/09/2024	6.5	50	0	10	0.65	1.216	-	-	Sandy loam
TSU-KEY 1A	25/09/2024	6.5	25	0	10	5.05	1.212	-	-	Sandy loam
TSU-KEY 3B	25/09/2024	6.5	25	0	10	5.1	1.28	-	-	Loamy sand
TSU-KEY 2A	25/09/2024	6.5	25	0	10	5.4	1.278	-	-	Sandy loam
TSU-COR 1C	25/09/2024	6.5	10	0	10	7.7	1.149	-	-	Loamy sand
TSU-P.12/25 LUDW B	25/09/2024	7	100	1	10	14.1	0.969	-	-	Slightly loamy
TSU-KEY 3A	25/09/2024	7.5	10	1	10	14.05	0.962	-	-	Slightly loamy
TSU-NAMF 2B	25/09/2024	7.5	10	0	10	6.2	1.022	-	-	Slightly loamy
TSU-COR 2B	25/09/2024	6	250	0	10	0.3	1.125	-	-	Slightly loamy
TSU-COR 1B	25/09/2024	7.5	10	0	10	11.15	1.253	-	-	Slightly loamy
TSU-NAMF 1A	25/09/2024	7.5	250	0	10	16.85	1.027	-	-	Sandy loam
TSU-KEY 2B	25/09/2024	6	10	0	10	3.05	1.189	-	-	Loamy sand
TSU-NES 1B	25/09/2024	7	10	0	10	4.7	1.101	-	-	Sandy loam
TSU- LUD 1B	25/09/2024	7	10	0	10	11.6	1.057	-	-	Slightly loamy
TSU-P.12/25 LUD A	25/09/2024	7.5	10	0	10	12.25	1.042	-	-	Sandy loam
TSU-NES 1A	25/09/2024	7	10	0	10	8.75	1.187	-	-	Sandy loam
TSU-LUDWIG 1A	25/09/2024	6	10	0	10	10.65	1.031	-	-	Sand
TSU-TULI 1A	25/09/2024	6.5	10	0	10	12.4	1.105	-	-	Slightly loamy
TSU-COR 1A	25/09/2024	6.5	25	0	10	3.35	1.227	-	-	Loamy sand
GRO-WENGE 2 1B	26/09/2024	5	25	0	10	8.9	1.072	-	-	Sand
GRO-WERIGEL 1A	26/09/2024	5	250	0	10	4.5	1.096	-	-	Sand
GRO-ROUX 1A	26/09/2024	7	10	0	10	12.2	1.178	-	-	Sandy loam
GRO-KAL K 1A	26/09/2024	6	10	0	10	8.9	1.149	-	-	Sandy loam
GRO-KALK 1B	26/09/2024	5.5	25	0	10	8.55	1.039	-	-	Sandy loam
OTA-VALENCIA 1A	26/09/2024	6	10	0	10	1.2	1.269	-	-	Sand
OTA-FONTEIN 1C	26/09/2024	6.5	10	0	10	1.05	1.105	-	-	Slightly loamy
OTA-FONTEIN 1A	26/09/2024	6	25	0	10	2.15	1.155	-	-	Slightly loamy
OTA-FONTEIN 1B	26/09/2024	6.5	25	0	10	1.25	1.138	-	-	Sand
OTA-VALENCIA 1B	26/09/2024	6	25	0	10	0.5	1.253	-	-	Sand

OTA-NEHI 1A	26/09/2024	6.5	25	0	10	12.3	1.137	-	-	Slightly loamy
OTA-NEHI 1B	26/09/2024	5.5	25	0	10	9.5	1.108	-	-	Sandy loam
GRO-NOP 1B	26/09/2024	7	10	0	10	12.7	1.191	-	-	Slightly loamy
Shadikongoro_Sediment		4.8	10.0	0.0	10.6	16.4	1.3	2.8	6.3	
Ndonga Linena_Sediment		5.3	10.0	0.0	7.5	20.2	1.3	1.5	5.3	
Shitemo_Sediment		6.0	10.0	0.0	10.0	23.5	1.3	1.0	5.3	
Sikondo_Sediment		5.1	10.0	0.0	10.0	6.3	1.3	5.3	11.7	
Grootfontein_Sediment		5.9	55.0	0.0	10.0	9.3	1.1	-	-	
Tsumeb_Sediment		6.8	48.1	0.1	10.0	8.5	1.1	-	-	
Otavi_Sediment		6.1	20.7	0.0	10.0	4.0	1.2	-	-	