ASSESSMENT OF WATER QUALITY IN A DRAINAGE CHANNEL AT PANDAMATENGA COMMERCIAL ARABLE FARMS FOR POSSIBLE AGRICULTURAL REUSE

by

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Submitted in partial fulfilment of the requirements for the degree
Master of Science in Agricultural Engineering (Soil and water Engineering)
in the

DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING

at the

BOTSWANA UNIVERSITY OF AGRICULTURE AND NATURAL RESOURCES

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DECLARATION

I, **Simon Peter Kakooza** hereby declare that all the work in this thesis is original. This work has never been presented to any University for the award of a degree nor has it been submitted to other Institutions of higher learning by any person for any academic award. This work has been submitted to the Department of Agricultural and Biosystems Engineering at the Botswana University of Agriculture and Natural Resources in partial fulfilment of the requirements for the degree Master of Science in Agricultural Engineering (Soil and water Engineering).

Sign………………………………....

Date…………………………………

APPROVAL

I certify that this thesis entitled “Assessment of Water Quality in a Drainage Channel at Pandamatenga Commercial Arable Farms for Possible Agricultural Reuse” has been developed under my supervision and it’s ready for submission.

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ACKNOWLEDGEMENT

First and foremost, special thanks and gratitude goes to Mobility of African Scholars for Transformative Engineering Training (MASTET) for the scholarship they granted me to pursue this master's degree. I gratefully acknowledge the help of Prof. Khumoetsile Mmolawa, Dr Gilbert Gaboutloeloe and Ms Anne Clift-hill who took their precious time to review, comment and correct different drafts of this thesis. I am optimistic that all I have learnt from your vast pool of knowledge will propel me to greater heights during my academic and professional life. Special thanks also go to the Department of Agricultural and Biosystems Engineering together with Prof. Cecil Patrick for the endless support towards the logistical and financial needs during the study period.

Special thanks go to the Department of Crop Production under the Ministry of Agricultural Development and Food Security of Botswana who accorded me permission to access the Pandamatenga Commercial Arable Farms to conduct my studies. I wish also to thank the Faculty of Sciences of the Botswana University of Agriculture and Natural Resources, Mr Ronald Samaxa a Senior Manager (Water Quality) at Water Utilities Corporation, and Ms Kgokong Keaboletswe of the Botswana International University of Science and Technology for granting me free access to their laboratory facilities to analyse the samples used during the study.

I also acknowledge the support of farmers within the Pandamatenga Commercial Arable Farms area who allowed me to access their farms to conduct studies and make observations and take photographs relevant to the research. Thanks go to Prof. Mmolawa, Eddie Bowe, Thato Modukanele, Onthatile Onalenna, Odirile Gabanapelo and Phatsimo Mokgweetsi who also helped and supported me during the data collection and analysis process.

Finally, special thanks go to my dear wife Symone Kakooza and son Amias Matthew Kakooza for their patience, sacrifice and support which enabled me to complete my study.

ABSTRACT

Botswana is a semi-arid country with low rainfall and a lack of water resources. The country has reached its full potential in terms of surface water development, that is, the construction of dams, owing to the flat topography in most parts of the country. With an economy in transition, Botswana needs water for economic growth in the areas of households, energy, agriculture, tourism, manufacturing and mining. Agricultural Drainage Water (ADW) reuse is therefore an ideal alternative.

This research, therefore, was set out to assess the quality of water in the drainage channel located in the northern plain of the Pandamatenga Commercial Arable farms for possible agricultural reuse. This was achieved by analysing physical parameters (pH, TDS, EC), microbiological parameters (E. coli, Faecal coliform, total coliforms) and chemical parameters (Ca^{2+}, Pb^{2+}, Na^{+}, NO_3, Cl^{-}, SO_4^{-2}, Fe^{2+}, Mn^{2+}, Cu^{2+}, Mg^{2+}, HCO_3^{-}) of sampled runoff along the drainage channel and comparing it to the BOS 463:2011 – Water quality for Irrigation standard and Wastewater quality standard BOS 93:2012. The results obtained from the ADW quality analysis were then used in an Irrigation Water Quality Index (IWQI) model to assess the possibility of reusing the agricultural drainage water.

The results of the study revealed that almost all ADW quality parameters were below the permissible limit as per BOS 463: 2011 and BOS 93: 2012 standards. However, high levels of Total coliforms, E. coli and faecal coliforms were registered in most of the water samples. The IWQI values computed from the five parameters of SAR, EC, sodium, chloride and bicarbonate during the study revealed that 95% of the samples fell within the “severe restriction” category, 5% of the samples fell under the “moderate restriction” and no samples belonged to the “no restriction” category. Although 84% of the analysed ADW passes the quality mark of the wastewater and irrigation standards, the low levels of EC and SAR detected during the study period imply that there is a mineral imbalance, thus making the ADW unsuitable for direct reuse. Additionally, the high levels of microbiological parameters indicate that irrigating “ready-to-eat” crops with such water increases the risk of food borne illness. Therefore, using this ADW will require mixing it in proper ratios with pure water to improve its quality for reusability during irrigation or using the ADW with trickle or drip irrigation systems since they present a lower risk for potential contamination of crops as compared to an overhead spray system.

TABLE OF CONTENTS

LIST OF APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ADW	Agricultural Drainage Water
AfDB	African Development Bank
APHA	American Public Health Association
BOBS	Botswana Bureau of Standards
cfu	Colony Forming Unit
DWA	Department of Water Affairs
ECE	Economic Commission for Europe
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
GoB	Government of Botswana
ICP-OES	Inductively Coupled Plasma – Optical Emission Spectroscopy ()
IDW	Inverse Distance Weighted interpolation
IWQI	Irrigation Water Quality Index
IWRM-WE	Integrated Water Resources Management and Water Efficiency
NMPWWS	National Master Plan for Wastewater and Sanitation
SADC	South African Development Community
SADCAS	Southern African Development Community Accreditation Services
UNEP	United Nations Environment Programme
WASAG	Water Scarcity in Agriculture in the Context of Climate Change
WHO	World Health Organisation
WQI	Water Quality Index
WUC	Water Utilities Corporation

1.0 Introduction

1.1 Background

Water scarcity is one of the greatest challenges of the 21st century with agriculture being both a cause and a victim of water scarcity. Freshwater resources are under great stress from irrigation and food production, accounting for an estimated 70% of global water withdrawals (FAO-WASAG, 2018). Botswana is a semi-arid country with low rainfall and a lack of water resources. The country is experiencing year-on-year droughts which are exacerbated by climate change but it is also facing increasing pressure on freshwater supplies due to rapid urbanization and climate change, requiring various measures to remediate the situation (IWRM-WE, 2013). Botswana has reached its full potential in terms of surface water development, that is, the construction of dams, owing to the flat topography of the country (UNDP, 2012). All of Botswana's perennial rivers are shared with neighbouring countries. These rivers include Okavango, Zambezi, Orange-Senqu and Shashe-Limpopo (ECE, 2019). With an economy in transition, Botswana needs water for economic growth in the areas of households, energy, agriculture, tourism, manufacturing and mining. Wastewater reuse is therefore an alternative (ECE, 2019).

With the country having dry spells for the biggest part of the year, most commercial farmers in Botswana rely on irrigation for growing their crops (UNDP, 2012). Fields get wet when it rains or when irrigated, forcing water to penetrate the soil and be stored in its pores. When all the pores are filled with water, the soil becomes saturated and can no longer absorb water. Sustained rain or irrigation can cause puddles on the ground (Brouwer et al., 1991). The prolonged presence of excess water in the plant root zone causes stunted growth in some crops and therefore calls for remedial measures of reclaiming the soil such as removing the excess water through pipes, conduits, canals or any other preferred means. The removal of this excess water either from the ground surface or from the root zone is called drainage. Drained water in normal circumstances is discharged as runoff onto open grounds, channels or water bodies. The dire need of conserving depleting water resources has seen drainage water being reused for irrigation in many parts of the world, mainly in India; Egypt; Israel; China; North Africa; and the Middle East (Pereira et al., 2014). There are a number of reports on its use (Shahid et al., 2013; Singh, 2009; Minhas et al., 2006; Sharma and Minhas, 2005; Rhoades et al., 1992).

Through the African Development Bank (AfDB), the Government of Botswana (GoB) acquired a loan to finance development at the Pandamatenga Agricultural Infrastructure Development Project (Patrick et al., 2008). The funds were used to develop an appropriate water control and drainage system for Pandamatenga farms. The Pandamatenga Commercial Arable farms are located in the Chobe district of Botswana, bordering Zimbabwe to the East (Figure 1). Pandamatenga plains are known to be flat with heavy textured vertisol soils and a relatively higher average rainfall of 600 mm per annum, more than any other part of the country, thus, convincing the Government of Botswana (GoB) to allocate the area to farmers, with the intention of boosting cereal production (Patrick et al., 2008). The farms comprise four lacustrine plains; the Northern, Central, Southern and newly established Eastern plains which have now been fully developed for agricultural production (Figure 2). These four plains have been demarcated into approximately 112 farms of an average size of 100 – 1,000 ha, total production area being approximately 61,000 ha.

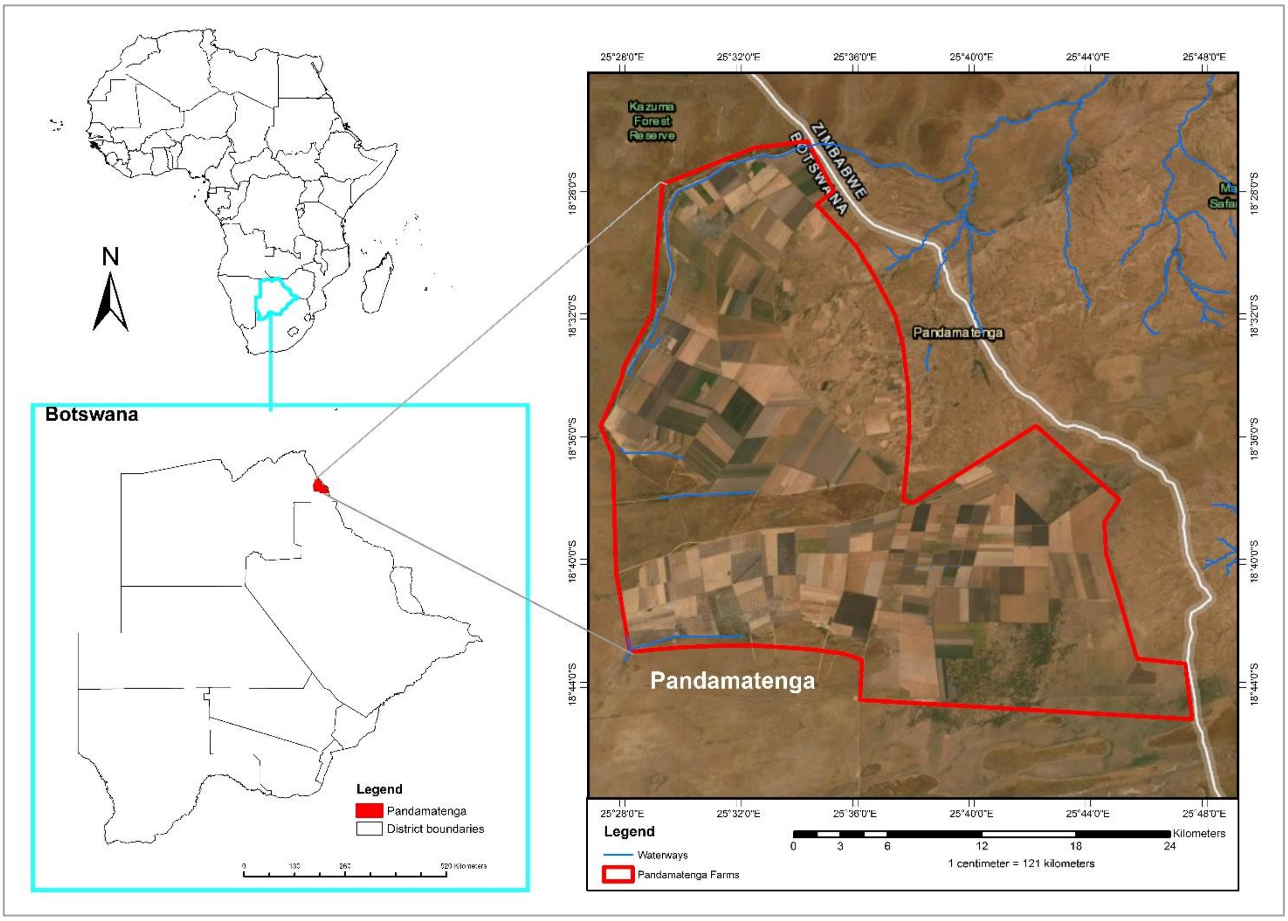


Figure 1: A map of Botswana showing Pandamatenga Arable Farms.

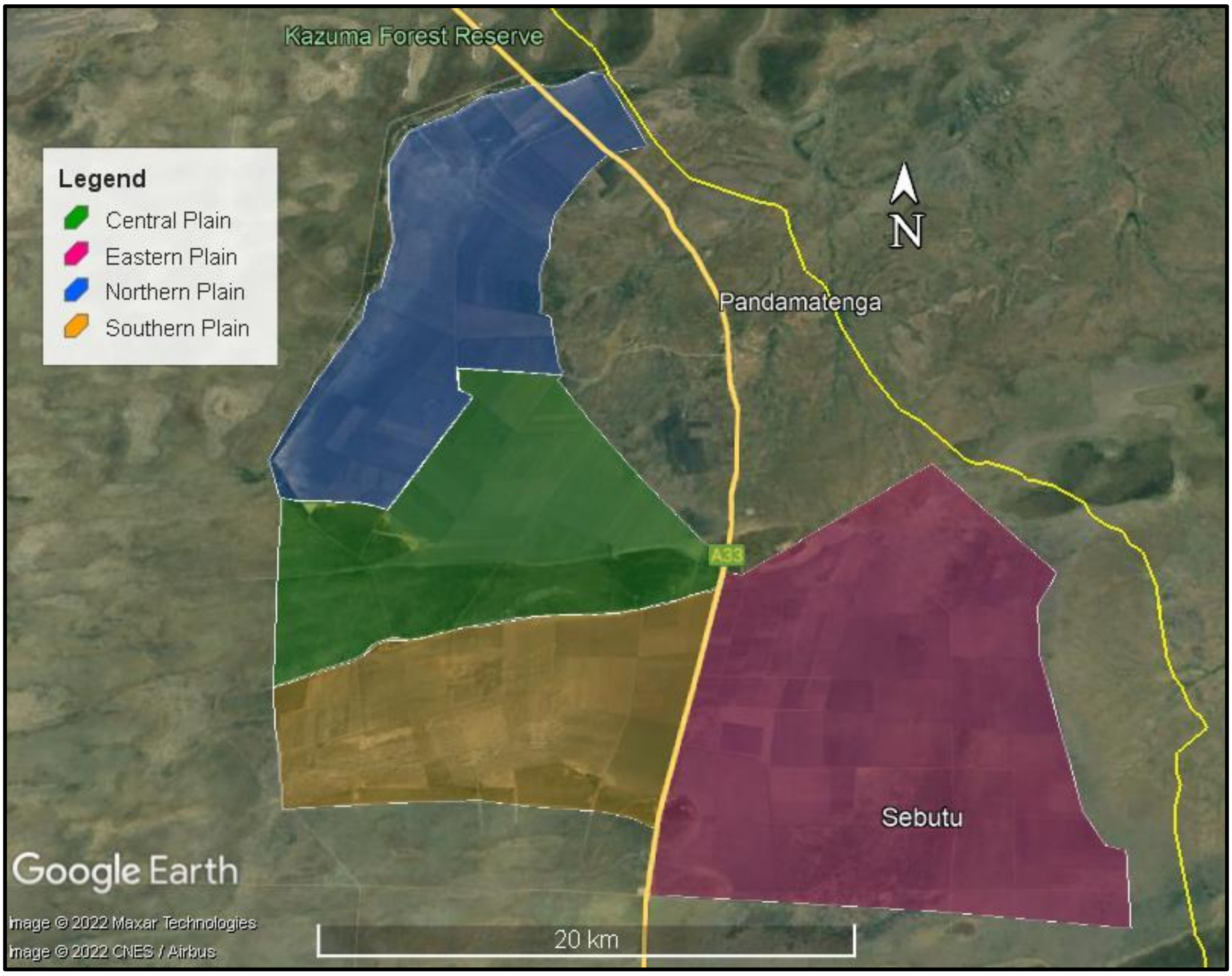


Figure 2: A map of Pandamatenga Arable Farms showing the different plains.

For the purpose of preventing surface water ponding and controlling runoff without causing erosion brought about by the heavy rains and irrigation practices, surface drainage was developed on the Pandamatenga farms after conducting a series of feasibility studies. Excess water collected from the soil surface flows as runoff over the naturally sloping ground toward shallow drainage channels along the roads before being conveyed into the nearby open waterways and open lands. Each of the four plains has got interconnected sub-drainages that discharge into 10 main channels, 2 in the northern plain, 2 in the central plain, 5 in the southern plain and 1 in the eastern plain (Figure 3). The drainage channels in the Central and Southern plains of the farms discharge runoff into open lands located in the West and South of the farms respectively; these channels are exposed to high evaporation and low recharge which leads to low channel water residence time. The main drainage channel in the northern plain discharges into the open waterways of one of the tributaries of the Matetsi river which enters into Zimbabwe. The tributary is believed to add to the volume of water flowing within the channel, hence making the channel able to pool water for a much longer period throughout the year.

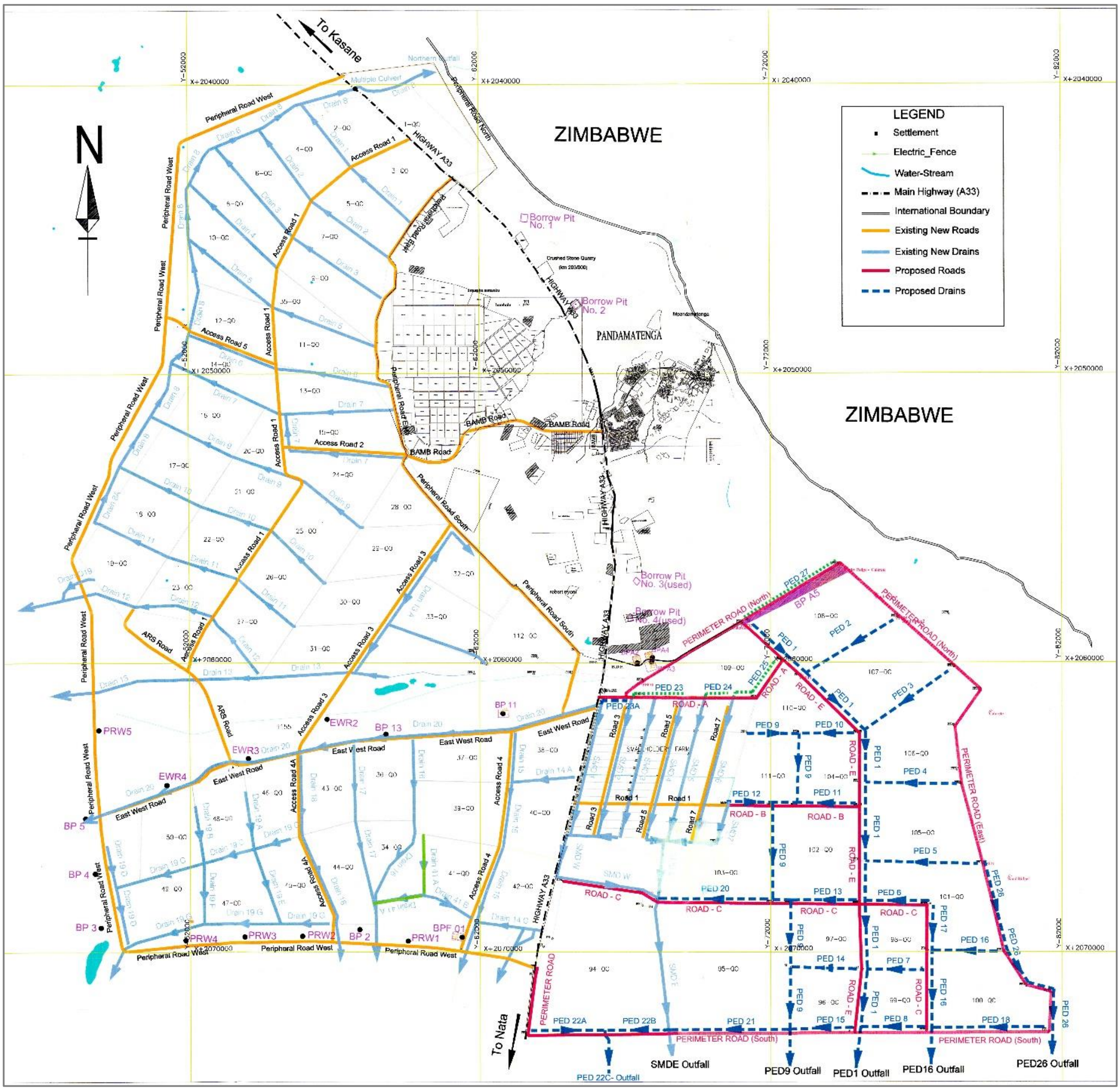


Figure 3: General drains and road layout in the different plains within Pandamatenga Farms.

The availability of agricultural drainage water (ADW) within the drainage channel for a long period creates a potential water source for agricultural reuse. However, to reuse ADW, it is necessary to evaluate its quality. Also, the expected water quality may differ depending on the type of irrigation. Therefore, a thorough strategy is needed to spatial temporarily assess the water quality of drainage channels in potentially water-stressed countries (Bouwer, 1996). This will provide insight into the types of crops that can be irrigated and the long-term environmental impacts that could adversely affect agricultural productivity. The drainage water of high salinity can be diluted by blending it with fresh water in suitable mixing ratios depending on salinity concentration (Tanji and Kielen, 2002). According to the Food and Agriculture Organization (FAO), there are several different water quality guidelines related to irrigated agriculture (Ayers and Westcot, 1985). Each has been useful, though none has been entirely satisfactory because of the wide variability in environmental conditions. Botswana Bureau of Standards (BOBS) provides Wastewater quality standard BOS 93:2012 and Water quality for irrigation standard – BOS 463:2011. For this study, some water quality parameters were selected from both standards to assess if the ADW meets the required permissible levels, and these include, potential of hydrogen (pH), electrical conductivity (EC), total dissolved solids (TDS), sodium (Na^+), nitrates (NO_3^-), chlorides (Cl^-), sulphates (SO_4^{-2}), iron (Fe^{2+}), manganese (Mn^{2+}), copper (Cu^{2+}), magnesium (Mg^{2+}), calcium (Ca^{2+}), Lead (Pb^{2+}), E. coli and Faecal coliform. For the suitability of ADW reuse, the Irrigation Water Quality Index (IWQI) model developed by Meireles et al (2010) in Brazil was used in this study. This model was found to be suitable and efficient to evaluate the water quality for irrigation purposes in arid areas by a number of researchers (Al-Saadi et al., 2021; Hanna et al., 2018; Mohammed and Hassan, 2015; Al-Mussawi, 2014; Khalaf and Hassan, 2013; Mutasher, 2013). The parameters mainly required by the model to determine the IWQI are electrical conductivity (EC), Sodium Absorption Ratio (SAR), sodium (Na^+), chloride (Cl^-), and bicarbonate (HCO_3^-).

This research, therefore, was set out to assess the quality of water in the drainage channel located in the northern plain of the farms for possible reuse. This was achieved by analysing physical parameters (pH, TDS, EC), microbiological parameters (E. coli, Faecal coliform, total coliforms) and chemical parameters (Ca^{2+}, Pb^{2+}, Na^+, NO_3, Cl^-, SO_4^{-2}, Fe^{2+}, Mn^{2+}, Cu^{2+}, Mg^{2+}, HCO_3^-) of sampled runoff along the drainage channel and comparing it to the BOS 463:2011 – Water quality for Irrigation standard and Wastewater quality standard BOS 93:2012. The results obtained from the water quality analysis were then used in an Irrigation Water Quality Index (IWQI) model to assess the possibility of reusing the agricultural drainage water.

1.2 Problem Statement

Water supplies continue to dwindle due to resource depletion and pollution, while population growth, industrial and agricultural expansion exacerbate the water scarcity problem. (Marowski, 1992). Agriculture remains the largest water consumer in Botswana, using 83 million cubic meters of water, accounting for 46.7% of total domestic consumption. Of this, a total of 48.3 million cubic meters is consumed by livestock and 34.7 million cubic meters are used for irrigation purposes. The second largest abstractor after agriculture is the water supply for domestic and industrial use, abstracting a total of 81 million cubic meters from the environment (Department of Water Affairs, 2017).

Irrigated agriculture has undoubtedly led to an exponential increase in food production, but has also led to the collapse of river ecosystems, the drying up of rivers, and eventually dams that support irrigated agriculture (IWRM-WE, 2013). Most commercial and a few subsistence farmers in Pandamatenga draw a substantial amount of groundwater which when coupled with the relatively heavy rainfall received in the area satisfies their crops' water requirements throughout the year. Such amounts of water applied on the farmlands are drained out of the soils through open channels to produce ADW. Most drainage routes may be contaminated by untreated agricultural and domestic wastewater discharges, but irrigation appears to be the best option for the reuse of ADW. Most pollutants that affect water quality in agricultural areas consist of simple inorganic ions, more complex organic molecules, or particles derived from anthropogenic activities (Goss et al., 2000). The most common challenge involved in decisions regarding ADW reuse is how to determine whether the quality of the drainage water is suitable for reuse (A. Allam et al., 2015).

Since the Pandamatenga farming area is discharging ADW into one of the tributaries of the Matetsi river, and there is no documented quality of the ADW leaving these northern plains, it was therefore the intention of this study to determine the quality of ADW leaving the northern plains of the farms into the river for possible agricultural reuse.

1.3 Objectives

1.3.1 Main objective

The main goal of this study was to assess the water quality in the northern drainage channel within the Pandamatenga Commercial Arable farms, and the water's suitability for reuse.

1.3.2 Specific objectives

i. To assess the water quality along selected sub-drainages which discharges into the main drainage channel, in comparison with the selected BOBs standards.
ii. To assess the water quality along the main drainage channel in the northern plain before it joins the open receiving waters of the Matetsi river.
iii. To compare the water quality between the selected sub-drainages and the main drainage channel in the northern plain.
iv. To assess the possibility of reusing the water for irrigation purposes by using an Irrigation Water Quality Index model developed by Meireles et al (2010).

1.4 Research questions

i. Is the quality of water within the main drainage channel influenced by the runoff coming from the different sub-drainages of the farms?
ii. Can the water in the main drainage channel be directly reused for irrigation purposes without subjecting it to a pretreatment process?

1.5 Significance of the study

This study is informed by some of the water management challenges observed in the Pandamatenga farms. One of the challenges at Pandamatenga farms is the amount of water abstracted from groundwater sources for irrigation purposes. Unfortunately, water abstractions are not metered which makes it difficult to ascertain the actual quantities withdrawn from groundwater. However, the National Water Master Plan Review (SMEC and EHES, 2006) predicted the groundwater abstraction in Botswana to grow to an estimated value of between 30 to 40 million cubic meters between the years 2020 – 2025, and should the Pandamatenga project become fully functional, then the demand would increase to between 300 and 400 million cubic meters annually. This, therefore calls for alternative measures geared towards alleviating the pressure posed on the resources of a country that is already water-stressed. The other challenge was from the runoff discharged from the farms through the drainage channel, to the nearby Matetsi River without ascertaining its quality upon discharge. From the consultations conducted, farmers believed that the drainage runoff is tainted with pesticides and other chemicals from farm practices, and therefore could not afford the risk of pooling the runoff for future reuse, but rather let it flow freely into the open waters downstream. Noteworthy, it is this same water that is consumed by both the domestic and wild animals within the area.

This research, therefore, helps to clear the uncertainty lying around the quality of the ADW runoff by showing how it compares with the selected BOBS standards, and what proper control and mitigation measures would be required to improve the quality of the water where the analysed parameters have values higher than the permissible requirements. The control of water quality would benefit the region's water resources bank since it encourages reusing the runoff thus leading to a reduction in the demand for groundwater meant for irrigation. Plates 1 to 3 below show the state of the study area at the time of the site visits.

Plate 1: Solar powered boreholes and water reservoir installed at one of the farms

Plate 2: Centre pivot used to irrigate crops at one of the farms

Plate 3: State of the main drainage channel during the first site visit

1.6 Scope of the Study

The study focused on the agricultural drainage water in one of the major drainage channels located in the Northern plain of Pandamatenga Commercial Arable farms in the Chobe District of Botswana. Physical, chemical and biological parameters of water samples were measured and compared to generally accepted BOBS standards (BOS 463:2011 and BOS 93:2012) to establish the quality of ADW from the different sections of the farms and also determined the runoff's suitability for purposes of reusing it. The parameters examined during the study were pH, conductivity, total dissolved solids, temperature, salinity, copper, iron, lead, manganese, chloride, magnesium, sodium, calcium, nitrate, sulphate, bicarbonate, E. coli, Faecal coliforms and total coliforms. A summary of the obtained results is represented in Chapter 4 from all the sampling stations. Figures are used to present the variations of the different parameters at sampling stations on the dates of sampling.

2.0 Literature review

2.1 Broad perspective of water resource management

Water resources are of significant importance for human livelihoods, socio-economic development and ecosystem health. In recent decades, rapid population growth and skyrocketing living standards have led to a sharp increase in human water demand and consumption. (Shiklomanov, 2000; Döll, 2009; Wada and Bierkens, 2014; Huang et al., 2018). Water scarcity is turning out to be one of the greatest risks to sustainable development in many parts of the world, as water demand approaches or even exceeds total renewable freshwater resources. (Kummu et al., 2016). Human water demand, socioeconomic considerations, and governmental policies all have an impact on water shortage in addition to hydro-climatic conditions, which affect the amount of freshwater accessible. (Dell'Angelo et al., 2018). As a result, it is possible to examine water scarcity from both a physical and an economic standpoint (Rosa et al., 2020). Physical water shortages can be categorized as blue water scarcity and green water scarcity, where blue water scarcity denotes a lack of freshwater availability in surface and groundwater bodies to support human water withdrawal and green water scarcity implies a lack of root-zone soil moisture to support crop production. (Liu et al., 2017). Even when renewable freshwater supplies are physically available, economic water scarcity is the state where a society's ability to use that water is constrained due to a lack of socioeconomic and institutional capability. (Rosa et al., 2020). The distribution, occurrence, and availability of water resources within the South African Development Community (SADC) are uneven both regionally and within individual nations, and the availability of water is highly influenced by rainfall (SADC, 2006).

2.2 Water resources in Botswana

According to Botswana National Water Policy (2012), the water resources of the country are distinguished by a strong dependence on globally shared and transboundary waters, wide regional variability, and extreme shortage. The majority of the water is situated in the northwest, a long way from the eastern corridor's population hub. The reliance ratio, which reflects the proportion of the nation's total renewable water resources that come from cross boarders, stands at 80 %, the highest in southern Africa.

The overall internal renewable water resources are only projected to be 2.4 km^3/year, despite the fact that the total renewable water resources that are currently available are in the range of 12.2 $km^{3/}$year. One of the lowest in the area is the projected 6,819 m^3 per person. Only 0.8 km^3/year of them are thought to be internal renewable surface water resources. Low rates of surface runoff and low rates of groundwater recharge are caused by low and irregular rainfall, high rates of potential evapotranspiration, and highly flat topography. A total of 95% of the nation's surface water is contained in the Okavango Delta, which also includes the Chobe and Linyanti Rivers.

Botswana's groundwater resources are limited, both in terms of quantity and quality, and they are dispersed unevenly across the nation. About 100,000 Mm^3 of groundwater is thought to be recoverable. However, because of the prevailing hydro-climatic characteristics and geological makeup of the aquifers, only 1% of this amount is rechargeable by rainfall (Masedi et al., 2000; SMEC and Ninham Shand, 2003). Nearly all of the area's water resources are discovered underground, and this water is the primary supply for the majority of Botswana's towns and smaller communities, the livestock industry, its power plants, and several mining activities (Du Plessis and Rowntree, 2003). Water is a limited resource in Botswana, thus careful planning is unavoidable. This planning should take both the immediate and long-term implications of water use into account. The four southern African nations of Botswana, Namibia, South Africa, and Zimbabwe are those that have already been deemed to be under "water stress"; their annual freshwater resources range from 1,000 to 1,700 m^3 (UNEP, 1999). The rapidly expanding population coupled with a fast rise in water demand is one of the causes contributing to Botswana's water shortage. If the pace of replenishment is slower than the rate of usage, this could result in the depletion of water resources. Therefore, it is clear that Botswana urgently requires a thoroughly thought-out water management policy since environmental water demands are certain to directly conflict with the needs of the agricultural, domestic, and industrial sectors (Du Plessis and Rowntree, 2003). Because of this, the focus of this study is on evaluating the viability of reusing agricultural drainage water, mostly for irrigation.

2.3 Botswana’s National Master Plan for Wastewater and Sanitation (NMPWWS), 2003

The NMPWWS (2003) was preceded by the Policy for Wastewater and Sanitation Management (2001). The policy intends to develop procedures for the protection and conservation of water resources as well as to enhance the health and well-being of Batswana through the provision of suitable and sustainable wastewater/ sanitation management. The NMPWWS came to the conclusion that wastewater is not regarded as an economic good in 2003 and that the focus of wastewater management is on its discharge. With the help of an Integrated Water Resource Management (IWRM) strategy, the NMPWWS hopes to transform this mentality. This is crucial because the wastewater treatment facilities will need to expand as a result of better sanitation, rising water consumption and living standards, and improved sanitation. Up until 2030, sanitation and wastewater management will be supported by the NMPWWS. As a result, it presented important suggestions for managing wastewater, some of which are discussed below.

2.3.1 Legislation, regulations and instruments

Legislation for the wastewater and sanitation sector must be enacted, including the right to a clean and healthy environment; empowering regulators and stakeholders to protect the environment from pollution; an institutional framework aimed at providing the best service with the resources available; and institutional/stakeholder participation in the planning, design and implementation of wastewater and wastewater management strategies; and finally, efficient and fair administration of legislation through appropriate processes, practices and economic tools.

2.3.2 Promotion of re-use of wastewater

The goal for 2030 is to boost the reuse of wastewater through agricultural reuse and decrease losses in the treatment systems from 20% to 96% of the outflow (or 48% of the inflow). Ten of the settlements in the nation with the highest population consider agricultural re-use to be economically viable. In 2030, it is estimated that 48% of inflows will be reused, 42% will be lost to evaporation and treatment losses, and 10% will be released into the environment.

2.4 Related studies on agricultural drainage water reuse.

Some countries have recently modified wastewater quality standards for safe reuse. Such countries include; France, Cyprus, (Hanseok et al., 2016; Paranychianakis et al., 2015), Greece (Agrafioti and Diamadopoulos, 2012), Italy (Angelakis and Durham, 2008; Maiolo and Pantusa, 2018), and Spain (Ortega and Iglesias, 2009). The type of treatment and industrial pollutants, the availability of an irrigation-ready area, the type of crop being grown, the irrigation method, the type of soil, the matching of supply and demand, the environmental impact, and the cost all play a significant role in whether or not treated wastewater can be used for irrigation (Gabr, 2018). Some of the studies addressed by Gabr, (2018) discuss the drainage water suitability for agriculture, sighting prior drainage water treatment before reuse was the main conclusion for most of the cases.

Allam and Negm, (2013) addressed the potential for irrigation at the northern Nile Delta within Kafr El-Sheikh Governorate while utilizing drainage water. Nine water quality parameters including BOD, COD, TSS, TDS, NO_3, NH_4, TP, pH, and salinity, were tested for the Nashart drain. The authors concluded that the drainage water was unfit for direct reuse for irrigation based on Egyptian requirements.

In the same governorate of Kafr El-Sheikh, Saad et al., (2015) conducted several field trials to determine the effects of agricultural drainage water, treated wastewater and mixed drainage or wastewater with freshwater on maize and cotton productivity. The authors used a split-plot design and assigned major plots to different irrigation water sources. The results showed that reusing low-quality water can produce positive crop yield, save fresh water and increase income for farmers.

El-Agha conducted an investigation on the Meet Yazid Canal catchment area's drainage system in 2019 by measuring and comparing four parameters (EC, DO, pH, and temperature) to the standards. The catchment area is located in the upper central region of the Nile Delta. The findings revealed that the main drains' water did not adhere to the requirements for reuse in agriculture (El-Agha et al., 2020).

Still within the Nile Delta, Shaban, (2020) used statistical assessment tools to examine the trend variability of drainage water reuse in terms of discharge and salinity utilizing data sets since 1984. The findings revealed that both metrics exhibited rising trends, except for the western Nile Delta, which had a negligible salinity increase. The author concluded that the mean drainage water reuse for this location has the potential to rise in the future based on predictive statistical tools.

Studies conducted in Africa, particularly in areas with similar climatic and water shortage conditions to Botswana, have been covered above. However, some studies conducted throughout the world highlight the reuse of ADW as a way to lessen the pressure mounted on freshwater sources.

2.5 Factors affecting water quality in agricultural areas

In particular, salinity, trace elements, and hazardous organic compounds, which require expensive treatment, are some of the major factors that make freshwater quality degradation more and more discernible. Water quality is seriously impacted by the significant problem of treated wastewater being pumped into fresh watercourses or lakes for procedures of treated wastewater dilution (Gabr, 2018). Simple inorganic ions, more complicated organic compounds, or particles are the most common contaminants impacting water quality in agricultural areas. These can come from many places, such as soils and decaying vegetation, but they can also come from animal dung (Goss et al., 2000). One of the nonpoint sources of pollution that have an impact on water quality is agricultural runoff. Recent studies (for example., Castillo et al., 2000; Ferrier et al., 2001; Valiela and Bowen, 2002) have found broad consensus that anthropogenic inputs related to land use, land cover, and point sources have a significant impact on the quantities of nitrogen and phosphorus in surface waters. Some of the other salient agricultural activities that pose a significant impact on water quality are discussed.

2.5.1 Sedimentation

Top soil that is lost due to field erosion is the most frequent agent of agricultural water contamination. The quality of the water is impacted by the soil or sediment that rainwater transports and deposits in neighbouring lakes or streams. Heavy metals, herbicides, and other contaminants that adhere to soil particles, including fertilizers, are also washed into water bodies. Aquatic life is threatened by these contaminants because they generate algal blooms and reduce oxygen levels. With rising suspended sediment concentrations and loading rates, turbidity, a measurement of the impact of water's suspended particulate material (SPM) on light scattering, increases. Additionally, factors including the water's colour and refractive index as well as particle size distribution play a role. Oftentimes, spring and autumn have higher suspended solid concentrations in streams than summer does (Braskerud, 2001; Braskerud et al., 2000).

2.5.2 Nutrients

An ecological concern is derived from the loading of nutrients (nitrogen and phosphorus) into waters from both point and nonpoint sources, which has an impact on the water quality in surface water bodies (Smith et al., 1999). Aquatic species require nutrients to survive, however too much nutrient input into water bodies can have an adverse effect on the water's intended usage (Bricker et al., 2008; Weaver et al., 2005; Freeman et al., 2001). Nitrates may be leached from surfaces or carried by runoff. (Blanchard and Lerch, 2000). Agricultural areas and grasslands have a strong association with nitrates (Ferrier et al., 2001), and concentrations are at their peak in the spring and around periods of heavy runoff. Topography, soil type, farming methods, and crop types are antecedent variables that affect water flow and pesticide dissemination. When calculating the compound's runoff potential, all of these variables are more important than the physicochemical properties of the constituent parts (Larson et al., 1995). Elements enhancing sediment storage are nitrogen and phosphorus sorption on sediments, the sedimentation of these elements in particle form, and the co-precipitation of phosphate with calcite (Withers and Jarvie, 2008). However, under specific pH and redox circumstances, the release of dissolved species from sediments can turn them into a source of nutrients (Gomez et al., 1999). Since phosphorus is frequently the limiting nutrient for algal growth in freshwaters, it is given special consideration (Correll, 1999; Berge et al., 1997).

2.5.3 Livestock grazing

Increased erosion is sometimes brought on by livestock overgrazing, which exposes the top soil. Regression of ecosystems, the introduction of invasive species, the obliteration of vegetation along floodplains, and the destruction of fish habitats can all be consequences of this. This means that it also has an impact on the habitat of flora and fauna in addition to water quality filtration (Khatri and Tyagi, 2015).

2.5.4 Irrigation

Depending on where the farm is located, irrigation is at most times employed to augment natural precipitation and safeguard crops from freezing or withering. Improper irrigation might compromise the quality of the water. For instance, in arid or dry places, precipitation may not penetrate the soil deeply enough to transfer minerals, causing irrigation water to evaporate and salt concentrations in the soil to increase. Over-irrigating a field can cause soil erosion and the movement of heavy metals, herbicides, and fertilizers. It might lessen the streams' and rivers' natural surface flows. (Khatri and Tyagi, 2015).

2.5.5 Pesticides

Agricultural pests are commonly eliminated with fungicides, insecticides, and herbicides. They may get into the water from atmospheric deposition, runoff from the fields, or even direct application. Due to the use of land for agriculture, water may get contaminated with a variety of toxins (Hooda et al., 2000; Lovell and Sullivan, 2006). Tapela, (2017) noted that the use of herbicides and pesticides by the Pandamatenga farmers was on the increase. The types of chemicals majorly used include *Endoflo, Lasso (alachlor), Supermatrine, Roundup (glyphosate), Mospilan, Cypermethrin, MCPA, Thionex, Atrazine, Metasistox, Demeton, Sulmethine, Phonex* and *Parathion* used majorly for sunflower.

Given the large variety of pesticides that are frequently used in agriculture, the presence of pesticides in water supplies is a problem for assessing the water's quality (Kimbrough and Litke, 1996; Nagafuchi et al., 1994). Pesticides are a class of potentially dangerous substances that endanger human health (Ayranci and Hoda, 2005). The most extensively used pesticides are herbicides, which account for more than 40% of all uses, followed by insecticides (around 30%) and fungicides at 20% (WHO, 1992). In addition to protecting food from pests and diseases, which can cause up to a third of crops to be damaged, pesticides also have a significant influence on harvesting quality and enormous output growth (Tadeo et al., 2019). Pesticides and their degradation products travel throughout the ecosystem as a result of widespread global consumption, and they can damage water sources (Menezes Filho et al., 2010).

Agricultural pesticide residues pollute water sources through both nonpoint and point forms of contamination, such as direct leaching or runoff from fields, or by discarding or washing used containers. Pesticides can contaminate groundwater and surface water to varying degrees, depending on their physicochemical properties. These qualities include their ability to dissolve in water, to be retained by soil elements, to degrade quickly, to do so in both abiotic and biotic ways, and to do so in any medium they are applied to (Fajardo et al., 2009) and independent variables, such as the topography of the region, locally occurring precipitation and wind patterns (Arias-Estévez et al., 2008; Martínez et al., 2000).

2.6 Physical, chemical and microbiological water parameters

According to WHO, (2004), water quality must meet the microbial, chemical and physical characteristic guidelines of international standards. Physical, chemical, and microbiological study of water from various sources is a viable way to monitor its quality because these data sets can help identify potential contaminant sources. Water contamination has the potential to dramatically alter its chemical composition, jeopardizing the system's overall equilibrium, resulting in financial losses, and making it impractical to consume. Selected water quality parameters are discussed below and how they affect the integrity of water for its intended various uses.

2.6.1 Temperature

Palatability, viscosity, solubility, odours, and chemical reactions are influenced by temperature (APHA AWWA, 2005). Thereby, the sedimentation and chlorination processes and biological oxygen demand (BOD) are temperature dependent (M. L. Davis, 2010). It also affects the bio-sorption process of the dissolved heavy metals in water (Abbas et al., 2014; White et al., 1997). Reduced yield and slower plant growth may occur if the irrigation water is relatively low (15°C). Most crops are thought to grow best in water that is about 25°C warm (Brower and Heibloem, 1986).

2.6.2 Potential of Hydrogen

The potential of hydrogen (pH) is the negative logarithm of the hydrogen ions concentration which gives an indication of the acidity or alkalinity of water. Acidic water contains extra hydrogen ions; one that is basic contains extra hydroxyl ions while pure water is neutral at 25°C (Alley, 2007). The pH value of natural groundwater sources generally ranges from 6 to 9 and varies depending on the geological nature of the parent rock, mineral deposits, wastewater discharges and aquatic biochemical activities, especially decomposition and respiration (Weibe, 2021). Water used for irrigation is typically alkaline, with a pH range of

7.2 to 8.5. The likelihood of salt issues increases as irrigation water pH rises above 8.2 (Ayers and Westcot, 1994)

2.6.3 Electrical conductivity

The quantity of ions present, their total concentration, mobility, and temperature all affect the electrical conductivity, which is a measurement of an aqueous solution's capacity to transmit an electric current. It can be used as an indication to determine if water is suitable for irrigation because it is connected to important water quality metrics due to the dilution effect of stream flow. Electrical conductivity is also thought to be a quick and accurate indicator of dissolved solids that indicates both the pollution status and the level of tropics in the aquatic body (Heydari et al., 2013; Gupta et al., 2009; Mustapha, 2008). A discharge or some other source of pollution entering a stream may be indicated by the considerable variations in conductivity.

2.6.4 Total Dissolved Solids

Total dissolved solids are expressions of the summation of all dissolved solids of organic and inorganic materials in water. It is a physicochemical parameter that affects other water characteristics such as electrical conductivity, taste and hardness. It has been reported that the desirable levels of total dissolved solids for water should be values not exceeding 500 mg/L, though with exceptions values of up to 1500 mg/L are allowed, (Khan and Khan, 1985). Total dissolved solids can be determined in situ using a standardized portable electrochemical meter and are expressed in milligrams per litre, (mg/L).

2.6.5 Total Alkalinity

Alkalinity is an expression of the ability of water to neutralize acids or its resistance to pH variations. Determination of the alkalinity of water helps to estimate the amount of lime that could be needed for given water softening (Alley, 2007). Groundwater alkalinity is generally attributed to the presence of bicarbonates that are formed as a result of chemical reactions taking place in the soils through which the water percolates. While values of up to 150 mg/L may be appropriate for certain plants, the optimal range for total alkalinity is between 30 to 100 mg/L. High alkalinity exceeding 150 mg/L is typically undesirable since it can result in an elevated pH of the growth media, which can cause a variety of nutritional issues (e.g., iron and manganese deficiency, calcium and magnesium imbalance). Low alkalinity (< 30 mg/L) has little buffering power against pH variations, which is troublesome, especially if acid fertilizers are used (Swistock, 2016).

2.6.6 Total Hardness

When calcium and magnesium ions are combined as their corresponding carbonates, the result is a property known as the total hardness of the water. It can be observed in the scum that forms when soap is used in water and may be brought on by natural geological processes or pollution brought on by anthropogenic activity. In water storage and distribution systems, hardness, which is measured in mg/L, results in deposited materials. According to Heath, (2004), total hardness levels for water range from less than 61 mg/L for soft water to 121–180 mg/L for hard water and above 180 mg/L for extremely hard water. High concentrations of hardness above will build up on contact surfaces, plug pipes and irrigation lines and also cause foliar deposits of scale, while extremely soft water may require fertilization with calcium and magnesium (Swistock, 2016).

2.6.7 Nitrate

Nitrogen occurs in water as organic, ammonia, nitrite and nitrate. In sewage, nitrogen is found in the form of ammonia which is converted to nitrites and nitrates upon microbes' activities. Nitrate is a nutrient for the growth of plants and is known to cause eutrophication, giving the water an unpleasant odour as well as reducing its clarity as a result of the growth of the algae which degrades the water quality. Nitrate is the oxidized and stable form of nitrogen in water; its sources are anthropogenic activities such as agriculture, emissions, sewage contaminations, waste disposals, and the decomposition of biological materials, (Beutler et al., 2014). The concentration of nitrate ions in freshwater is less than 3 mg/L; consumption of nitrate ions concentration above 10 mg/L is a potential risk of Blue baby Syndrome; a fatal disease characterized by the conversion of haemoglobin by nitrates into a form that is less inefficient or completely incapable of oxygen transportation in the body system, (Chapman, 1992). Nitrate ions in a water sample can be determined by the spectrophotometric method through a reaction with the NitraVer5 reagent. The cadmium metal in the reagent reduces nitrates in the sample to nitrites. The nitrite ions react in an acidic media with sulfanilic acid to form an intermediate diazonium salt. The salt couples with gentisic acid to form an amber-coloured solution, tests rest are obtained in mg/L at 500 µm, (Hach, 2005).

2.6.8 Chloride

Chloride ions' concentrations in groundwater are dependent on both natural and anthropogenic activities such as the disposal of agrochemicals, domestic and industrial wastes, (Zoeteman, 2015). Chloride can damage plants from excessive foliar absorption or excessive root uptake. Most plants can tolerate chloride up to 100 mg/L although as little as 30 mg/L can be problematic in a few sensitive plants (Swistock, 2016). The concentration of chloride ions in a water sample is measured spectrophotometrically when treated with mercuric thiocyanate. Chloride ions in the sample react with the mercuric thiocyanate to form mercuric chloride and liberate thiocyanate ions. Thiocyanate ions react with the ferric ions to form an orange ferric thiocyanate complex. The amount of this complex is proportional to the chloride concentration and is measured in mg/L at 455 nm, (Hach, 2005).

2.6.9 Sulphate

Sulphates occur in all-natural groundwater from sources such as volcanic activities, weathering, decomposition and combustion; levels vary depending on the geological nature of the aquifer, (Davies, 2007). Sulphates are derived from its compounds of heavy metals which are then leached into ground and surface water sources. Another source of sulphates in aquatic environments is through the disposal of domestic and industrial wastes, especially from the mining industry. The fate of dissolved sulphates in water includes a reduction to sulphides, volatilization as hydrogen sulphides, precipitation as insoluble salt and incorporation into the biomass. A study on groundwater quality by Curtis, (1989) indicates that high levels of sulphates favour an increase in phosphate levels and eutrophication in water thus affecting the aquatic ecosystems. The same study has shown that sulphate levels in natural waters vary between 2 mg/L to 80 mg/L; although in areas with sulphate minerals or susceptible waste disposal, concentrations higher than 1,000 mg/L may be observed.

Sulphate ions levels in a water sample are determined when it is treated with SulfaVer4 reagent. Sulphate ions in the sample react with barium in the SulfaVer4 and form a precipitate of barium sulphate. The amount of turbidity formed is proportional to the sulphate concentration and is measured in mg/L at 450 nm, (Hach, 2005).

2.6.10 Sodium

The source of sodium in natural water is its salts and mineral deposits. In regions with sodium mineral deposits, groundwater generally contains higher concentrations than surface waters, (World Health Organization, 1979). For natural portable water, the concentration of sodium ions is 200 mg/L at maximum. Anthropogenic activities capable of contributing its significant quantities to natural water include domestic and industrial waste discharges and agrochemicals which can increase the concentrations up to 300 mg/L. Sodium in excess of 50 mg/L may cause toxicity in sensitive plants, particularly in re-circulating irrigation systems (World Health Organization, 1979). If water with excess sodium and low calcium and magnesium is applied frequently to clay soils, the sodium will tend to displace calcium and magnesium on clay particles, resulting in the breakdown of structure, precipitation of organic matter, and reduced permeability (Swistock, 2016).

2.6.11 Calcium

One of the most typical natural occurrences is the presence of calcium ions and calcium salts (E. D. Chapman, 1996). They may originate from manmade sources like sewage and other industrial wastes or they may come from the leaching of soil and other natural sources. One of the most significant factors in hardness is typically calcium. Calcium compounds are stable in water when carbon dioxide is present, but their concentration drops when calcium carbonate precipitates due to an increase in water temperature, photosynthetic activity, and carbon dioxide loss due to an increase in pressure (Chapman, 1996).

When soil or water has a relatively high sodium level or a low calcium content, the rate at which irrigation water infiltrates the soil is reduced to the point where the crop cannot receive enough water as a result (Ayers and Westcot, 1999). According to Grattan, (2002), the soil aggregates on the surface break down into even smaller particles, hence clogging soil pores. The average calcium content in natural waterways is less than 15 mg/l, but in waters near carbonate-rich rocks, the concentrations can reach 30–100 mg/l (Chapman, 1996). Calcium levels below 40 mg/L will typically need fertilizer additions of calcium to prevent deficiency while high levels of calcium above 100 mg/L may lead to antagonism and a resulting deficiency in phosphorus and or magnesium (Swistock, 2016). High levels of calcium may also lead to clogged irrigation equipment due to scale formation

2.6.12 Magnesium

Sources of magnesium in drinking water include the decomposition of magnesium aluminosilicates and the dissolution of magnesium limestone, magnesite, gypsum and other minerals. Magnesium plays an important role as a cofactor and activator of more than 300 enzymatic reactions including glycolysis, adenosine triphosphate metabolism, transport of sodium, potassium and calcium through biological membranes, synthesis of proteins and nucleic acids, neuromuscular excitability and muscle contraction (Weibe, 2021). Magnesium in water tends to cause problems when it is below 25 mg/L necessitating the addition of magnesium in fertilizer. In plants, magnesium is a constituent of chlorophyll and therefore plays a role in the process of photosynthesis (Lenntech, 2021).

2.6.13 Iron

Iron is an abundant earth metal that occurs either as sulphates, oxides, hydroxides or carbonates. Its aeration in the soil has been attributed to generally causing changes in the quality of water as it percolates through its compounds. These quality changes are dependent on the: water table, leaching, oxidation and pH value, (National Research Council Committee et al., 1979). Iron’s presence in groundwater is from mineral sources; its concentration in water is influenced by chemical reactions taking place on the parent rock and by anthropogenic activities, (Drever, 1988). Iron has been attributed to the promotion of undesirable bacterial growth within water sources and supply structures by causing depositions on the piping systems, (International Standard Organization, 1988). Iron is an essential trace element in living organisms; in humans, its largest part is presented as haemoglobin, myoglobin, and haem-containing enzymes with other major fractions being stored in the body as ferritin and hemosiderin mainly in the spleen, liver, bone marrow and in the striated muscle, (Bothwell, 1979). Iron can be a complex water quality problem that not only affects plant growth but also can clog irrigation equipment. For micro-irrigation systems, iron levels need to be below 0.3 mg/L to prevent clogging. Levels above 1.0 mg/L can cause foliar spotting in overhead irrigation systems. Very high iron above 5.0 mg/L can cause severe staining and plant toxicity in sensitive species (Swistock, 2016).

2.6.14 Manganese

Manganese’s water characteristic is similar to iron though its concentration in unpolluted waters is usually less than half the concentration of iron, (Davis et al., 1970). It has a low permissible concentration because it causes an unpleasant taste in water. Oxides of manganese are common in swampy areas and are known to accumulate in aquatic environments, (Tuo et al., 2012). Manganese can clog irrigation equipment and cause foliar staining. Concentrations above 2.0 mg/L can be directly toxic to some plant species (Swistock, 2016). Consumption of water with manganese ions concentration beyond 0.1 mg/L is known to have health effects such as liver damage, neurotoxicity, chronic respiratory inflammation and birth defects, heart defects, imperforate anus and deafness, in addition to aggressive behaviour and disturbances in libido, (Ezemonye et al., 2019).

2.6.15 Lead

Lead is a highly poisonous heavy metal with carcinogenic properties. It occurs naturally in groundwater as a result of geologic processes on its deposits. Other sources of lead in the environment include waste disposal and corrosion of its compounds; it is commonly found in the air, soil and water, (Prasad, 2010). In biological processes, lead frequently takes the place of other metals (such as zinc, calcium, and iron), which is hazardous. It is the displacement of other metals in molecules that interferes with proteins that control gene expression and disruption of the neurological system (De Silva et al., 2021).

2.6.16 Total Coliforms and Fecal Coliforms

The presence of biotic factors such as plants, fungi and bacteria in a water resource has been found to be a useful indicator of the water quality; some microorganisms can give an indication of the level of pollution (Abbas et al., 2014). Studies indicate that waterborne diseases such as typhoid, leptospirosis, tularemia, shigellosis, and cholera among others are caused by bacteria and outbreaks of these diseases have been associated with a lack of good sanitary practices (Peavy et al., 1985). The existence of bacteria in water indicates that it has been polluted and that it presents a health risk to its user. The introduction of bacteria into water is a result of both natural and anthropogenic activities. Human faeces for example may contain pathogenic microbes which are bacterial, viral or parasitic. Though some types of bacteria found in groundwater are harmless, ingestion of pathogenic organisms could cause health challenges to its consumers. Further, the presence of microbes in water affects its palatability for drinking purposes, (Nathanson, 1997).

In the recent past, the importance of the detection of bacteriological contaminants in drinking water sources has been occasioned by an increase in sewage areas and bacteriological discharges. Irrespective of the advanced methods of wastewater treatment and disposal, human faeces are principal sources of bacteriological contaminants. The principal source of disease-causing agents in water is biological wastes mainly emanating from improper disposal, adsorptions and runoffs. Other sources include the leaching of biological materials into groundwater sources with the risks of contamination being elevated by their poor construction or maintenance (Weibe, 2021).

Coliform is a class of bacteria that survive in the water longer than most pathogens, (Tomar, 1999). Total coliforms are the summation of microbes found in the environment; living in soils, plants and the intestines of animals. Although some coliforms are not harmful, their presence in water indicates that the source is vulnerable to contamination by harmful microbes and requires urgent professional attention. Determination of the entire spectra of pathogens is not only expensive but also complicated; measurement of this parameter is used to measure the extent of pollution and sanitary quality of water. Sewage-contaminated water will always contain coliform, (Nathanson, 1997).

Faecal coliform is a class of bacteria that occur only in wastes of warm-blooded animals. Unlike other members of the total coliform, they can breed at extreme temperatures. Their presence in water is an indication of recent faecal contamination and risk of microbe pathogens, (Nathanson, 1997). In order to do a bacteriological water quality assessment, it is good practice to determine suggestive organisms which are easy to detect and identify and are of similar origin as the pathogens, these organisms should be of the same or advanced survival characteristics as the pathogens and must not be pathogenic.

2.7 Developed methods for assessing water quality

There are various methods that can be used to offer a comprehensive evaluation of the quality of ADW. One of these methods, the Water Quality Index (WQI), is regarded as the most promising one for evaluating and categorizing the quality of ADW and its appropriateness for reusing in irrigation (Paun et al., 2016). WQI employs a mathematical technique that reduces the number of variables with a major impact on ADW quality to a set of parameters. This number enables experts to decide appropriately based on the accepted standards for the acceptability of the quality of ADW for reuse in the irrigation of agricultural crops (Assar et al., 2019).

The utilisation of WQI, Elsokkary, (2012) employed the Water Quality Index (WQI) developed by the Canadian Council of Ministers of the Environment to assess the drainage water from a few drains in Upper Egypt and the Nile Delta. According to the author, the majority of Upper Egypt's drains fall into the very poor to the very good category, while those in the Nile Delta fell into the very poor to good category. El-Sayed and Shaban created a new WQI for the reuse of drainage water in Egypt in 2019. They did this utilizing data sets of years 2000 – 2015, that were gathered on water quality. As a benchmark, the index was used for the Nile Delta's drainage water (El-Sayed and Shaban, 2019).

In the case of irrigation water quality indicators (IWQI), only a select group of irrigation water quality components are taken into account based on their recommended limits for all soil types (US EPA, 2019). The following irrigation and soil management issues led to a broad grouping of these criteria into two quality indicators (Bortolini et al., 2018), among other factors like salinity (which affects crop water availability), permeability (which influences soil penetration rate), toxicity (which impacts sensitive crops), as well as some other factors which affect susceptible crops (Ayers and Westcot, 1985b). The two quality indicators that were taken into consideration were the agronomic indicators, which are related to soil quality and include pH, EC, and SAR parameters, and the management indicators, which include total suspended solids (TSS), bicarbonates (HCO_3), sulfides, manganese (Mn), and iron (Fe). Only a few water quality parameters, including electrical conductivity (EC), sodium adsorption ratio (SAR), and concentrations of sodium (Na), chloride (Cl), and bicarbonate (HCO_3) ions, were used to compute the IWQI based on the two quality indicators (Abbasnia et al., 2018; Spandana et al., 2013; Zaman et al., 2018). A specific approach for evaluating water quality for agricultural use, the IWQI was created by Meireles et al. in 2010.

2.7.1 Irrigation Water Quality Index – IWQI

To assess the quality of drainage water for potential reuse, the Brazilian (IWQI) model created by Meireles et al., (2010) was employed in this study. The IWQI was created using the five water quality indicators listed below: electrical conductivity (EC), sodium adsorption ratio (SAR), sodium concentration (Na), chloride concentration (Cl), and bicarbonate concentration (HCO_3) (Abbasnia et al., 2018). As presented in Tables 1 and 2, the weight of water quality parameters including the water quality measurement parameter value (qsi), and the aggregation weights (w_i) were determined depending on each parameter value and finally considered in the criteria which were proposed by Ayers and Westcot, (1985). In this particular model, the lower value represents the poor quality of water and vice versa. The value of (*qsi*) was calculated based on the following equation:

$$\text{qsi} = \text{qsi}_{\text{max}} - \left[\frac{\left(\text{V}_{\text{ij}} - \text{V}_{\text{inf}}\right) \times \text{qsi}_{\text{ampl}}}{\text{V}_{\text{ampl}}}\right] \qquad (1)$$

Where; qsi_{max}, is the maximum value of (*qsi*) for the category in which the parameter is located; V_{ij}, is the measured value for the parameter; V_{inf}, is the value that represents the lower limit of the category to which the parameter is located; qsi_{ampl}, is category ampleness between the maximum and minimum *qsi* values; V_{ampl}, is category ampleness in which the parameter is located. It should be noted that the highest measured value is taken into consideration as the highest limit when finding (V_{ampl}) for the last category of each parameter.

Table 1: The weights of IWQI parameters (Meireles et al., 2010)

Parameters	w_i
EC	0.211
Na^+	0.204
HCO_3^-	0.202
Cl^-	0.194
SAR	0.189
Total	**1.000**

Table 2: Irrigation water quality parameters and their proposed limiting values

qsi	**EC (µS/cm)**	**SAR $(meq/L)^{0.5}$**	**Na (meq/L)**	**Cl (meq/L)**	**HCO_3 (meq/L)**
85 – 100	200 – 750	3	2 – 3	<4	1 – 1.5
60 – 85	750 – 1500	3 – 6	3 – 6	4 – 7	1.5 – 4.5
35 – 60	1500 – 3000	6 – 12	6 – 9	7 – 10	4.5 – 8.5
0 – 35	<200 or >3000	12	<2 or >9	>10	<1 or >8.5

Each measurable factor listed above is given a weight based on how important it is in relation to other factors and how it affects the overall quality of irrigation water. The individual IWQI can then be calculated by applying the formula below using the multiplying factors shown in Table 1 above:

$$\mathrm{IWQI} = \sum_{i=1}^{n} (qsi \times wi) \tag{2}$$

Where (IWQI) is a dimensionless number ranging from 0 to 100 divided into five categories as shown in Table (3). Each category of IWQI indicates the restrictions in the irrigation water use which are; the salinity problems risk, the soil water infiltration problems, and the plant's toxicity.

Table 3. Classifications of the different Categories of IWQI (Meireles et al., 2010)

IWQI	**Category; the restriction of water use**	**Advice**	
		Soil	**Plant**
85 – 100	No restriction (NR)	It can be used when the soil is less likely to be affected by salinity and sodicity.	There is no risk of toxicity for most plants
70 – 85	Low restriction (LR)	It can be used for irrigated soils of fine texture or moderate permeability, being advised of the leaching of the salts. Salinisation of thicker textured soils may occur and it is recommended to avoid use in soils with high clay levels.	Avoid use in plants with salt sensitivity
55 – 70	Moderate restriction (MR)	It can be used on soils with high or medium permeability, which helps to wash out salts easily from the soil.	Plants with moderate salt tolerance still grow
40 – 55	High restriction (HR)	It can be used in un-compact soils (high permeability). A multi-irrigation program can be adopted, when the electrical conductivity is above 2000 µS/cm and SAR is above 7.	This water should be used for irrigation of plants with a high to medium tolerance of salts, with special management and practices to reduce the salinity effect, the water with low concentrations of HCO_3, Cl and Na is excluded.
0 – 40	Severe restriction (SR)	You should avoid using this water for irrigation under normal conditions. It can be used in special and specific cases. It is imperative to wash the soil frequently to prevent increasing its saltwater content and also to avoid the accumulation of salts.	This water is used for irrigation of plants with high tolerance to salinity only, and the water with low levels of Na, Cl and HCO_3 is accepted.

2.7.2 Adjusted Sodium Adsorption Ratio

The sodium adsorption ratio (SAR) is an irrigation water quality parameter used to the management of soils affected by the presence of sodium. Based on the concentrations of the principal earth and alkaline cations in the water, it serves as a gauge of the water's appropriateness for irrigation of agricultural land (Table 4). As evaluated by measurement of pore water collected from the soil, it is a common diagnostic metric for the sodium danger of a soil (Fipps, 2003). This ratio is calculated according to the following equation:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})}{2}}} \qquad (3)$$

Where; Na^{+} is sodium concentration; Mg^{2+} is magnesium concentration and Ca^{2+} is calcium concentration.

The units of (meq/litre) are used to express each parameter's concentration in equation (3) above. The breakdown of calcium by rainfall and irrigation water typically causes changes in the concentration of calcium in the soil water; however, equation (3) does not account for these changes. This issue was fixed by changing equation (3) to use the equilibrated calcium concentration (Ca_{eq}^{2+}) instead of the calcium concentration (Ca^{2+}) to account for the shift in calcium. The "Adjusted Sodium Adsorption Ratio" (SAR_{adj}) or "Corrected Sodium Adsorption Ratio" (SAR°), which can be calculated, is therefore obtained by equation (4) (Ayers and Westcot, 1985; Mutasher, 2013). The mathematical method outlined by Lesch and Suarez, (2009) is used to estimate the equilibrated calcium concentration.

$$\mathrm{SAR}_{adj} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{(\mathrm{Ca}_{eq}{}^{2+} + \mathrm{Mg}_{eq}{}^{2+})}{2}}} \qquad (4)$$

Table 4: Water classification based on SAR values (Richards, 1954)

Sodium Adsorption Ratio (SAR)	**Classification**
< 10	Excellent
10 – 18	Good
18 – 26	Doubtful
> 26	Unsuitable

2.7.3 Soluble magnesium percentage (Mg %).

One of the most significant qualitative factors in assessing the suitability of water for irrigation is the percentage of soluble magnesium in the water. Because of how it affects plant growth, it is regarded as crucial. When this percentage falls below fifty, it becomes suitable for plant growth; yet, when it rises beyond fifty, it becomes a risk (Hussein, 2018). This parameter is evaluated by equation (5) given by Szabolcs, (1964), where the concentration of each cation is expressed in meq/L:

$$\text{Mg}\ \% = \frac{\text{Mg}^{2+}}{(\text{Ca}^{2+} + \text{Mg}^{2+})} \times 100 \qquad (5)$$

Where; Mg^{2+} is magnesium concentration and Ca^{2+} is calcium concentration.

2.7.4 Permeability Index (PI).

Another metric for determining if water is suitable for irrigation is the permeability index (PI). It measures the soil's ability to move water (permeability). It is impacted by the prolonged use of irrigation water (with a high salt concentration), as it is impacted by the Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^- ions in the soil. (Rawat et al., 2018). According to Doneen, (1954) who developed the PI index, it is calculated by the equation (6). The concentration of all ions is taken in meq/L:

$$\text{PI} = \frac{\text{Na}^{+} + \sqrt{\text{HCO}_3^{-}}}{\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^{+}} \times 100 \qquad (6)$$

Where; HCO_3^- is bicarbonate concentration in meq/L; Na^+ is sodium concentration in meq/L; Mg^{2+} is magnesium concentration in meq/L and Ca^{2+} is calcium concentration in meq/L.

2.7.5 Soluble Sodium Percentage (SSP).

An essential consideration when evaluating sodium risks is soluble sodium percentage. It is also used to assess the water quality for usage in agriculture. When used for irrigation, water with a high salt content can inhibit plant development and reduce soil permeability. Table 5 shows a categorisation system for evaluating irrigation waters based on SSP as put up by Wilcox, (1955). The following equation (7) was used to determine the SSP:

$$\mathrm{SSP} = \frac{\mathrm{Na}^{+}}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+})} \times 100 \tag{7}$$

Table 5: Water categorisation based on SSP values.

Soluble Sodium Percentage (SSP)	**Water classification**
$0 \le \%\mathrm{Na} \le 20$	excellent
$20 < \%\mathrm{Na} \le 40$	good
$40 < \%\mathrm{Na} \le 60$	permissible
$60 < \%\mathrm{Na} \le 80$	doubtful
$\%\mathrm{Na} \le 100$	unsuitable

3.0 Research Methodology

3.1 Study area

Pandamatenga is a village in the Chobe District, Botswana covering an area of approximately 280, 380ha. The Pandamatenga farms (Figure 1) cover only 25,074 ha of this total land area (Tapela, 2017). The area is located in the North-west region of the country bordering Zimbabwe to the East within geographical coordinates of latitude 18˚26′ to 18˚43′ and longitude 25˚27′ to 25˚37′. The study was conducted on the longest drainage channel (approximately 23km) within the Northern plain of the farms, which also drains into the Matetsi river (Figure 4).

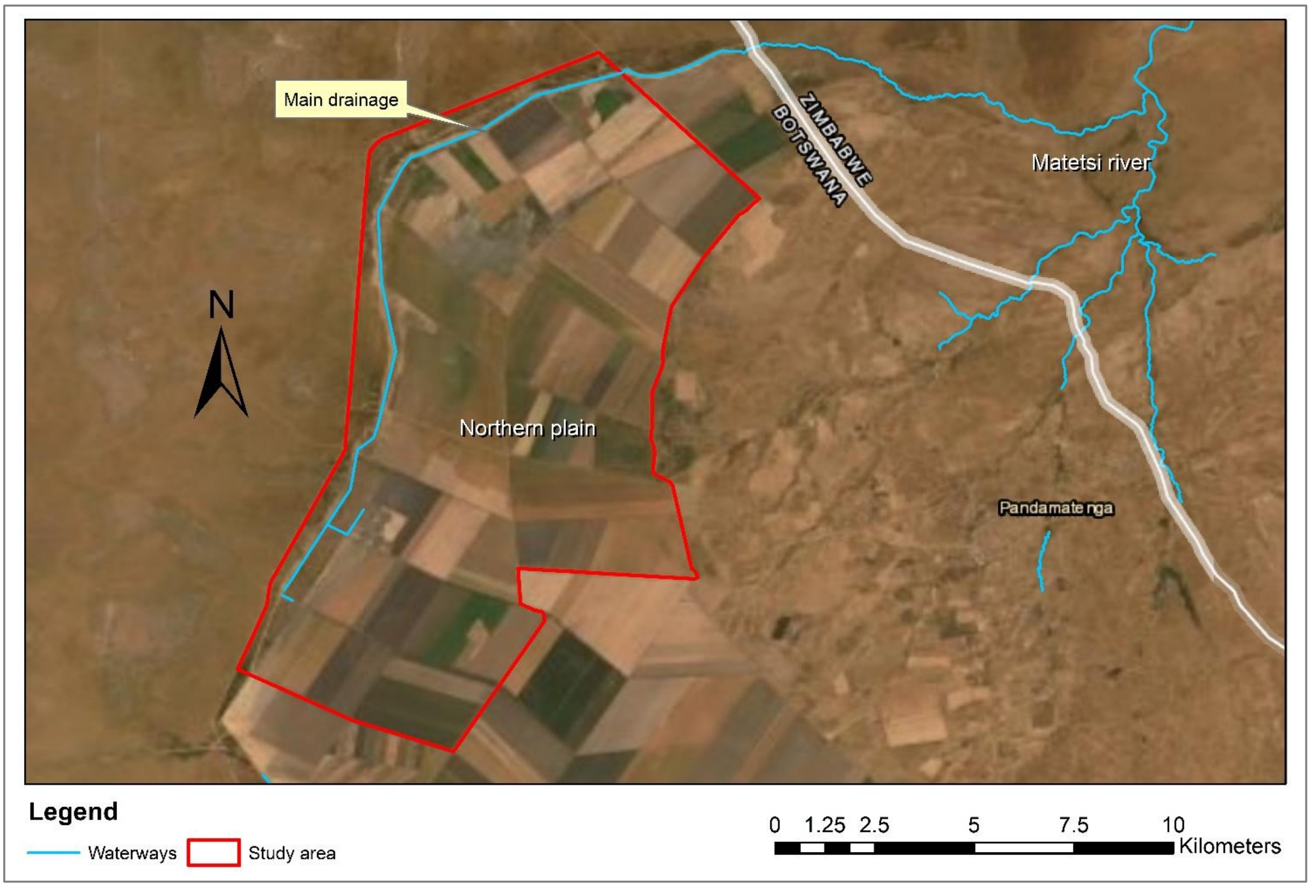


Figure 4: A map of Pandamatenga Arable Farms showing the study area.

The Pandamatenga region experiences a semiarid climate with hot, humid summers and dry, moderate winters. Rainfall comes from conventional processes and has a 600 mm annual average but is highly variable, especially over short distances. Practically all rain falls between October and April, with December, January, and February being the wettest months (Kandondi et al., 2021). Due to the significant amount of rain that falls during brief, intense storms, some farms experience considerable runoff and are immediately swamped. Data collected from Botswana Meteorological Services for the period of July 2021 to July 2022 from 8 weather stations within Pandamatenga farms shows that the area received an average rainfall of 458mm (Figure 5). Significant rainfall was received between November and March with January registering the peak amount (Figure 6).

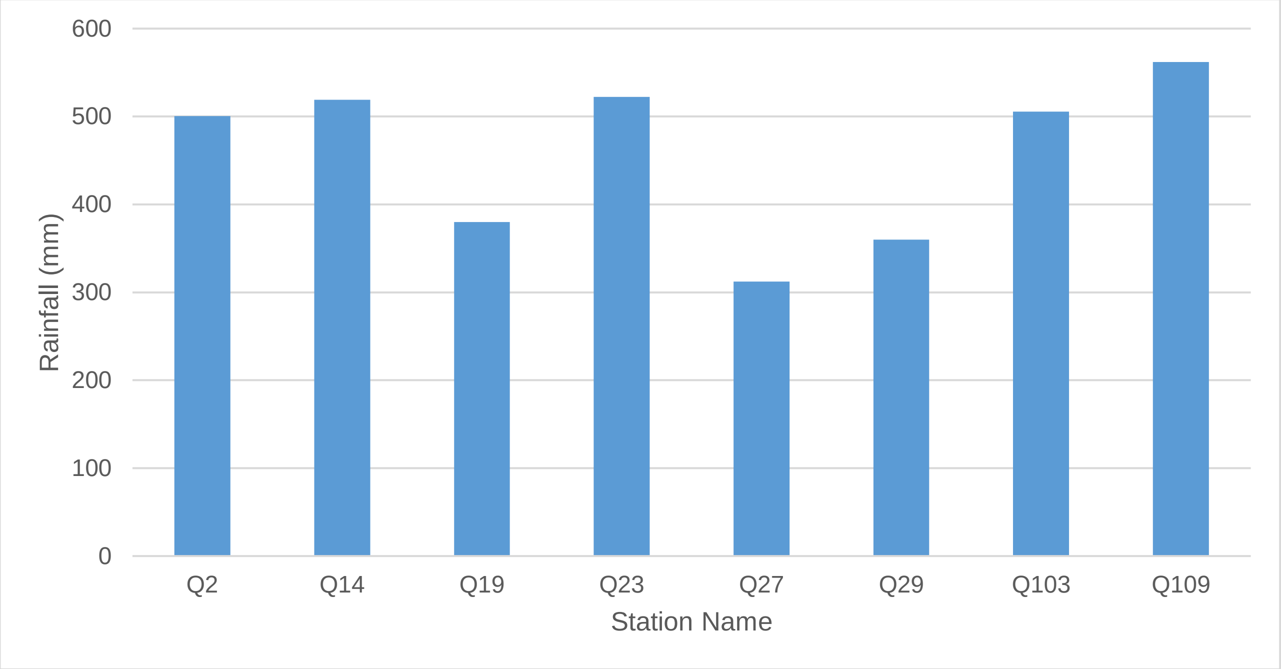


Figure 5: Rainfall data collected from 8 weather stations within Pandamatenga farms

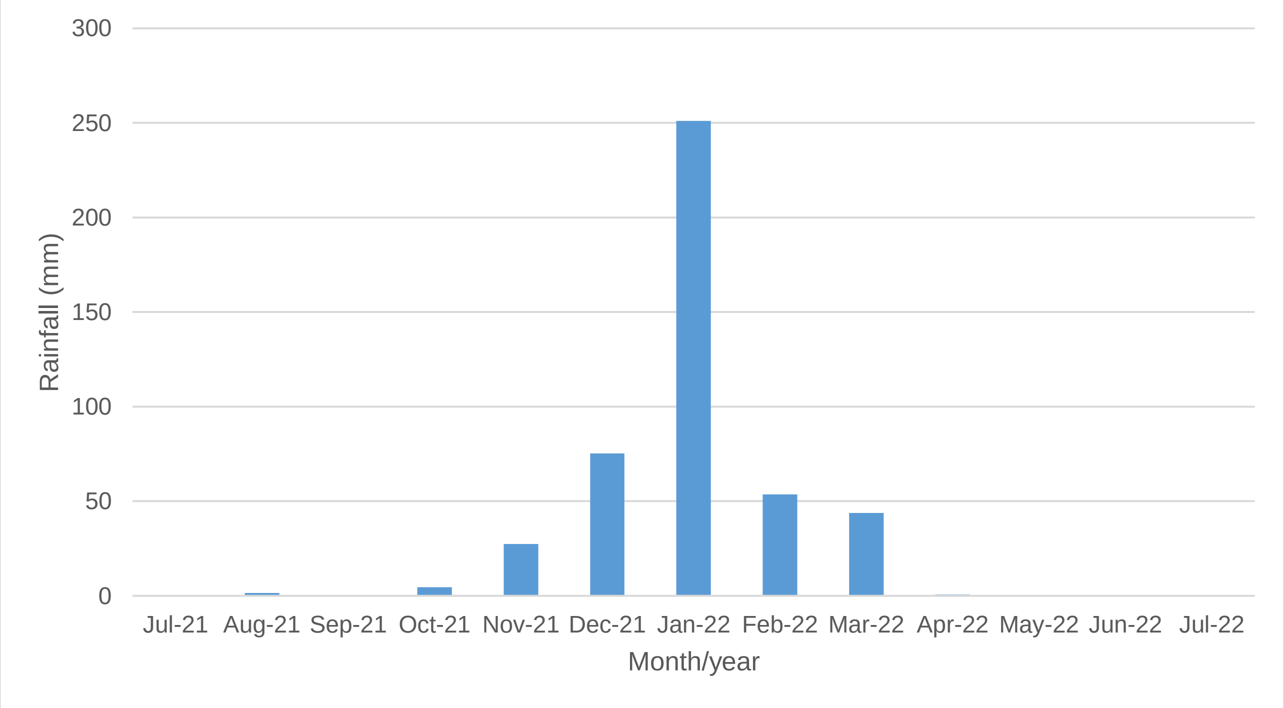


Figure 6: Monthly rainfall amount received between July 2021 – July 2022

Because of its rich "black cotton" vertisol soils, Pandamatenga was identified to be a location suited for rainfed arable cultivation or dryland farming. Sorghum, millet, wheat, maize, and a variety of beans are the principal crops farmed on the fields; they are planted between early November and late January. Sunflower is planted later in February since they can endure cold winter temperatures (Patrick et al., 2008). Along with acacia and mopane *(Colophospermum mopane)* species, the vegetation within the area is primarily broad grassland savannah (EIA Zambezi, 2009). The area is generally flat, with a gentle slope and elevation ranging between 995 – 1124m above sea level (Figure 7).

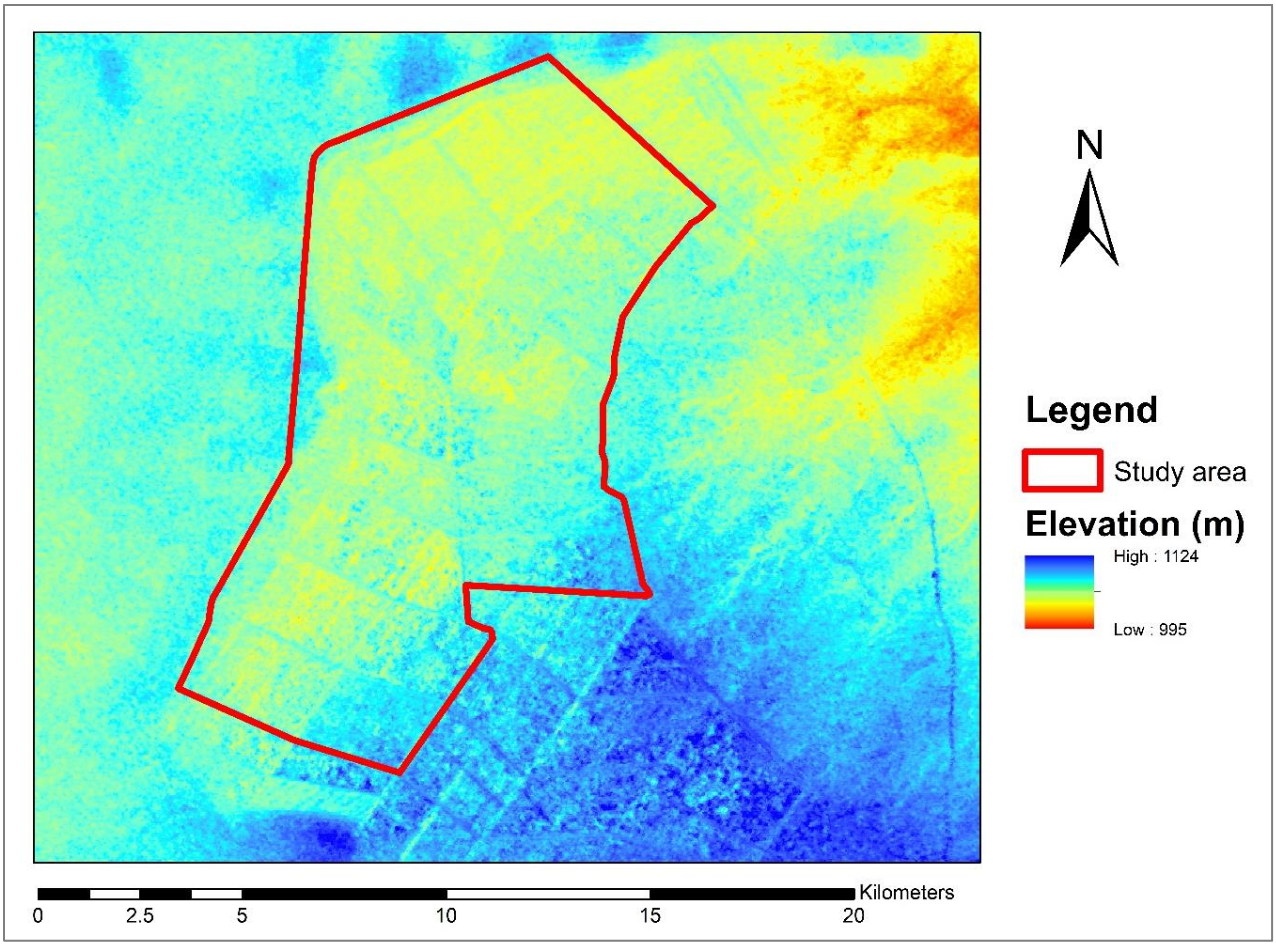


Figure 7: Elevation map of Pandamatenga focusing on the study area

The temperature of the Pandamatenga area is more amenable to farming as it has less extreme heat than the rest of the country as well, with mean maximum temperatures of 34°C in summer to 26°C in winter (Abdullahi and Bullen, 2008). From October to March, maximum temperatures in the range of 26 to 34^{o}C are common. The coldest months, from May to August, average minimum temperatures of 8 to 18^{o}C (Jain et al., 2006).

3.2 Study design

Executing the study involved both onsite and laboratory tests conducted on water samples collected from selected sampling sites along the drainage channel situated in the northern-down end of the farms. The water quality parameters tested were selected based on the Water quality for irrigation standard – BOS 463:2011 and the Wastewater (Physical, Microbiological and Chemical requirements) standard – BOS 93:2012. These standards represent overall water quality status and reflect each impairment category for a water system, including physical characteristics, oxygen content, nitrogen content, and human health aspects. The results obtained from the water quality analysis were then used in an Irrigation Water Quality Index (IWQI) model to assess the possibility of reusing the agricultural drainage water. The study was designed to cover one weather season of dry conditions since that is when irrigation is normally done to meet the crop water requirements. The water samples were collected once every month for the months of April, May, July and August, which define one dry season. The acquired onsite and laboratory measurements for the selected sample points were used to generate spatial maps and an appropriate irrigation water quality index which transformed the concentrations of water quality variables into a quality score.

3.3 Sample collection and analysis

Drainage water samples were collected from various water points in the sub-drainage (Plate 4) and the main drainage channel within selected locations (Figure 8) as per standards BOS ISO 5667 (Water quality sampling) and BOS ISO/IEC 17025 (General requirements for the competence of testing and calibration laboratories). Locations (longitude, latitude, and altitude) of the sampling points were recorded using a global positioning system (GPS). The samples were placed in plastic sample bottles prewashed using distilled water and rinsed three times with the same water. For chemical, microbiological and ionic constituents, a purposive sampling technique was used to assess how the water quality varies upstream, midstream and downstream of the drainage channel. A total of 21 samples, each measuring one litre in volume were collected from the different sampling points along the channels. The samples were then transported under controlled temperature in a cooler box to the laboratories, where the analyses were carried out within the sample holding times that vary from 1 – 28 days from the date of sample collection. The analyses of seven heavy metals such as Ca^{2+}, Cu^{2+}, Mg^{2+}, Fe^{2+}, Pb^{2+}, Mn^{2+}, and Na^{+}, the three anions as Cl^{-}, NO_3^{-}, $SO_4^{(2-)}$, and microbiological parameters were carried out based on WUC/CTM/004, WUC/CTM/005 and WUC/CTM/002 standards respectively using Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES). These standards were approved for use by the Southern African Development Community Accreditation Service (SADCAS). The standard solution for each tested element was prepared according to its concentration and used to calibrate the system before analysing each water sample. The results were recorded automatically on a computer connected to the ICP-OES system. In situ observations were recorded using an XS PC–5 Multimeter Tester kit (Plate 5) for the analysis of temperature, pH, electrical conductivity, salinity and TDS to assess the nature of the degree of contamination. The test kit was calibrated using standard buffer solutions before it was used in the field.

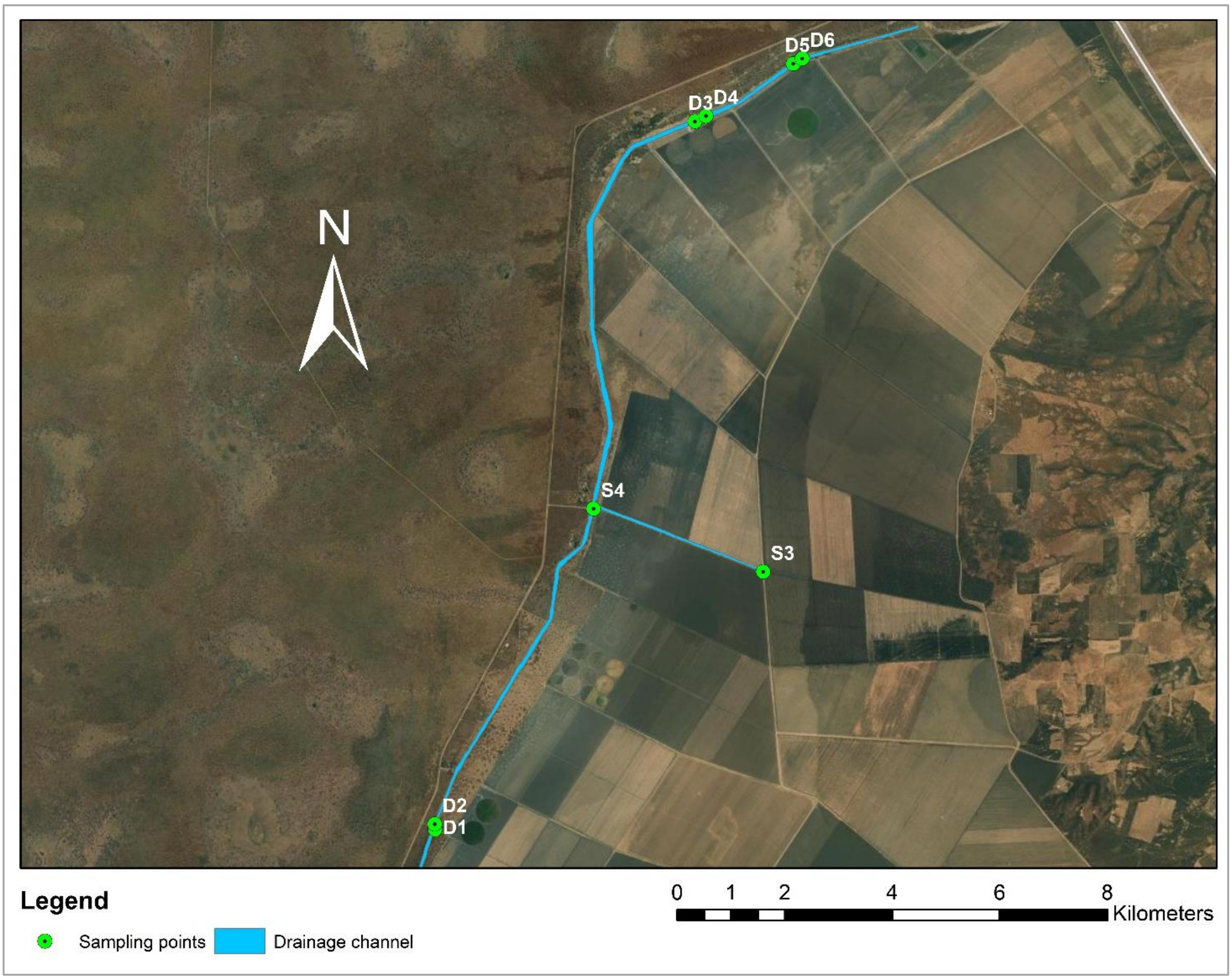


Figure 8: Sampling points along the sub-drainage and main drainage

3.3.1 Selection of sampling sites in sub-drainage

The study was designed to sample runoff from three different sub-drainage channels which are directly connected to the main drainage channel at the upstream, midstream and downstream points. Two sampling points were chosen in each sub-drainage to represent the quality of runoff as it flows through the sub-drainage and as it pours into the main drainage channel. At the time of data collection, all the sub-drainages within the study area did not have water in them apart from one which is represented by S3 and S4 in Figure 8. During the entire sampling period, point S3 was sampled only twice in the months of April and May, whereas point S4 was sampled only once in the month of April before both points dried up.

3.3.2 Selection of sampling sites in the main drainage channel

Six sampling points were selected within the main drainage channel to reflect the different activities along the canal that could be affecting the change in water quality; as it is shown in Figure 8, the furthest upstream sample points (D1 and D2) were used to assess the quality of water as it enters the canal, the midstream sample points (D3 and D4) were used to assess any changes in water quality from the time it entered the canal to those particular points, and the furthest downstream sample points (D5 and D6) were used to assess the quality of water as it left the farm area to join the open waters of Matetsi River. Similar to the sub-drainage, points D1 and D2 of the main drainage did not hold water for the entire sampling season (i.e., both points were sampled once in the month of April), whereas points D3, D4, D5 and D6 held water for the entire sampling period. This depicted a positive trend of the drainage channel drying up starting from points of high altitude to those with a low altitude (i.e., from west to east). To determine the quality of the ADW in the main drainage as it joined the open waters of Matetsi River and its capacity to be reused for irrigation, analyses of the physical, chemical and microbiological parameters were done for each sample collected during the study period.

3.3.3 Comparison of water quality in the sub-drainage and main drainage

The water samples collected from the sub-drainage were analysed independently to identify which one has got the highest level of contaminants in relation to the permissible standards. The mean values of these samples were calculated and compared with the mean values of the water quality at the downstream, midstream and upstream ends of the main drainage channel. This was used to identify the correlation between the ADW from the sub-drainage to that of the main drainage within the study area.

3.4 Evaluation of Irrigation Water Quality

In evaluating ADW for irrigation purposes, it was assumed that the water will be used under average conditions with respect to soil texture, infiltration rate, the quantity of water used, climate, and salt tolerance of the crop. The specific concentrations of different parameters of irrigation water were interrelated, and irrigation water indexes like soluble sodium percentage (SSP), adjusted sodium adsorption ratio (SAR_{adj}), soluble magnesium percentage (Mg%), permeability index (PI), and Irrigation Water Quality Index (IWQI) were calculated to assess water quality in the drainage canal for possible irrigation reuse.

3.5 Statistical analyses

The analysis results obtained were subjected to descriptive statistics to calculate basic summary statistics (i.e. mean, standard deviation, coefficient of variation, max value, quantiles (75%, 50%, 25%) and minimum values) for the water quality parameters, irrespective of sampling points and sampling period. Due to the non-parametric nature of the raw and computed water quality data collected, a Mann-Kendall trend test was used to determine if there is an 'increasing', 'likely increasing', 'decreasing', 'likely decreasing', 'stable' or 'no trend' for each parameter at every sampling location. A correlation matrix between all tested water quality parameters and sampling stations was done and the results were plotted into separate correlation matrix plots. All analyses were performed using AquaChem (version 10.0), a software package developed specifically for managing, analyzing, and plotting water quality data together with R (version 4.1.3) used for statistical computing and graphics.

3.6 Spatial analysis

For the duration of the study period, the spatial analysis was done using ArcMap (version 10.7) for a few selected parameters (EC, Na^+, HCO_3^-, Cl^-, and SAR). For the analysis, all of the research area's sampling points were taken into account using the inverse distance weighted (IDW) interpolation technique. This method assumes that the sampling points closer to the un-sampled points are more similar than those further away in their values, and it uses a linear combination of values at sampled points weighted by an inverse function of the distance from the point of interest to the sampled points to estimate the values of an attribute at un-sampled points. Using nearby data points that are located within a user-specified search radius, the IDW approach determines a value for each grid node. (Burrough et al., 2015)

Plate 4: Collecting water samples from the sub-drainage channel during the first site visit

Plate 5: Taking onsite readings of the physical parameters using an XS PC–5 Multimeter Tester kit

4.0 Results and Discussion

Physical, chemical and microbiological parameters were measured to establish the extent of ionic and organic concentrations in the ADW and determine how it affects the water's quality and suitability for irrigation reuse. Table A1 (Appendix 2) represents the summary of the obtained results at the eight sampling stations. The statistical results with respect to the minimum, maximum, mean, Standard Deviation (SD) and Standard Error (SE) values for tested water quality parameters within the four months of data collection are summarized in Table 6. The results reveal that apart from the microbiological parameters, the physical and chemical water quality parameters were below the permissible limits as per BOS 463: 2011 and BOS 93: 2012 standards.

Table 6: Statistical analysis from all stations

	MEAN	STDEV	CoV	MAX	Q75	Q50	Q25	MIN
Temp.	20.88	4.57	0.22	27.70	24.80	21.40	17.00	12.90
pH	7.59	0.50	0.07	8.28	7.94	7.62	7.36	6.54
Na	9.43	5.57	0.59	21.06	11.73	7.38	5.63	3.10
Ca	27.03	17.17	0.64	78.13	31.65	21.10	15.40	9.17
Mg	6.77	4.95	0.73	18.12	7.34	4.59	3.72	2.04
Fe	5.64	17.73	3.14	66.30	0.19	0.04	0.00	0.00
Cl	0.90	0.62	0.69	3.02	1.11	0.88	0.53	0.14
HCO3	26.26	9.88	0.38	60.50	27.00	24.00	20.00	14.00
EC	170.90	98.78	0.58	431.00	164.60	137.00	112.20	80.80
TDS	125.85	73.48	0.58	319.00	121.20	101.20	83.00	60.70
SO4	7.50	7.77	1.04	32.12	9.22	4.51	2.84	0.00
NO3	15.50	12.61	0.81	47.66	25.69	13.29	4.75	0.24
Pb	0.00	0.00	1.90	0.01	0.00	0.00	0.00	0.00
Mn	0.00	0.01	2.24	0.02	0.00	0.00	0.00	0.00
E. coli	3390.49	6002.99	1.77	21400.00	1900.00	560.00	0.00	0.00
Faecal coliforms	4355.24	6586.28	1.51	22400.00	4100.00	1500.00	640.00	0.00
Total coliforms	15380.48	17652.61	1.15	69300.00	20000.00	11200.00	2300.00	0.00
Cu	0.00	0.00	2.79	0.01	0.00	0.00	0.00	0.00
Salinity	79.03	48.62	0.62	206.00	76.30	62.70	50.10	36.40

4.1 Analysed physical parameters

The water samples collected from all the sampling stations were analysed for physical parameters characteristics onsite using an XS PC–5 Multimeter Tester kit. The physical parameters analysed include Temperature, pH, EC, Salinity, and TDS.

4.1.1 Temperature characteristics

Due to aquatic life's wide range of temperature tolerance, the water temperature may not be as significant in pure water, as in contaminated water. Temperature can tend to have significant effects on dissolved oxygen and biological oxygen demand (Ahipathy and Puttaiah, 2006).

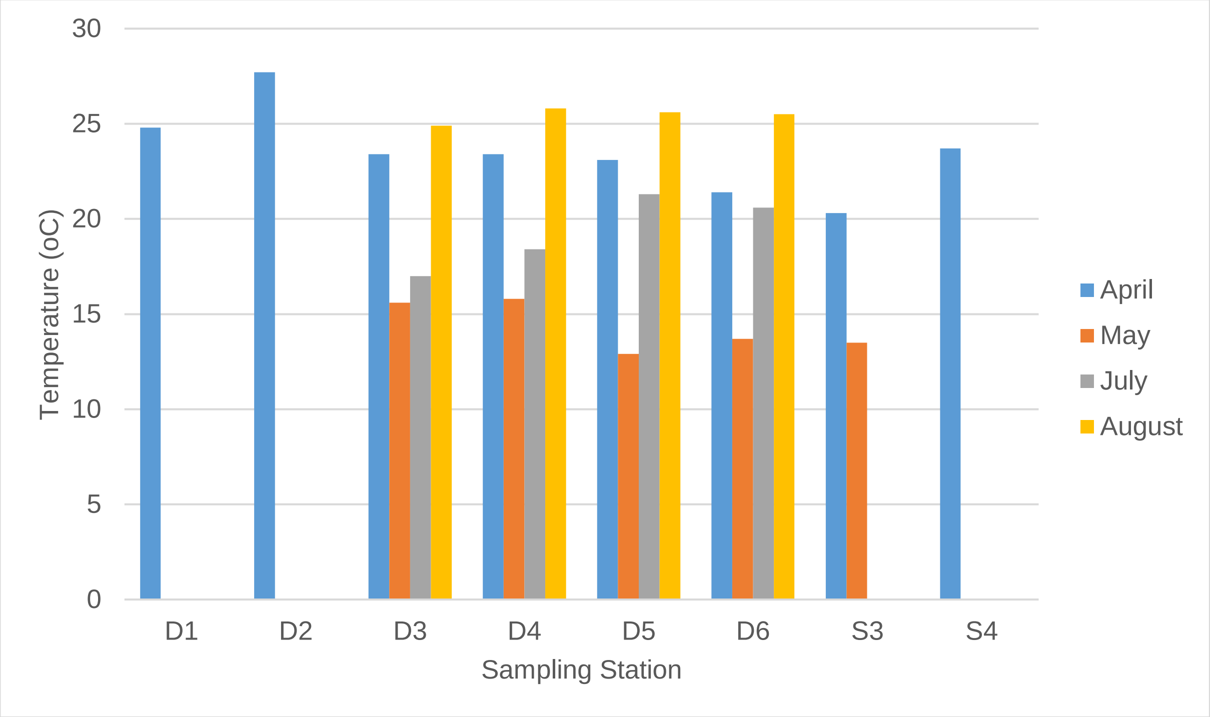


Figure 9: Temperature results collected throughout the sampling period

High temperatures were recorded in the months of April and August which are known to be dry and hot while low temperatures were recorded in the months of May and July which are characterised by cold and moist weather (Figure 9). Based on the results collected, the variation in ADW temperature can be attributed to the time of year, location, sample period, and temperature of runoff entering the drainage channel. Both the irrigation water and wastewater quality standards of Botswana set a permissible limit for water temperature as 25^{o}C and 35^{o}C respectively, however, a maximum of 27.7^{o}C, a minimum of 12.9^{o}C and a mean of 20.9^{o}C were recorded during the entire study (Table 6). The mean value being below the permissible levels implies that the temperature of the ADW qualifies it to be reused for irrigation or discharged as effluent.

4.1.2 pH characteristics

One of the most crucial aspects of water quality is pH. If the pH of a sample is less than 7.0, it is regarded as acidic, and alkaline if the pH is greater than 7.0. Metal pipes and plumbing systems may corrode as a result of acidic water whereas alkaline water demonstrates water disinfection (Rahmanian et al., 2015). According to Botswana quality standards recommendations, irrigation water and wastewater should have a pH of between 6.5 – 8.4 and 6.0 – 9.0 respectively.

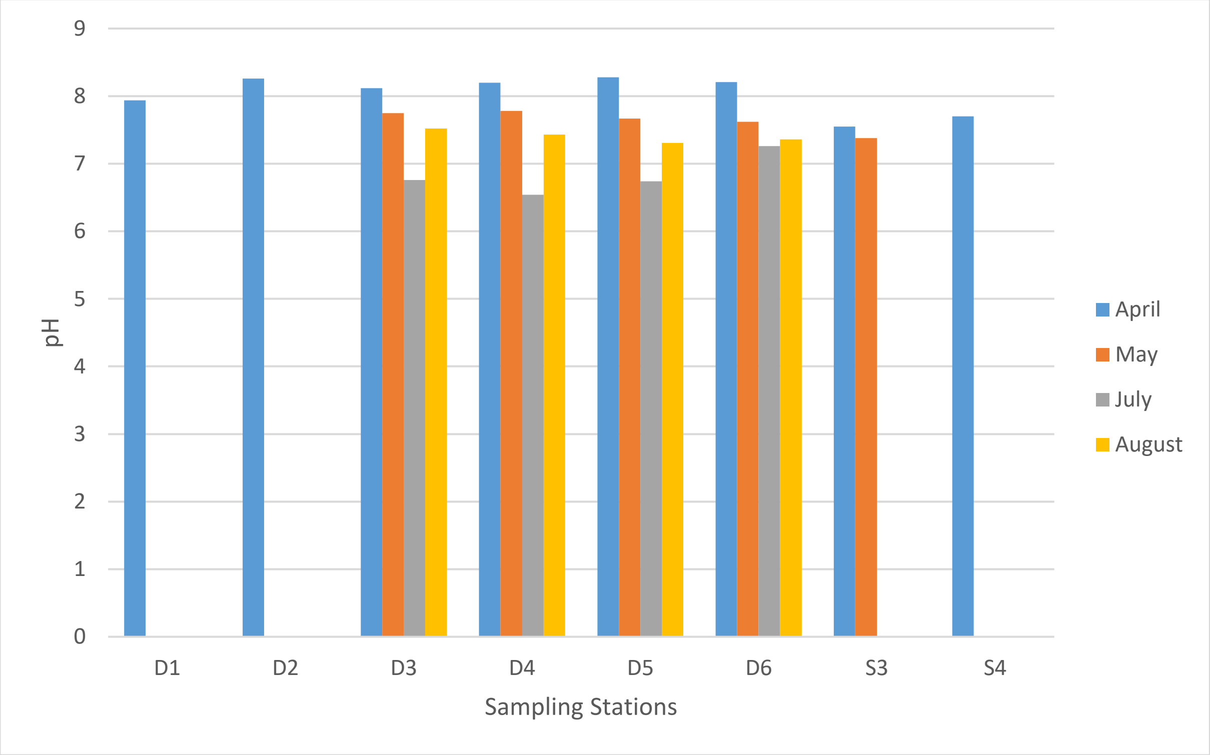


Figure 10: pH results collected throughout the sampling period

Figure 10 shows that the pH values were relatively similar throughout the sampling period presenting a likelihood of a decreasing trend with time. The trend of increasing pH values could cause the ADW source to be acidic in the future which affects the reuse of the water. According to the pH results presented in Table 6, all water from the sampling stations along the drainage channels were moderately alkaline in nature (i.e. between 6.5 – 8.3). These values being within the allowable pH range for reuse in irrigation purposes implies that the pH of the ADW was in the recommended range for reuse.

4.1.3 Electrical Conductivity (EC) characteristics

Electrical conductivity is the ability of water to carry an electric current. The presence of dissolved solids such as calcium, chloride, and magnesium in water samples carries the electric current through the water. According to Ayers and Westcot, (1999), the EC degree of restriction on reuse is: <700 µS/cm (none); 700–3000 µS/cm (slight to moderate); >3000 µS/cm (severe). The conductivity of water must be closely monitored for agricultural operations because excessive conductivity eliminates plant species that are necessary for food and habitat formation (Rahmanian et al., 2015). The irrigation water quality standard of Botswana sets a permissible limit for the EC as 3000 µS/cm.

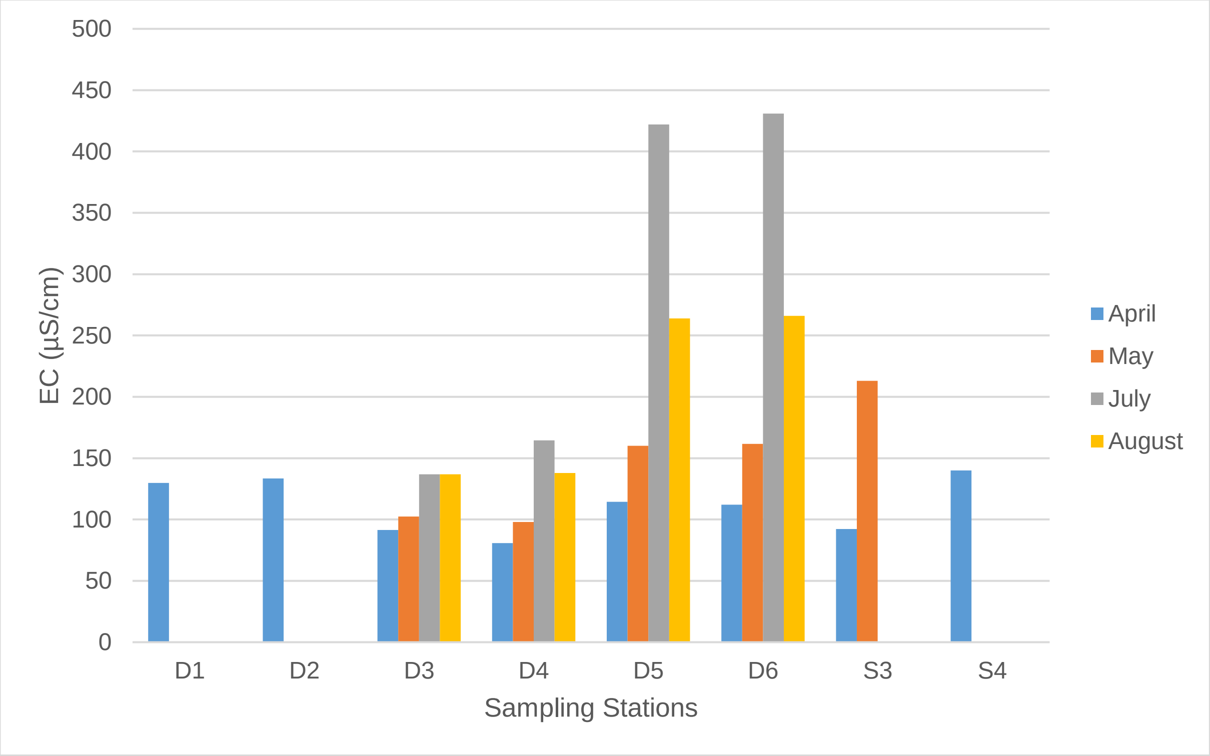


Figure 11: EC results collected throughout the sampling period

Electrical conductivity in this study varied from 80.8 – 431 µS/cm which presents a low (insignificant) amount of salts in the ADW (Table 6). In this context, the values recorded for EC increased with time (Figure 11), and this could be attributed to the enrichment of salts in the drainage channel when the volume of water decreased as the drainage channel was progressively drying up. These values are probably influenced as well by the anthropogenic activities around the drainage channel and geological weathering conditions resulting in high concentrations of dissolved minerals.

4.1.4 Salinity characteristics

Salinity is a measure of the content of salts in soil or water. Salts are easily carried by water flow because they are highly soluble in both surface and groundwater. Water with too much dissolved salt can have an impact on ecosystem health and agriculture. Conductivity and salinity are linked measurements because dissolved ions raise salinity (Australian Government Initiative, 2022). Both the Irrigation water and wastewater quality standards of Botswana have no set permissible limits for water salinity but a relationship can be drawn from the values of EC.

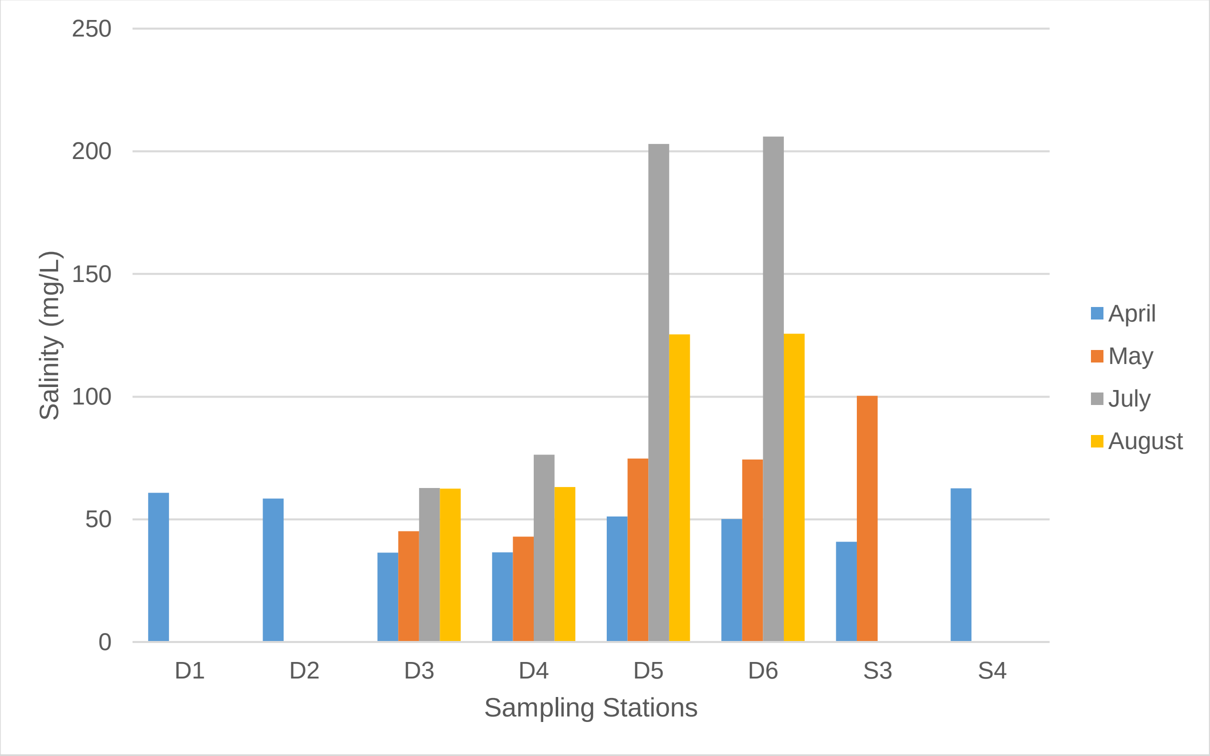


Figure 12: Salinity results collected throughout the sampling period

Results in Table 6 reveal that the ADW salinity at the eight sampling sites ranged from 36.4 to 206 mg/L. The highest salinity value of 206 mg/L was observed during the month of July 2022 at Station D6 and the minimum salinity value of 36.4 mg/L was observed during the month of April 2022 at Station D3 (Figure 12). Just like EC, the values of salinity increased with time and this could be also attributed to the enrichment of salts in the drainage channel as the volume of water decreased while the channel was drying up.

4.1.5 Total Dissolved Solids (TDS) characteristics

TDS are the inorganic matter and small amounts of organic matter, which are present as a solution in water. TDS values over 500 mg/L indicate the presence of slightly elevated salt concentration and can be related to other problems such as hardness (Abbasnia et al., 2018). Based on TDS measurements, the degree of restriction on reuse is; none (<450 mg/L); slight to moderate (450 –2000 mg/L); severe (>2000 mg/L) (Ayers and Westcot, 1999). Figure 13 shows that the values of TDS increased on a monthly basis and this is attributed to the concentration of both organic and inorganic matter increasing as the level of water decreased.

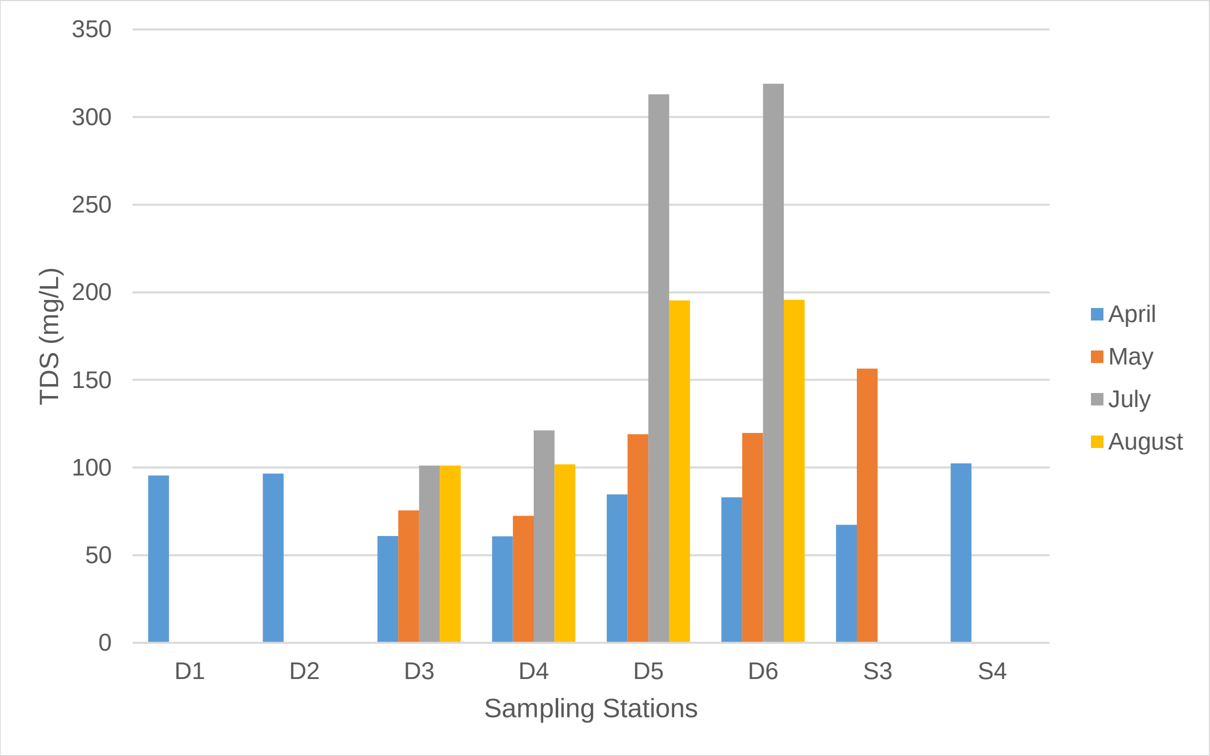


Figure 13: TDS results collected throughout the sampling period

Both the irrigation water and wastewater quality standards of Botswana set a permissible limit for TDS in water as 2000 mg/L. In this particular study, a maximum of 319 mg/L, and a minimum of 60.7 mg/L with a mean of 125.9 mg/L were recorded (Table 6). This, therefore, qualifies the TDS of ADW fit for reuse during irrigation or when discharged as effluent since all the values are way below the permissible standard.

4.2 Analysed chemical parameters

Laboratory testing was done to determine the concentrations of different chemical parameters contained in the water samples collected from each sampling station. Calcium, copper, iron, lead, magnesium, manganese, sodium, chloride, nitrate, sulphate, and bicarbonate are among the chemical parameters that were examined.

4.2.1 Calcium characteristics

Calcium is one of the most abundant elements found in natural water. It is an important ion in imparting hardness to the waters. At high pH, much of its quantities may get precipitated as calcium carbonate (Yadav, 2016). In this study, there is a definite increasing trend in values of calcium concentration in the water samples at the sampling stations apart from Station D4 which registered one peak value in May and lower values in April, July and August (Figure 14).

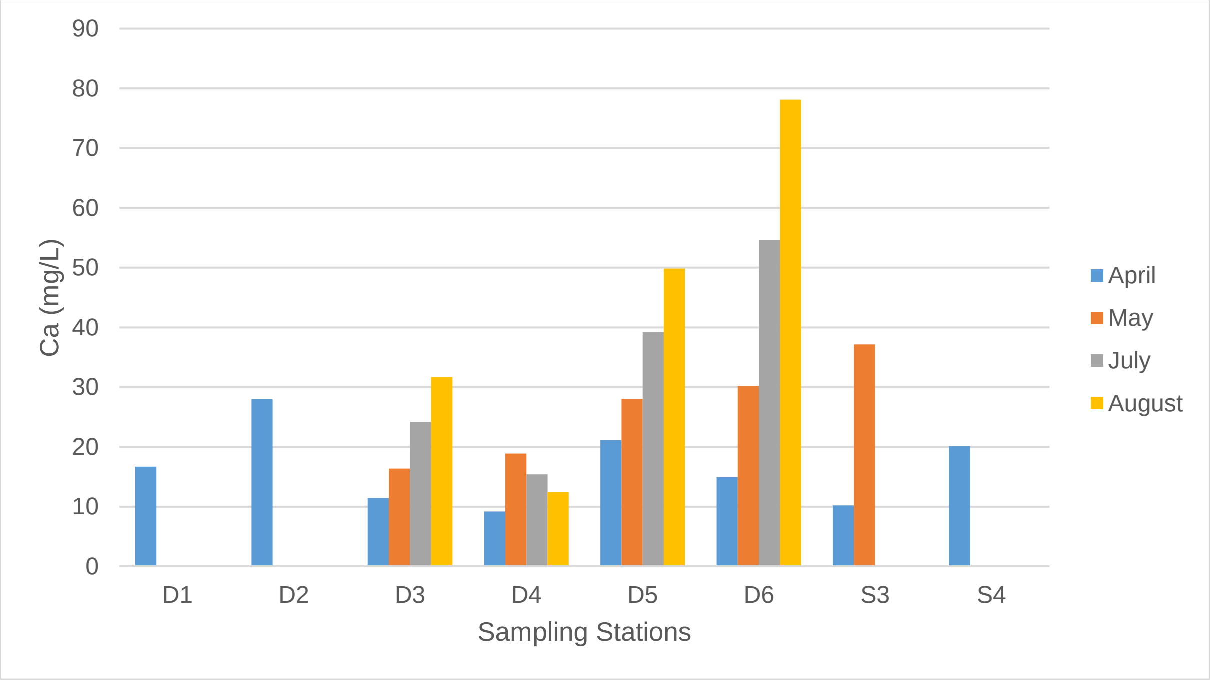


Figure 14: Calcium results collected throughout the sampling period

The calcium hardness of ADW samples ranged from 9.17 to 78.13 mg/L with an overall mean of 27.03 mg/L of successive four months of analysis (Table 6). Due to its natural occurrence in water, both the irrigation and wastewater quality standards of Botswana do not set a permissible standard though irrigation water that contains ample calcium is most desirable.

4.2.2 Magnesium characteristics

Magnesium is determined as the difference between total hardness and calcium hardness. Magnesium also occurs in all kinds of natural waters, but its concentration remains generally lower than calcium hardness (Yadav, 2016). There is no definite trend in values of magnesium concentration in ADW samples collected from all the stations as witnessed in Figure 15.

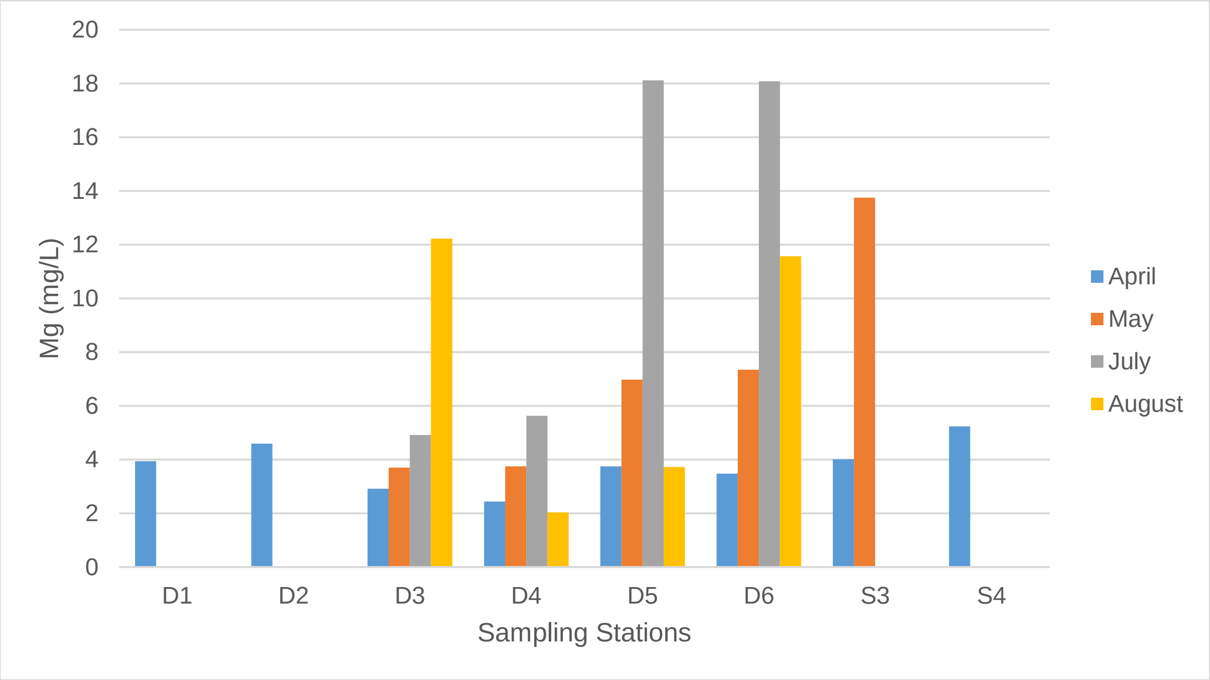


Figure 15: Magnesium results collected throughout the sampling period

The magnesium concentration ranged from 2.04 to 18.12 mg/L with an overall mean of 6.77 mg/L for four successive months of analysis (Table 6). Just like calcium, both the irrigation and wastewater quality standards of Botswana do not set a permissible standard due to its natural occurrence in water, though irrigation water that contains ample concentration is most desirable.

4.2.3 Sodium characteristics

Sodium values ranged from 3.10 to 21.06 mg/L and the average value was 9.43 mg/L in all of the studied samples of successive four months (Table 6). The maximum value of sodium examined was in the month of August at Station D6 and the minimum value of sodium was measured in the month of April at Station D4 (Figure 16).

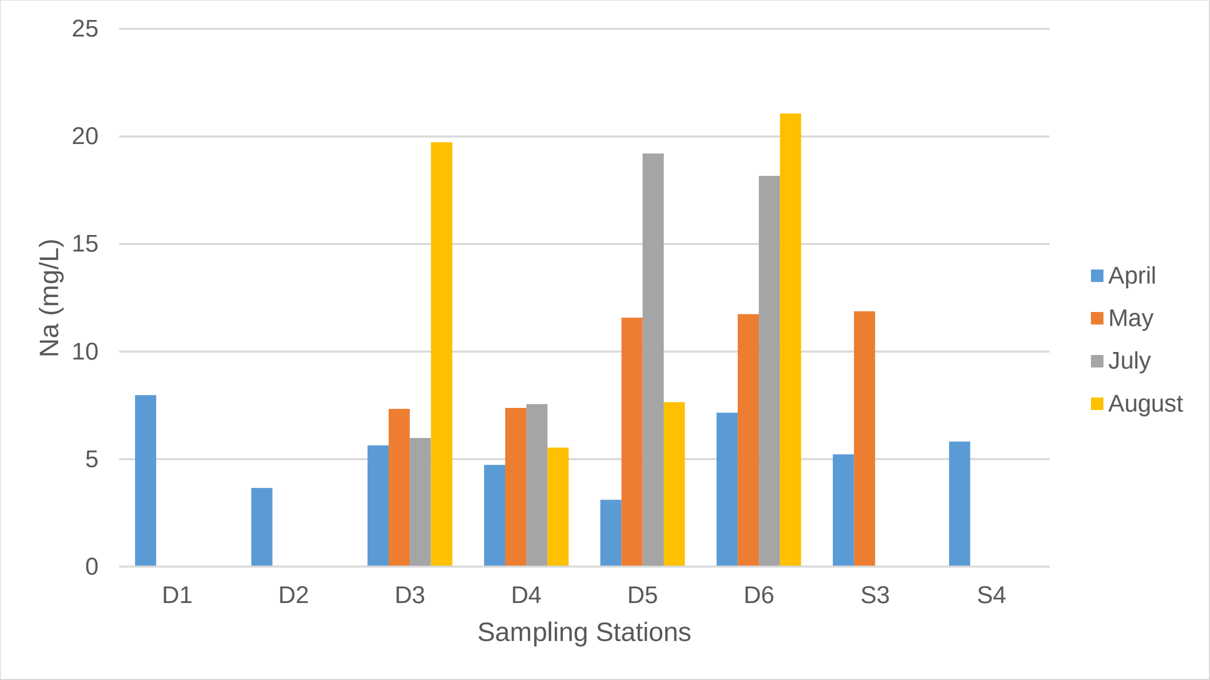


Figure 16: Sodium results collected throughout the sampling period

Both the irrigation water and wastewater quality standards of Botswana set a permissible limit for sodium concentration in water as 230 and 400 mg/L respectively. The values of the samples analysed in this study were far below the set limits which makes the sodium ion concentration in the ADW suitable for irrigation and at the same time harmless as effluent.

4.2.4 Chloride characteristics

In all kinds of water, chlorides are present naturally. A high concentration of chlorides is thought to be a sign of pollution brought on by organic wastes with either industrial or animal origins. Higher concentration of chloride is hazardous to human, causes problems in irrigation water and are bad for aquatic life as well (Rahmanian et al., 2015). This study in Figure 17 shows that the chloride parameter has got an increasing trend within the consistently sampled stations or points.

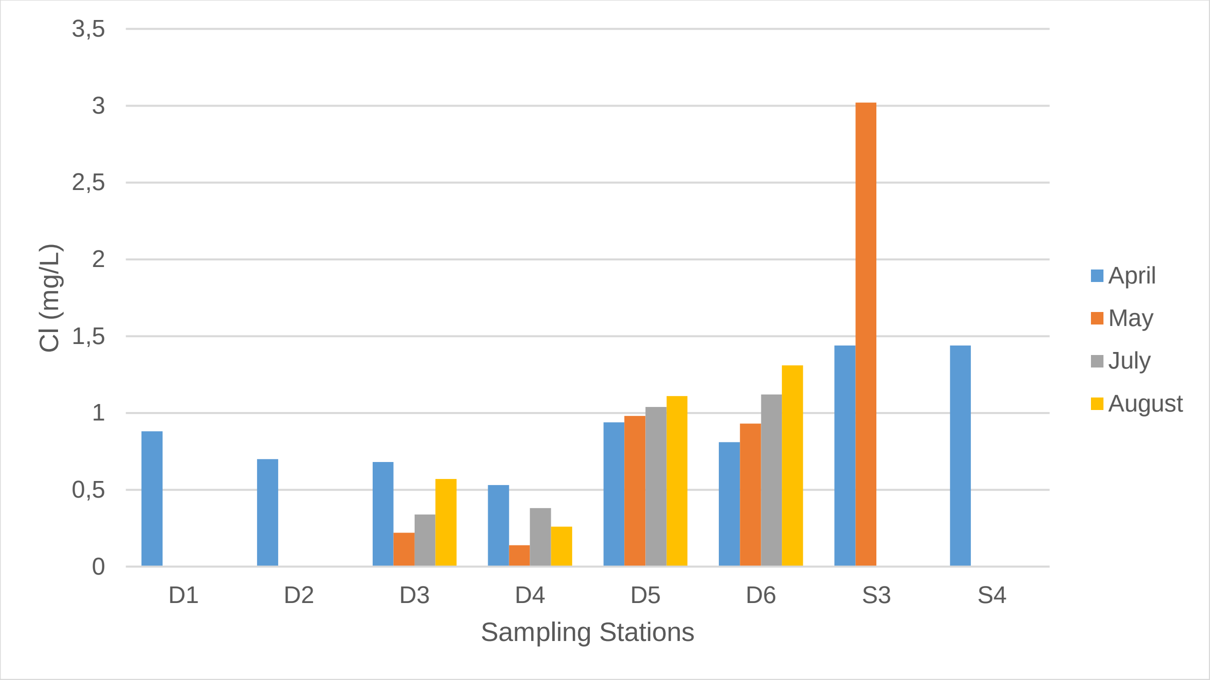


Figure 17: Chloride results collected throughout the sampling period

Chloride values ranged from 0.14 to 3.02 mg/L and the mean value was 0.89 mg/L in all of the studied samples (Table 6), over the successive four months. The recorded values are way below the permissible values of the irrigation and wastewater standards (350 and 600 mg/L respectively), which implies that the calcium concentration in the ADW is almost insignificant.

4.2.5 Nitrate characteristics

High nitrate levels are caused by a variety of factors, including overuse of fertilizers in agriculture, residential effluent, sewage disposal, and leaching from rubbish dumps. When nitrate or ammonia is reduced or oxidized by bacteria, nitrite ions are produced. The presence of nitrite indicates either incomplete oxidation of organic materials, a lack of oxygen, or an overabundance of contaminants in the water system (Mishra et al., 2022). Nitrate is one of the critical nutrients for the growth of algae and helps accelerate eutrophication.

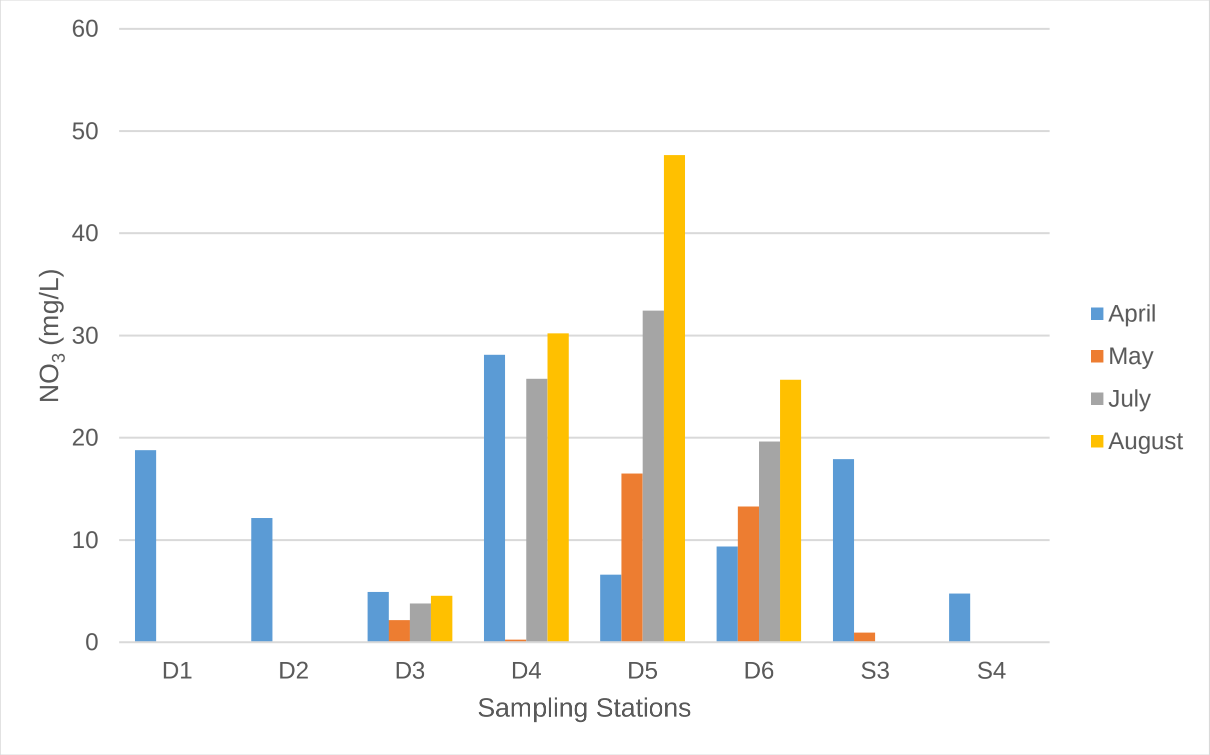


Figure 18: Nitrate results collected throughout the sampling period

Nitrate content in the ADW samples varied from 0.24 to 47.66 mg/L with an overall average of 15.50 mg/L for successive four months of analysis (Table 6). The maximum allowable limit of nitrate in irrigation and wastewater as per BOS 463:2011 and BOS 93:2012 is 30 and 50 mg/L. There are some exceedance values recorded at station D5 in the months of July and August (Figure 18) in regard to the BOS 463:2011. However, they don't affect the average water quality since the mean lies below the permissible values.

4.2.6 Sulphate characteristics

Sulphate is a naturally occurring anion found almost in all kinds of water bodies. This is also an important anion imparting hardness to the waters. In this study, the sulphate ion concentration in ADW samples ranged from 0 to 32.12 mg/L with an overall average of 7.50 mg/L for the successive four months of analysis (Table 6). The analysed results showed no significant trend since some stations had decreasing values while others registered increasing or zero (no values) as witnessed in Figure 19.

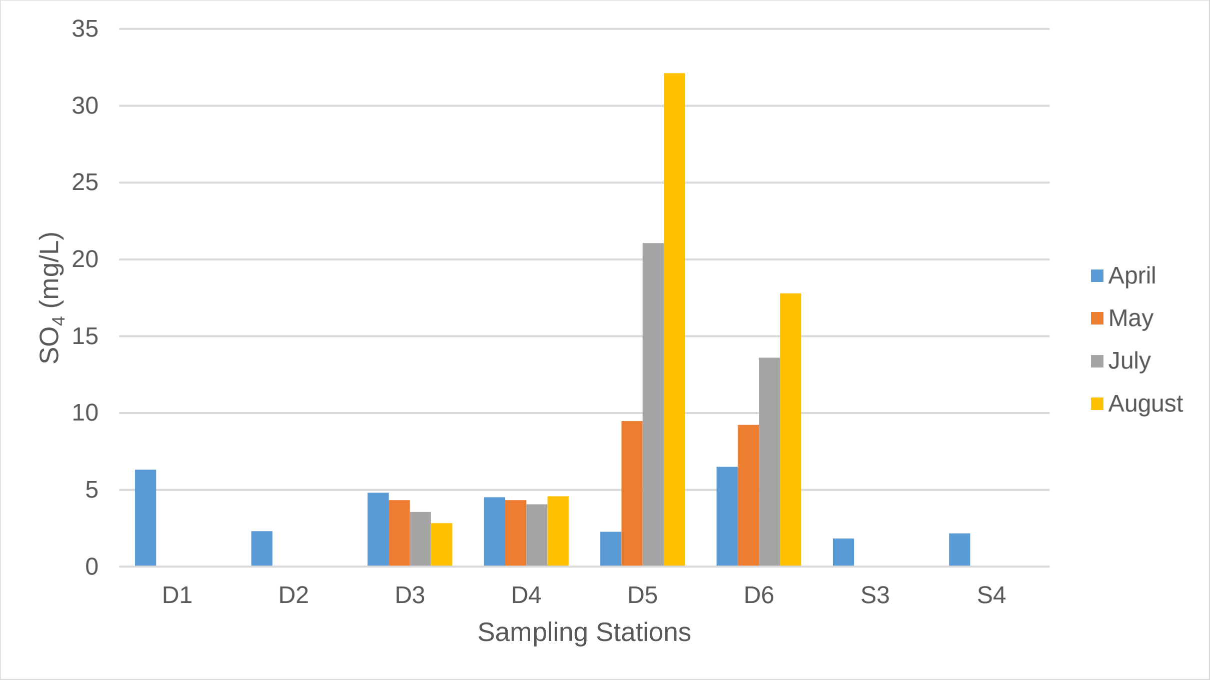


Figure 19: Sulphate results collected throughout the sampling period

The maximum allowable limit of sulphates in irrigation water as per BOS 493:2011 is 200 mg/L. The recorded values show that all the stations registered minimal to zero amounts of sulphate which may be attributed to minimal anthropogenic influences within the study area.

4.2.7 Bicarbonate characteristics

Bicarbonate ions ranged from 14 to 60.5 mg/L with an overall average of 26.26 mg/L in the analysed samples during the successive four months (Table 6). Minimum values of bicarbonate concentration were observed in the month of May at Stations D3 and D4 and in the month of July at Station D5 the maximum value of bicarbonate ions was observed (Figure 20).

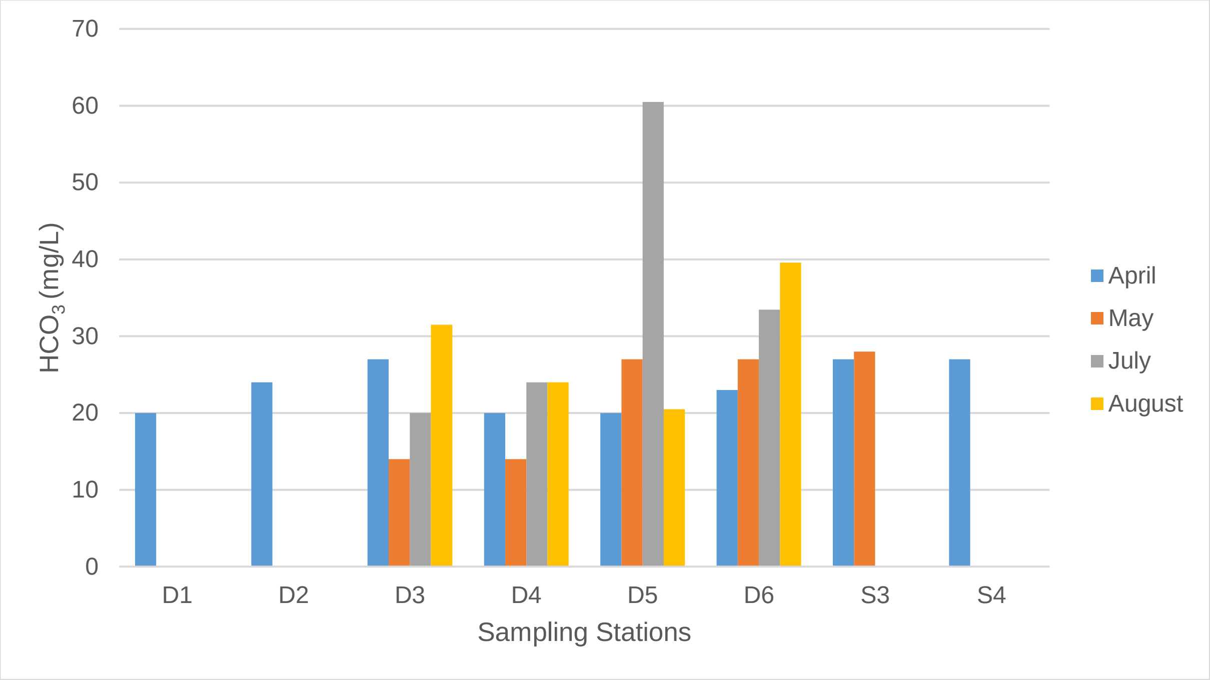


Figure 20: Bicarbonate results collected throughout the sampling period

The maximum allowable limit of bicarbonate ions in irrigation water as per BOS 493:2011 is 92 mg/L. The recorded values show that all the stations registered no levels of exceedance which relieves the ADW from any threat accrued to bicarbonate pollution.

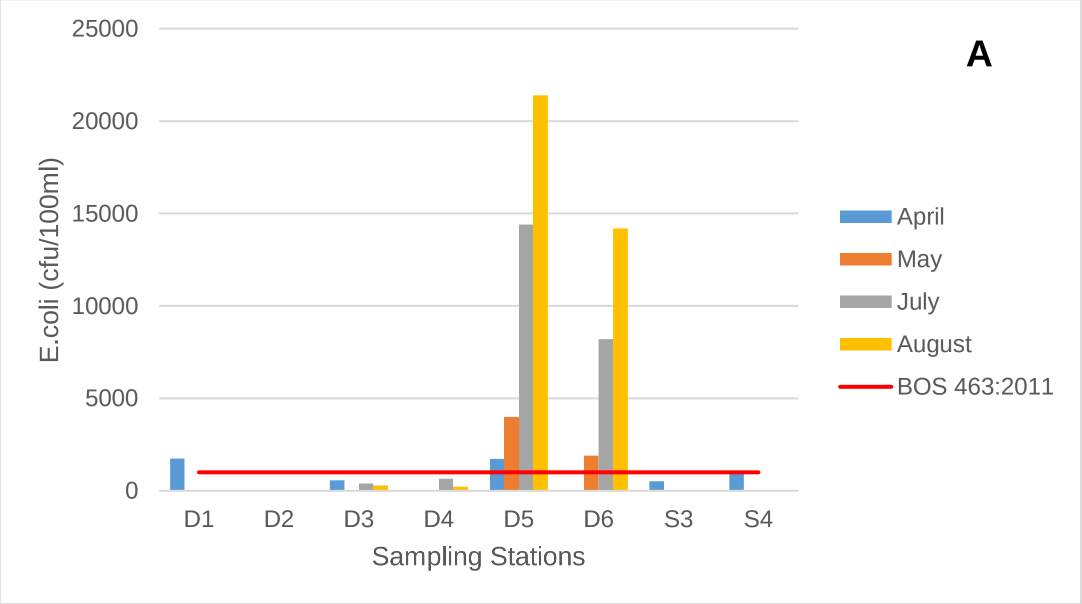
4.2.8 Characteristics of heavy metals

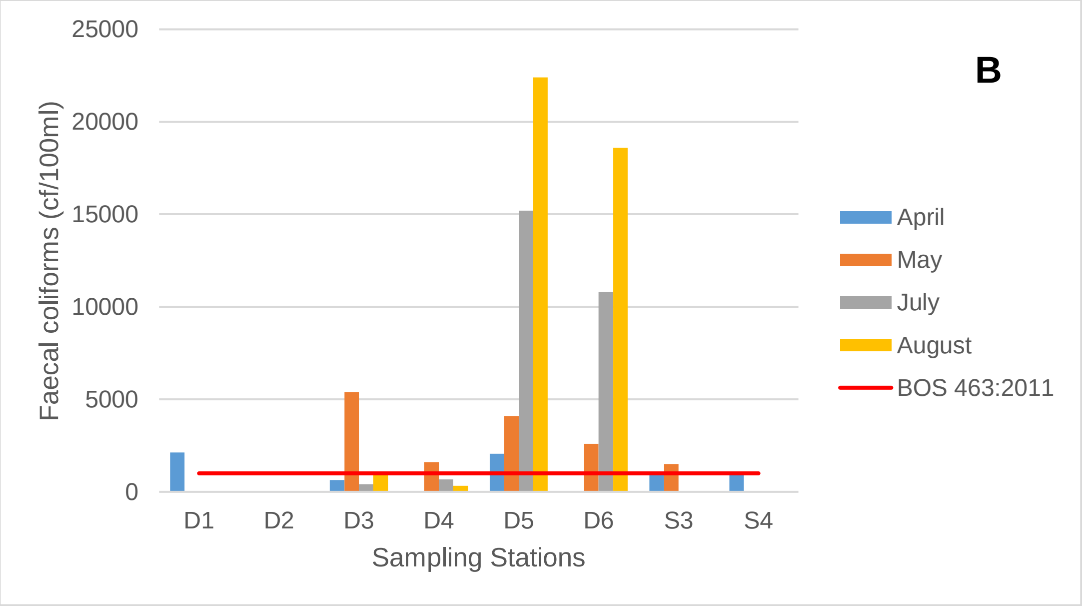
Heavy metals like Fe^{2+}, Cu^{2+}, Mn^{2+}, and Pb^{2+} were analysed during the four months. The heavy metals analysed were non-detectable in most of the samples and those that had values of the metals under study were under permissible limits of both the BOS 493: 2011 and BOS 93:2012. The majority of Fe^{2+} values ranged from 0 to 0.27 mg/L apart from two outliers recorded at Stations D5 and D6 in the month of May with values of 66.3 and 50.6mg/L respectively as shown in Tables A1 and 6.

4.3 Analysed microbiological parameters

Microbiological tests were conducted to determine the extent of contamination brought about by living things, particularly people who reside or work nearby, particularly around drainage systems. Coliform bacteria are used as the indicator organism in these tests. These indicator organisms once detected are proof that human or other warm-blooded animal faeces have polluted the ADW. Results from this study show that the ADW contained high values of coliform bacteria throughout the sampling period. The recorded values of E. coli ranged from

220 to 21400 cfu/100ml with a mean of 3391 cfu/100ml, faecal coliform values ranged from 320 to 22400 cfu/100ml with a mean of 4355 cfu/100ml, and the total coliforms ranged from 1800 to 69300 cfu/100ml with a mean of 15381 cfu/100ml (Table 6). Some of these recorded values are way higher than the permissible limits (Figure 21:a – c) which imply that the ADW is exceedingly contaminated with coliform bacteria. This is accrued to the wild and domestic animals that drink from the drainage channel and end up leaving their droppings in the water (Plate 6).





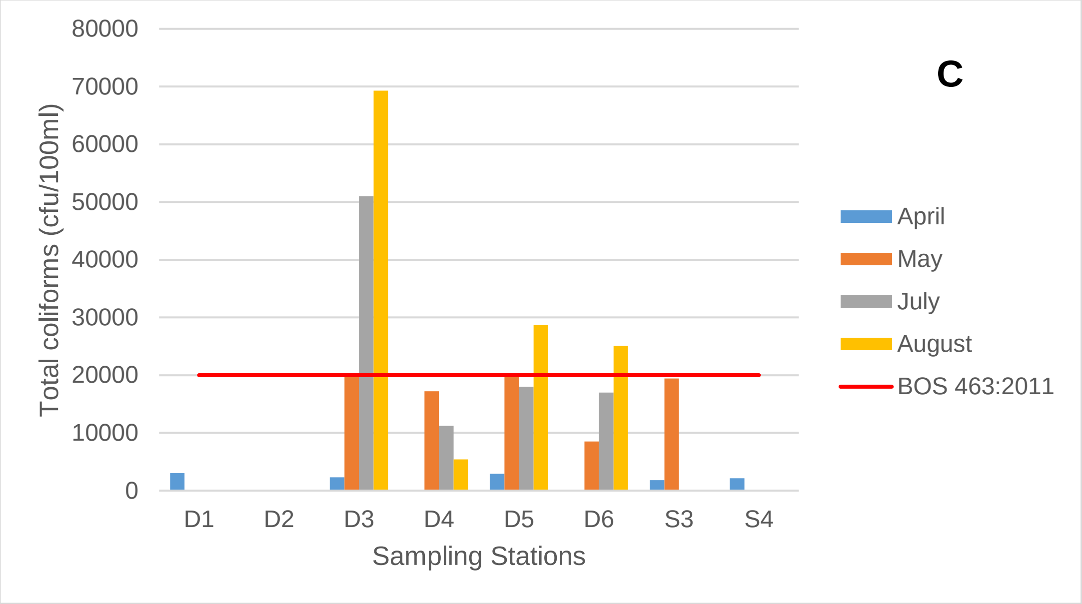


Figure 21(a-c): Microbiological results collected throughout the sampling period

Plate 6: Animal dropping in proximity to the drainage water

With such levels of contamination, the use of trickle or drip irrigation systems presents a lower risk for potential contamination of crops as compared to an overhead spray system.

This is due to the lower chance of interaction between water and the crops. In such a scenario, irrigating "ready-to-eat" crops with such ADW increases the risk of food-borne diseases.

4.4 Existing relationship between ADW from the sub-drainage and main drainage

Before the ADW joins the main drainage channel, it passes through the sub-drainages which collect water drained from the different sections of the farms. Different farm practices could impact the quality of drainage water, for example, the application of fertilizers and herbicides. The water drained from such modified soils carries with it chemical elements that can turn out to be pollutants. Since the sub-drainages discharge into the main drainage channel, this study assessed the relationship between the ADW from the sub-drainages and main drainage in order to find out if the water from the former has a significant effect on the water in the latter.

Statistical analysis was done using the Wilcoxon Signed Rank Test to establish the relationship between the averages of ADW parameters in the sub-drainage and main drainage. The tested null hypothesis is that "the quality of water within the main drainage channel is influenced by the runoff coming from the different sub-drainages of the farms." However, it should be noted that only one sub-drainage was sampled out of the three that were initially earmarked, and its sample period was less than that of the main drainage channel, thus using a nonparametric test to aid in determining whether the corresponding data population distributions are identical without assuming them to follow a normal distribution as shown in Table 7.

Table 7: Related-Samples Wilcoxon Signed Rank Test Summary

Total N	19
Test Statistic	140.000
Standard Error	21.122
Standardized Test Statistic	3.006
Asymptotic Sig. (2-sided test)	.003

- **Null hypothesis** – The quality of water within the main drainage channel is influenced by the runoff coming from the different sub-drainages of the farms.

- **Confidence level** – 95%
- **Criteria alpha** – 0.05

The results in Table 7 show that the p-value turned out to be 0.003, which is less than the 0.05 significance level. Therefore, at a 95% confidence level, the null hypothesis is rejected. This implies that the quality of ADW in the sub-drainage has no significant effect on that in the main drainage since their populations are non-identical.

4.5 Mann-Kendall Trend Test

Cognizant of the fact that the data was collected for only four months, there was a need of assessing the trend in the water quality within the drainage channel against time. Since the nature of the collected data is not uniformly distributed, a Mann-Kendall trend test was employed to assess the trend. Mann-Kendall is a non-parametric test widely used to detect significant trends in time series. It also has the advantage that it is not affected by the actual distribution of the data. Thus, this method is highly suitable to be applied in detecting trends of skewed hydrologic time series containing outliers (Samsudin et al., 2017).

In this study, the Mann-Kendall trend test was conducted to detect the trends of water quality data within the study area. Confidence levels of 90% and 95% were applied in the study to assess whether the parameters had an “increasing”, “likely increasing”, “stable”, “decreasing”, “likely decreasing” or “no” trend. The test was based on the correlation between the observed parameters and their time series. The results obtained from the Mann-Kendall trends test (Table 8) showed that eight parameters including Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, EC, TDS, Mn^{2+} and Salinity had their p-values smaller than 0.1 indicating that there is an existence of significant difference for that particular parameter. The statistic S of the same parameters shows a high positive value, which is an indication that there is an upward (increasing) trend. pH and Pb^{2+} showed a high negative S value, which indicates a downward (decreasing) trend implying that there is no significant difference occurring for the parameters. The temperature registered a stable trend whereas Fe^{2+}, $SO_4^{(2-)}$, NO_3^{-} and Total coliforms registered no trend. The parameters which registered S values between –50 and 50 showed a likelihood of either an increasing or decreasing trend.

Table 8: Trend analyses from all stations (Mann-Kendall Test)

	Kendall's tau statistic	**Two-sided p-value**	**Kendall Score (S)**	**Denominator (D), tau = S/D**	**Variance of S**	**Confidence interval**	**Resulting trend conclusion**
Temp	-0.158	0.334	-33.000	209.499	1095.667	83.316	stable
pH	-0.210	0.194	-44.000	210.000	1096.667	90.294	likely decreasing
Na	0.219	0.174	46.000	210.000	1096.667	91.290	likely increasing
Ca	0.267	0.097	56.000	210.000	1096.667	95.163	increasing
Mg	0.282	0.080	59.000	209.499	1095.667	96.013	increasing
Fe	0.020	0.926	4.000	195.499	1031.333	53.721	no trend
Cl	0.568	0.000	119.000	209.499	1095.667	99.982	increasing
HCO3	0.401	0.016	80.000	199.750	1066.667	99.222	increasing
EC	0.352	0.027	74.000	210.000	1096.667	98.625	increasing
TDS	0.352	0.027	74.000	210.000	1096.667	98.625	increasing
SO4	0.062	0.717	13.000	209.499	1095.667	64.152	no trend
NO3	0.095	0.566	20.000	210.000	1096.667	71.693	no trend
Pb	-0.537	0.003	-79.000	147.071	686.333	99.855	decreasing
Mn	0.412	0.026	51.000	123.814	506.333	98.686	increasing
E. coli	0.242	0.142	49.000	202.361	1068.333	92.902	likely increasing
Faecal coliforms	0.225	0.164	47.000	208.495	1093.000	91.795	likely increasing
Total coliforms	0.019	0.928	4.000	207.990	1092.000	53.617	no trend
Cu	0.283	0.133	31.000	109.407	399.667	93.327	likely increasing
Salinity	0.324	0.043	68.000	210.000	1096.667	97.847	increasing

4.6 ADW Quality Assessment for Irrigation

Since this study aimed at assessing the possible reusability of ADW for irrigation on the Pandamatenga farms, it was critical to determine the quality of the water for the specific purpose of irrigation and how this water would affect the soil and crops. Besides affecting crop yield and soil physical conditions, assessing irrigation water quality can help in determining fertility needs, irrigation system performance and longevity, and how the water can be applied. This study primarily focused on using the Irrigation Water Quality Index (IWQI) developed by Meireles et al., (2010) to determine the quality and suitability of ADW as irrigation water. Other water quality indices which influence water quality and its suitability for irrigation include Sodium Absorption Ratio (SAR), Soluble Sodium Percentage (SSP), Permeability Index (PI), and Soluble Magnesium Percentage (%Mg).

4.6.1 Irrigation Water Quality Index

The Irrigation Water Quality Index (IWQI) was calculated according to Equation 2. The water suitability for irrigation was based on the five physicochemical parameters of EC, SAR, Na^+, Cl^-, and HCO_3^-. The concentration units of the selected parameters were converted from (mg/L) to (meq/L) before starting data analysis, according to the conversion factors given by Lesch and Suarez (2009).

The computed IWQI values during the course of the four months ranged from 22.7 to 51.7, with a mean value of 28.6 (Table 9). Accordingly, 95% of the samples that were analyzed fell within the severe restriction range, which restricts the usage of the ADW to irrigating only plants with a high tolerance to salt (Appendix 1), while foregoing irrigation under normal circumstances with an exception for waters with extremely low values of Na^+, Cl^- and HCO_3^-. Only 5% of the samples under investigation fell under the moderate restriction that limits the use of ADW for moderate salt-tolerance plants and calls for moderate to high permeable soil, considering moderate soil leaching processes. No samples were identified with no restriction range.

Although most of the analysed parameters were below permissible levels, the low levels of EC and SAR detected during the study period imply that there is a mineral imbalance, thus making the ADW unsuitable for reuse. This is according to studies developed by Pearson and Bauder, (2006), De Nys et al., (2002), and Rhoades et al., (1992) that considered the concentration of salts in irrigation water, showing the importance of the balance of salts and excessive leaching of the stability of soil aggregates that might cause problems of reduced infiltration, reduced hydraulic conductivity and/or presence of surface crust.

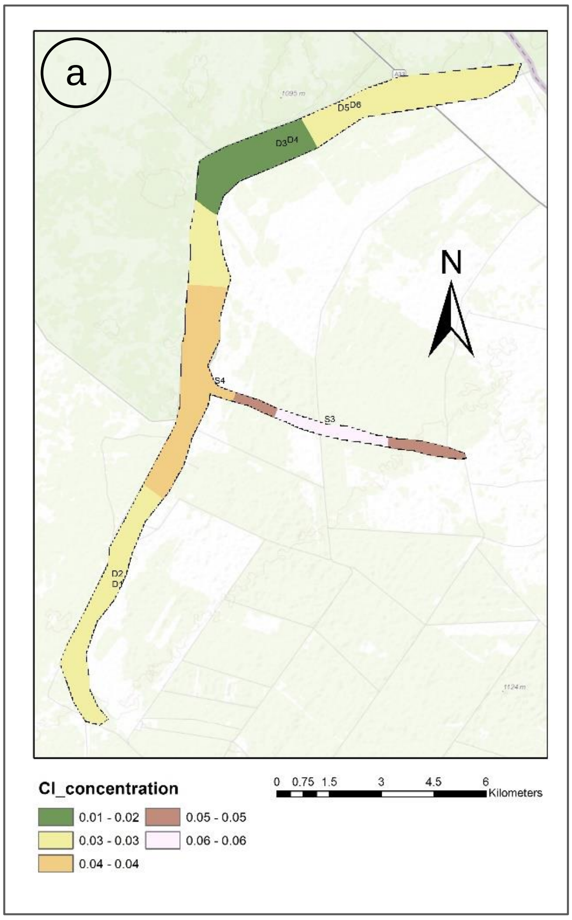
Table 9: Calculated Irrigation Water Quality Index (IWQI)

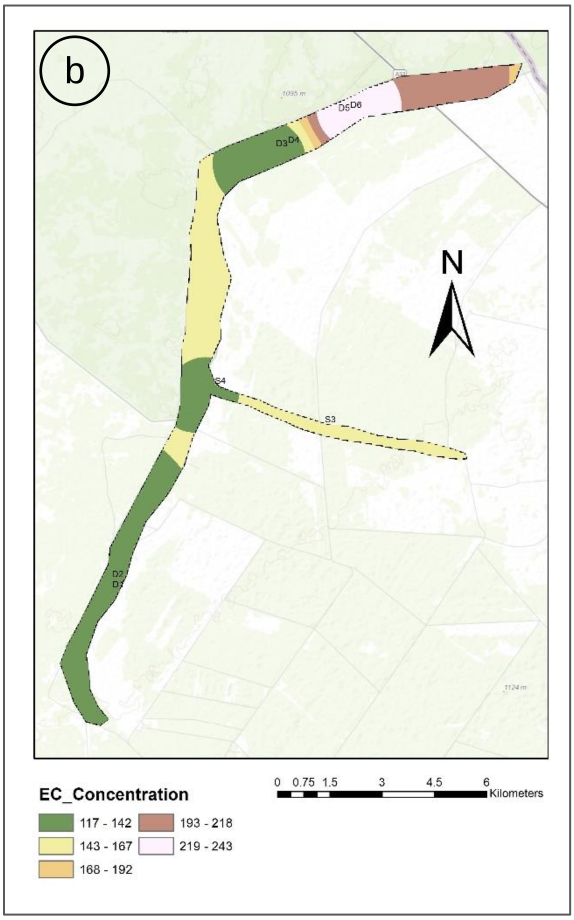
Site_no	**Sampling date**	**SAR$_{adj}$**	**Na$^+$**	**Cl$^-$**	**EC**	**HCO$_3^-$**	**IWQI**	**Type of restriction**
Site D1	21/04/2022	0.468	29.829	34.152	21.225	26.360	27.9	Severe restriction
Site D2	21/04/2022	0.176	32.419	34.322	20.996	25.120	28.9	Severe restriction
Site D3	21/04/2022	0.353	31.182	34.341	24.014	24.264	28.6	Severe restriction
Site D4	21/04/2022	0.346	31.735	34.484	24.929	26.360	29.4	Severe restriction
Site D5	21/04/2022	0.173	32.789	34.096	22.265	26.360	29.4	Severe restriction
Site D6	21/04/2022	0.425	30.290	34.218	22.422	25.419	28.1	Severe restriction
Site S3	21/04/2022	0.321	31.432	33.634	23.956	24.264	28.6	Severe restriction
Site S4	21/04/2022	0.292	31.068	33.634	20.588	24.264	27.9	Severe restriction
Site D3	23/05/2022	0.474	30.188	34.784	23.140	28.468	28.7	Severe restriction
Site D4	23/05/2022	0.460	30.159	34.862	23.498	28.468	57.1	Moderate restriction
Site D5	23/05/2022	0.511	27.959	34.058	19.434	24.264	26.6	Severe restriction
Site D6	23/05/2022	0.504	27.886	34.105	19.358	24.264	26.6	Severe restriction
Site S3	23/05/2022	0.432	27.818	32.252	16.949	23.991	25.8	Severe restriction
Site D3	13/07/2022	0.310	30.972	34.668	20.772	26.360	28.5	Severe restriction
Site D4	13/07/2022	0.408	30.064	34.629	19.199	25.120	27.5	Severe restriction
Site D5	13/07/2022	0.555	24.690	34.002	11.254	17.575	22.7	Severe restriction
Site D6	13/07/2022	0.554	25.087	33.928	11.094	22.612	23.8	Severe restriction
Site D3	31/08/2022	0.740	24.491	34.446	20.784	23.084	25.6	Severe restriction
Site D4	31/08/2022	0.363	31.242	34.745	20.710	25.120	28.2	Severe restriction
Site D5	31/08/2022	0.332	30.013	33.937	15.086	26.198	26.9	Severe restriction
Site D6	31/08/2022	0.600	24.005	33.753	15.021	21.228	24.0	Severe restriction

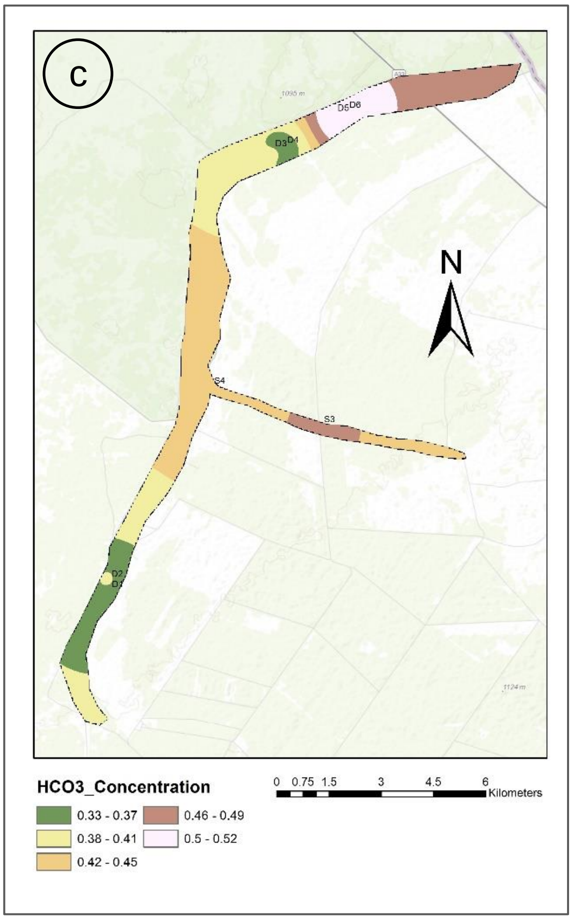
The computed IWQI values were further subjected to IDW interpolation in order to generate spatial maps that show the distribution trend of the selected parameters within the drainage channel. The IDW method was carried out using the Spatial Analyst Extension of ArcGIS (Version 10.7). The mean of the data collected for each of the five parameters (i.e. EC, SAR, Na^+, Cl^-, HCO_3^-) from the sampled points was used in the calculation of each interpolated cell while the drainage channel was used for the mask. From the spatial maps (Figures 23a-e) it can be deduced that the concentrations of the tested parameters steadily increased from the southern to the northern direction. This trend follows the direction of water flow and also the fact that the water in the drainage channel was drying up from the south to the north.

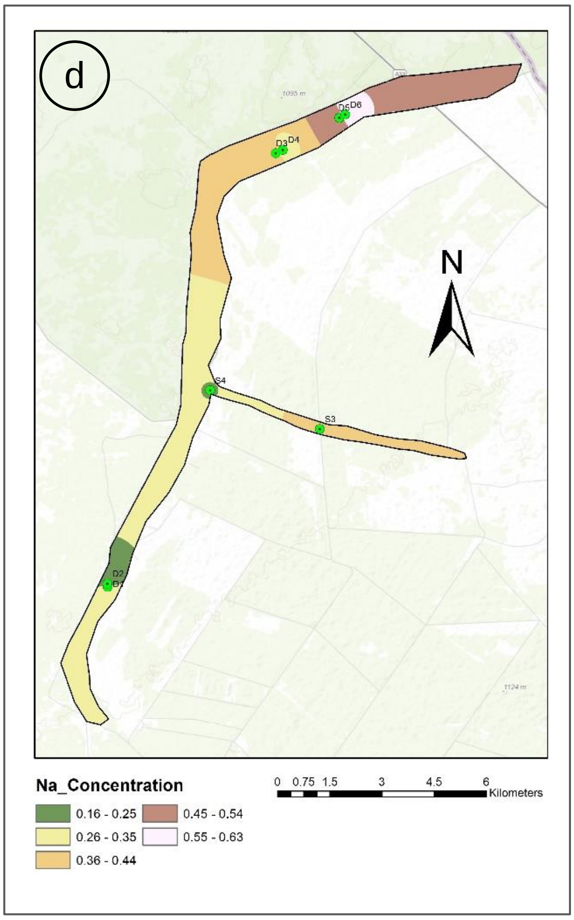
It can also be deduced that as the water flows within the drainage channel, it carries along with it all sorts of contaminants it picks up on its way and this leads to a build-up in concentrations of the various parameters downstream of the channel. Figure 24 indicates that the ADW from the biggest part of the study area falls under the severe restriction category and therefore its use for irrigation should be avoided under normal conditions. In special cases, the water may be used but on specific plants. The same figure shows that a small section within the study area has got ADW which falls under the high restriction category, suitable to be used on plants with moderate to high tolerance to salts with special salinity control practices. It is noteworthy that after the rainy season, steady water flow within the drainage channel ceases and this leads to the formation of water pools within the channel. The pool that holds ADW for the longest time is located at the sampling points D3 and D4 (Figure 24). This explains why the ADW at this location is not as bad as the rest of the locations since it has been deduced that the volume of water within the channel has got a trickledown effect on the ion concentrations pertained in the water.

Figure 24 depicts the regional distribution of the IWQI within the drainage channel and might be viewed as a general map of suitability for supplying irrigation water from the drainage channel. It is now much simpler for a decision maker to evaluate the quality of ADW for irrigation purposes and further locate the best suitable place for drawing the water since the map provides the spatial distribution of ADW quality in plain as index values.


a
D5 D6
D3 D4
S4
S3
D2
D1
N
Cl_concentration
0.01 - 0.02
0.05 - 0.05
0.03 - 0.03
0.06 - 0.06
0.04 - 0.04
0 0.75 1.5 3 4.5 6 Kilometers


b
D5 D6
D3 D4
S4
S3
D2
D1
N
EC_Concentration
117 - 142
193 - 218
143 - 167
219 - 243
168 - 192
0 0.75 1.5 3 4.5 6 Kilometers


c
D5 D6
D3 D4
S4
S3
D2
D1
N
HCO3_Concentration
0.33 - 0.37
0.46 - 0.49
0.38 - 0.41
0.5 - 0.52
0.42 - 0.45
0 0.75 1.5 3 4.5 6 Kilometers


d
D5 D6
D3 D4
S4
S3
D2
D1
N
Na_Concentration
0.16 - 0.25
0.45 - 0.54
0.26 - 0.35
0.55 - 0.63
0.36 - 0.44
0 0.75 1.5 3 4.5 6 Kilometers

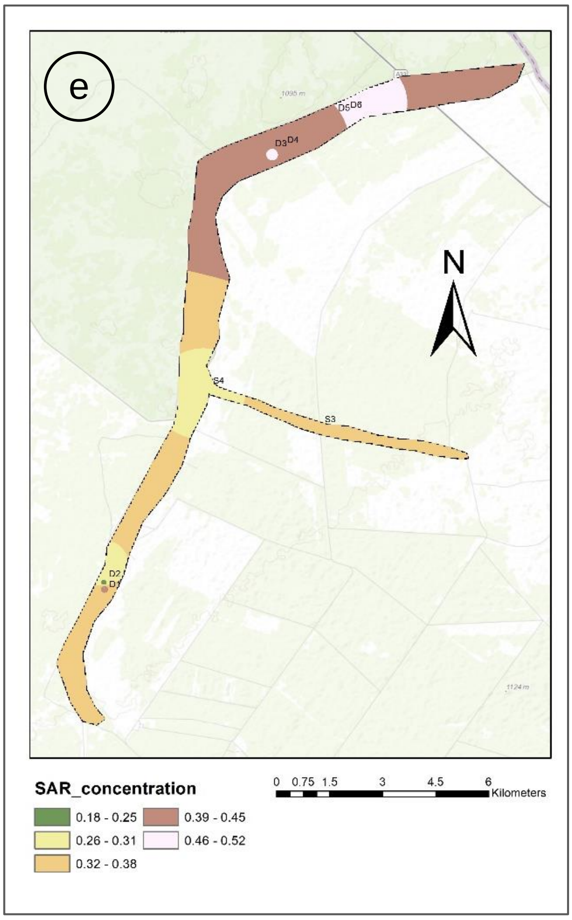


Figure 23 (a – e): Spatial maps for the parameters used to compute the IWQI i.e Cl^{-}, EC, HCO_3^{-}, Na^{+} and SAR.

Figure 24: Combined parameter maps to generate a single IWQI map

4.6.2 Adjusted Sodium Adsorption Ration (SAR_{adj})

Adjusted SAR was computed using equation 4 depending on the ion concentrations of sodium, calcium, and magnesium (all ionic concentrations are represented in milli-equivalent per litre). Table 9 shows the SAR_{adj} level for each ADW sampled during the study. The SAR_{adj} values were in the range of 0.17 to 0.74 with a mean value of 0.42. All of the ADW samples fall under the excellent category of the classification system developed by Richards, (1954) based on values in Table 4. The life of vegetation is typically not threatened by SAR levels below 3.0 but is seriously threatened by SAR levels above 12.0, which reduce soil permeability and cause an increase in soil swelling or dispersion. SAR can indicate the degree to which irrigation water tends to enter cation exchange reactions in the soil. The replacement of calcium and magnesium with sodium is hazardous because it causes damage to the soil structure by making the soil compact and impervious (Rosu et al., 2014).

4.6.3 Soluble Sodium Percentage (SSP)

The SSP is an important parameter that can be used to evaluate the ADW quality and its appropriateness for irrigation purposes. The SSP was calculated, based on sodium, calcium and magnesium concentrations in the collected samples, using equation 7 where all ionic concentrations are expressed in milliequivalents per litre. The SSP ranged between 8.23 and 24.93 (Table 10). Based on the Wilcox, (1955) classification of irrigation water as shown in Table 5, 48% of the tested samples belonged to the excellent category whereas 52% belonged to the good category. The low level of sodium implies that the ADW does not pose threat to vegetation as well as the soil and can be cautiously used for agricultural purposes as irrigation water.

4.6.4 Permeability Index (PI)

A permeability index-based criterion was developed by WHO, (1989) to determine whether water is suitable for irrigation. Accordingly, the PI is classified under Class I (>75 %), Class II (25–75 %), and Class III (>25 %) orders. The PI in this study ranged between 21.98% and 90.07% with an average of 53.97%. Based on the results shown in Table 10, 19% of the tested samples fell under Class I and 81% of the samples were categorised under Class II. Class I and Class II waters are categorized as good for irrigation with 75% or more of maximum permeability.

4.6.5 Soluble Magnesium Percentage (%Mg)

A magnesium percentage of irrigation water of more than 50% is considered to be harmful and unsuitable for irrigation use. This would adversely affect the crop yield, as soils become more alkaline. The magnesium ratio values of the study area ranged from 10.96 to 43.27. All the ADW samples tested (Table 10) have a magnesium percentage below 50 which implies that the ADW can be cautiously used for irrigation.

Table 10: Other calculated indices including SSP, PI and Mg%

Site no.	Calcium (meq/L)	Magnesium (meq/L)	Sodium (meq/L)	Chloride (meq/L)	HCO_3 (meq/L)	SSP	PI	Mg%
D1	0.83	0.32	0.35	0.02	0.33	23.05	61.11	28.00
D2	1.40	0.38	0.16	0.02	0.39	8.23	40.66	21.28
D3	0.57	0.24	0.24	0.02	0.44	23.23	86.35	29.69
D4	0.46	0.20	0.21	0.01	0.33	23.81	90.07	30.49
D5	1.05	0.31	0.13	0.03	0.33	9.01	47.27	22.66
D6	0.74	0.29	0.31	0.02	0.38	23.21	69.03	27.74
S3	0.51	0.33	0.23	0.04	0.44	21.30	83.70	39.33
S4	1.00	0.43	0.25	0.04	0.44	15.00	54.43	30.06
D3	0.82	0.30	0.32	0.01	0.23	22.16	55.44	27.17
D4	0.94	0.31	0.32	0.00	0.23	20.44	50.93	24.69
D5	1.40	0.57	0.50	0.03	0.44	20.34	47.20	29.11
D6	1.50	0.60	0.51	0.03	0.44	19.48	44.89	28.64
S3	1.85	1.13	0.52	0.09	0.46	14.75	34.11	37.92
D3	1.21	0.40	0.26	0.01	0.33	13.91	44.53	25.10
D4	0.77	0.46	0.33	0.01	0.39	21.05	61.25	37.61
D5	1.95	1.49	0.84	0.03	0.99	19.51	42.77	43.27
D6	2.73	1.49	0.79	0.03	0.55	15.79	30.57	35.29
D3	1.58	1.01	0.86	0.02	0.52	24.93	45.80	38.90
D4	0.62	0.17	0.24	0.01	0.39	23.35	84.23	21.26
D5	2.49	0.31	0.33	0.03	0.34	10.63	29.18	10.96
D6	3.90	0.95	0.92	0.04	0.65	15.89	29.85	19.62

4.7 Correlation of water quality parameters

In the present study, the correlation coefficients (r) among various water quality parameters were calculated using the Mann-Kendall Test and the numerical values of correlation coefficients (r) are tabulated in Table 11. The degree of line association between any two of the water quality parameters as measured by the simple correlation coefficient (r) is presented as a 19 x 19 correlation matrix. According to the results, EC and TDS; EC and

Mg^{2+}; EC and salinity; Mg^{2+} and TDS; salinity and TDS; Na^{+} and Mg^{2+}; Mg^{2+} and salinity; Ca^{2+} and Faecal coliform; SO$_4^{(2-)}$ and E. coli; Faecal coliform and SO$_4^{(2-)}$; and E. coli and Faecal coliform indicate high correlations (above 0.8). Out of the 190 correlation coefficients, 11 correlation coefficients (r) are found to be with highly significant levels ($0.8< r < 1.0$), and 29 values of r belong to the moderate significant coefficient levels ($0.6< r < 0.8$), 10 correlation coefficients fit within the significant coefficient levels ($0.5< r < 0.6$) of r values. Out of all the correlation coefficients, 130 cases were calculated as positive correlations making a percentage of 68.4% while 60 cases were calculated as negative correlations to make a percentage of 31.6%. In summary, high correlation coefficient between water quality parameters illustrates that EC, TDS, Mg^{2+}, Salinity and Faecal coliforms had significant interaction with other parameters. Therefore, these five parameters had high concentrations as a result of natural occurrences as well as anthropogenic activities. Figure 25 below further classifies the analysed parameters with respect to the correlation strength. The blue colour signifies a positive correlation while the burgundy colour signifies a negative correlation. The stronger the colour the stronger the correlation and vice versa.

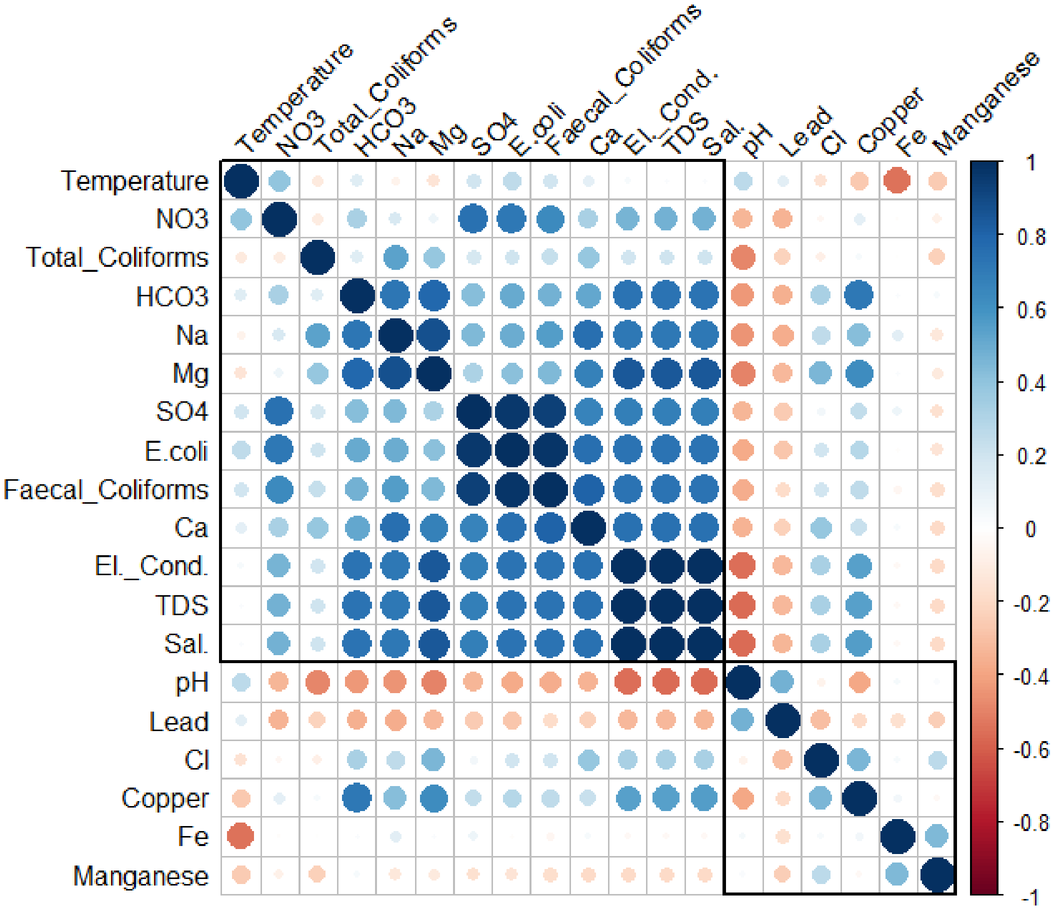


Figure 25: Combined parameter maps to generate a single IWQI map

Table 11: Correlation coefficient (r) among the analysed water quality parameters

	pH	***Temp***	***EC***	***TDS***	***Na***	***Mg***	***Ca***	***Mn***	***Fe***	***Cu***	***Pb***	***Cl***	***SO4***	***HCO3***	***NO3***	***Sal***	***E.coli***	***Faecal coliform***	***Total coliform***
pH	1																		
Temp	0.262817	1																	
EC	-0.55882	0.032334	1																
TDS	-0.5614	0.026901	0.999784	1															
Na	-0.44733	-0.06384	0.714824	0.715681	1														
Mg	-0.49182	-0.14467	0.843188	0.842968	0.873289	1													
Ca	-0.34971	0.110642	0.744278	0.743111	0.751691	0.675577	1												
Mn	0.028977	-0.25806	-0.1929	-0.19123	-0.12975	-0.11618	-0.19234	1											
Fe	0.041752	-0.54924	-0.03589	-0.03134	0.128033	0.022403	0.035106	0.448066	1										
Cu	-0.38231	-0.26663	0.547798	0.548289	0.423761	0.627819	0.22041	-0.03871	0.050138	1									
Pb	0.473939	0.121815	-0.32104	-0.32766	-0.36497	-0.32275	-0.23785	-0.24715	-0.16966	-0.19773	1								
Cl	-0.06001	-0.15588	0.32425	0.320854	0.253788	0.45925	0.384171	0.264629	0.033003	0.453439	-0.30545	1							
SO4	-0.33688	0.197776	0.681309	0.682151	0.442023	0.319919	0.660519	-0.16064	0.076252	0.243366	-0.25865	0.058086	1						
HCO3	-0.4391	0.135009	0.738976	0.735764	0.72732	0.783012	0.512487	0.035056	0.023084	0.710892	-0.3551	0.325613	0.422792	1					
NO3	-0.33251	0.396791	0.466844	0.470362	0.162807	0.076734	0.32354	-0.07221	-0.01171	0.118226	-0.3493	-0.0419	0.749549	0.326544	1				
Sal	-0.56435	0.027153	0.999689	0.999888	0.716928	0.843115	0.743211	-0.19171	-0.03209	0.550867	-0.33189	0.326063	0.683847	0.737083	0.475201	1			
E. coli	-0.37778	0.253227	0.734554	0.734404	0.49441	0.412003	0.757684	-0.14706	-0.01847	0.280987	-0.2727	0.196177	0.967154	0.50509	0.718458	0.736597	1		
Faecal_coliform	-0.36938	0.19279	0.735212	0.735144	0.551231	0.446639	0.807373	-0.17922	-0.04721	0.258414	-0.1816	0.190372	0.935561	0.472639	0.637863	0.736737	0.976649	1	
Total_coliform	-0.48543	-0.11956	0.197292	0.200906	0.532472	0.383837	0.38764	-0.23998	-0.00932	0.033245	-0.22748	-0.08746	0.173532	0.137397	-0.10736	0.201391	0.204501	0.237565	1

5.0 Conclusion and recommendations

5.1 Conclusion

1) The analysis of ADW samples collected in the months of April, May, July and August 2022, from different locations along the drainage channels within the northern plain of Pandamatenga Commercial Arable Farms in the Chobe district of Botswana revealed that almost all water quality parameters (pH, electrical conductivity, TDS, salinity, temperature, calcium, magnesium, sodium, chloride, nitrate, sulphate, and bicarbonate) are below the permissible limit as per BOS 463: 2011 and BOS 93: 2012 standards.

2) The heavy metals which were analysed (copper, iron, lead and manganese) were non-detectable in most of the samples with some only having insignificant values way below the BOS standards. In comparison to all other parameters, there is an acute problem of extremely high levels of Total coliforms, E. coli and faecal coliforms.

3) Only 28.6% of ADW samples had no trace of E. coli content and the remaining 71.4% of samples were having very high E. coli concentrations. Similarly, 38.1% and 80.9% of the analysed parameters had low levels of Faecal coliform and Total coliforms respectively, while the rest of the percentages exceeded the permissible limits. Such high values are attributed to the wild and domestic animals that drink from the drainage channel and end up leaving their droppings in the water.

4) The tested hypothesis also revealed that there is no significant relationship between the quality of water within the main drainage channel as a result of the runoff coming from the different sub-drainages of the farms. The IWQI values computed from the five parameters of SAR, EC, sodium, chloride and bicarbonate during the course of the four months of sampling ranged from 22.7 to 51.7, with a mean value of 28.6. Accordingly, 95% of the samples that were analysed fell within the “severe restriction” range, 5% of the samples under investigation fell under the “moderate restriction” and no ADW samples belonged to the “no restriction” category. Although 84% of the analysed ADW passes the quality mark of the wastewater and irrigation standards, the low levels of EC and SAR detected during the study period imply that there is a mineral imbalance, thus making the ADW unsuitable for direct reuse. Additionally, the

high levels of microbiological parameters indicate that irrigating “ready-to-eat” crops with such ADW increases the risk of food-borne diseases. Therefore, using this ADW will require mixing it in proper ratios with pure water to improve its quality for reusability during irrigation or using the ADW with trickle or drip irrigation systems since they present a lower risk for potential contamination of crops as compared to an overhead spray system.

5.2 Recommendations

1) The monitoring and analysis should be done over a longer period of time, spanning both the wet and dry seasons, in order to conduct a thorough investigation of the ADW quality within the study area. A set of data must be collected over a minimum of one to two years throughout this monitoring in order to verify the validity of the study.
2) Conducting a study on the cost of recovery of the ADW and the benefits that can be achieved by doing so will be worth trying.

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Appendix 1: Relative salt tolerance of agricultural crops (Ayers and Westcot, 1985)

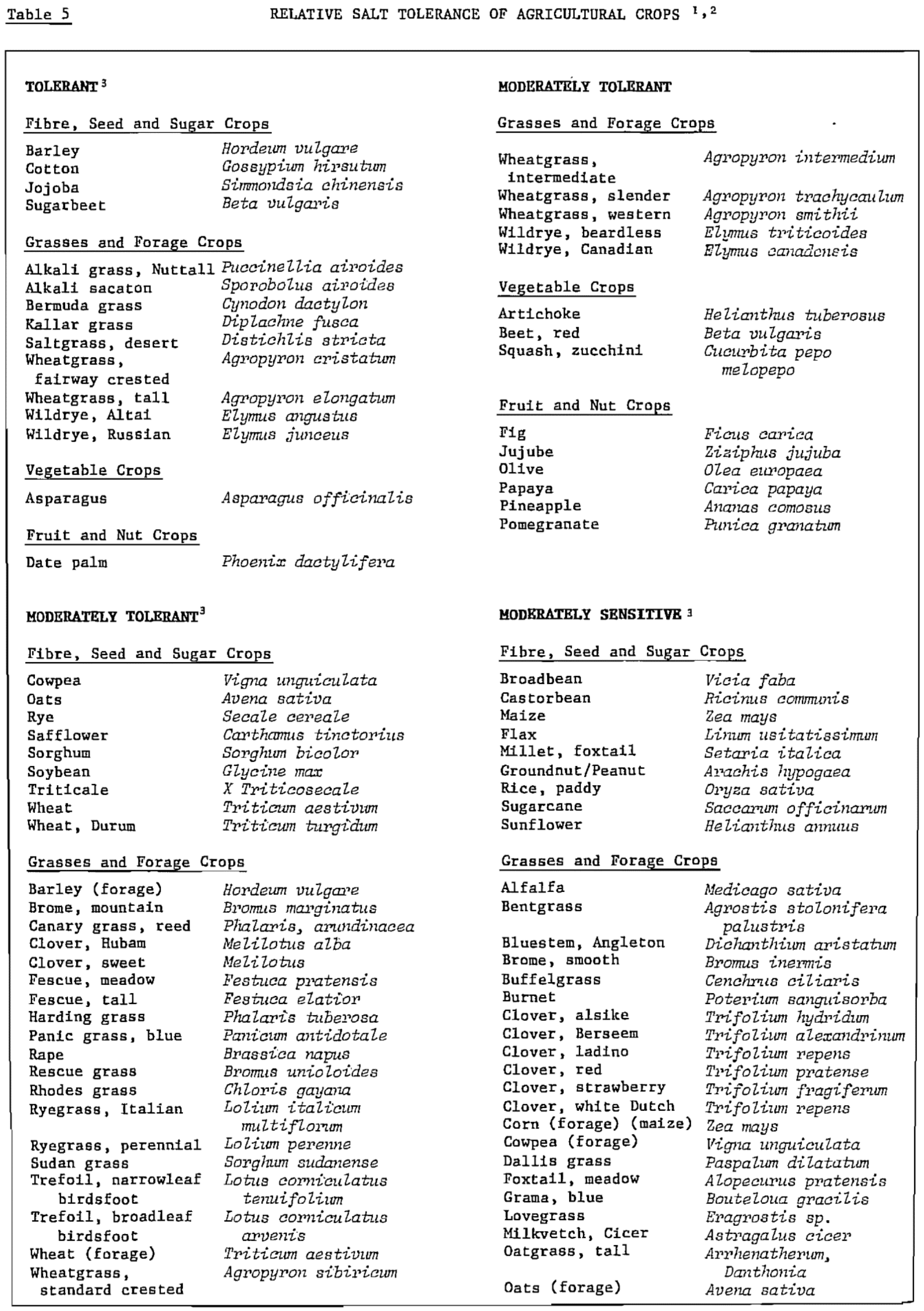

Table 5 RELATIVE SALT TOLERANCE OF AGRICULTURAL CROPS [1,2]

TOLERANT [3]

Fibre, Seed and Sugar Crops

Barley	*Hordeum vulgare*
Cotton	*Gossypium hirsutum*
Jojoba	*Simmondsia chinensis*
Sugarbeet	*Beta vulgaris*

Grasses and Forage Crops

Alkali grass, Nuttall	*Puccinellia airoides*
Alkali sacaton	*Sporobolus airoides*
Bermuda grass	*Cynodon dactylon*
Kallar grass	*Diplachne fusca*
Saltgrass, desert	*Distichlis stricta*
Wheatgrass, fairway crested	*Agropyron cristatum*
Wheatgrass, tall	*Agropyron elongatum*
Wildrye, Altai	*Elymus angustus*
Wildrye, Russian	*Elymus junceus*

Vegetable Crops

Asparagus	*Asparagus officinalis*

Fruit and Nut Crops

Date palm	*Phoenix dactylifera*

MODERATELY TOLERANT [3]

Fibre, Seed and Sugar Crops

Cowpea	*Vigna unguiculata*
Oats	*Avena sativa*
Rye	*Secale cereale*
Safflower	*Carthamus tinctorius*
Sorghum	*Sorghum bicolor*
Soybean	*Glycine max*
Triticale	*X Triticosecale*
Wheat	*Triticum aestivum*
Wheat, Durum	*Triticum turgidum*

Grasses and Forage Crops

Barley (forage)	*Hordeum vulgare*
Brome, mountain	*Bromus marginatus*
Canary grass, reed	*Phalaris, arundinacea*
Clover, Hubam	*Melilotus alba*
Clover, sweet	*Melilotus*
Fescue, meadow	*Festuca pratensis*
Fescue, tall	*Festuca elatior*
Harding grass	*Phalaris tuberosa*
Panic grass, blue	*Panicum antidotale*
Rape	*Brassica napus*
Rescue grass	*Bromus unioloides*
Rhodes grass	*Chloris gayana*
Ryegrass, Italian	*Lolium italicum multiflorum*
Ryegrass, perennial	*Lolium perenne*
Sudan grass	*Sorghum sudanense*
Trefoil, narrowleaf birdsfoot	*Lotus corniculatus tenuifolium*
Trefoil, broadleaf birdsfoot	*Lotus corniculatus arvenis*
Wheat (forage)	*Triticum aestivum*
Wheatgrass, standard crested	*Agropyron sibiricum*

MODERATELY TOLERANT

Grasses and Forage Crops

Wheatgrass, intermediate	*Agropyron intermedium*
Wheatgrass, slender	*Agropyron trachycaulum*
Wheatgrass, western	*Agropyron smithii*
Wildrye, beardless	*Elymus triticoides*
Wildrye, Canadian	*Elymus canadensis*

Vegetable Crops

Artichoke	*Helianthus tuberosus*
Beet, red	*Beta vulgaris*
Squash, zucchini	*Cucurbita pepo melopepo*

Fruit and Nut Crops

Fig	*Ficus carica*
Jujube	*Ziziphus jujuba*
Olive	*Olea europaea*
Papaya	*Carica papaya*
Pineapple	*Ananas comosus*
Pomegranate	*Punica granatum*

MODERATELY SENSITIVE [3]

Fibre, Seed and Sugar Crops

Broadbean	*Vicia faba*
Castorbean	*Ricinus communis*
Maize	*Zea mays*
Flax	*Linum usitatissimum*
Millet, foxtail	*Setaria italica*
Groundnut/Peanut	*Arachis hypogaea*
Rice, paddy	*Oryza sativa*
Sugarcane	*Saccarum officinarum*
Sunflower	*Helianthus annuus*

Grasses and Forage Crops

Alfalfa	*Medicago sativa*
Bentgrass	*Agrostis stolonifera palustris*
Bluestem, Angleton	*Dichanthium aristatum*
Brome, smooth	*Bromus inermis*
Buffelgrass	*Cenchrus ciliaris*
Burnet	*Poterium sanguisorba*
Clover, alsike	*Trifolium hydridum*
Clover, Berseem	*Trifolium alexandrinum*
Clover, ladino	*Trifolium repens*
Clover, red	*Trifolium pratense*
Clover, strawberry	*Trifolium fragiferum*
Clover, white Dutch	*Trifolium repens*
Corn (forage) (maize)	*Zea mays*
Cowpea (forage)	*Vigna unguiculata*
Dallis grass	*Paspalum dilatatum*
Foxtail, meadow	*Alopecurus pratensis*
Grama, blue	*Bouteloua gracilis*
Lovegrass	*Eragrostis sp.*
Milkvetch, Cicer	*Astragalus cicer*
Oatgrass, tall	*Arrhenatherum, Danthonia*
Oats (forage)	*Avena sativa*

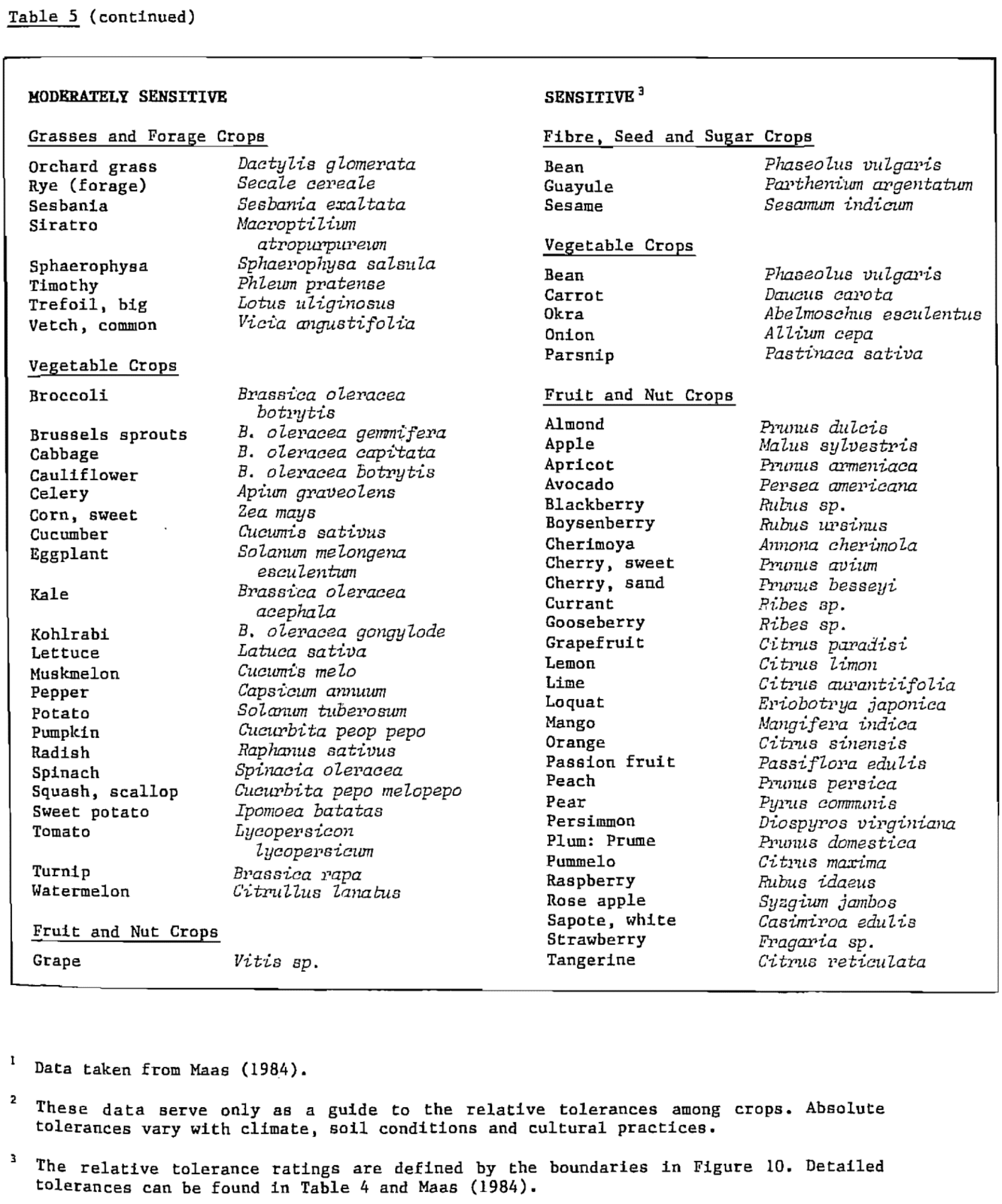

Table 5 (continued)

MODERATELY SENSITIVE

Grasses and Forage Crops

Orchard grass	*Dactylis glomerata*
Rye (forage)	*Secale cereale*
Sesbania	*Sesbania exaltata*
Siratro	*Macroptilium atropurpureum*
Sphaerophysa	*Sphaerophysa salsula*
Timothy	*Phleum pratense*
Trefoil, big	*Lotus uliginosus*
Vetch, common	*Vicia angustifolia*

Vegetable Crops

Broccoli	*Brassica oleracea botrytis*
Brussels sprouts	*B. oleracea gemmifera*
Cabbage	*B. oleracea capitata*
Cauliflower	*B. oleracea botrytis*
Celery	*Apium graveolens*
Corn, sweet	*Zea mays*
Cucumber	*Cucumis sativus*
Eggplant	*Solanum melongena esculentum*
Kale	*Brassica oleracea acephala*
Kohlrabi	*B. oleracea gongylode*
Lettuce	*Latuca sativa*
Muskmelon	*Cucumis melo*
Pepper	*Capsicum annuum*
Potato	*Solanum tuberosum*
Pumpkin	*Cucurbita peop pepo*
Radish	*Raphanus sativus*
Spinach	*Spinacia oleracea*
Squash, scallop	*Cucurbita pepo melopepo*
Sweet potato	*Ipomoea batatas*
Tomato	*Lycopersicon lycopersicum*
Turnip	*Brassica rapa*
Watermelon	*Citrullus lanatus*

Fruit and Nut Crops

Grape	*Vitis sp.*

SENSITIVE[3]

Fibre, Seed and Sugar Crops

Bean	*Phaseolus vulgaris*
Guayule	*Parthenium argentatum*
Sesame	*Sesamum indicum*

Vegetable Crops

Bean	*Phaseolus vulgaris*
Carrot	*Daucus carota*
Okra	*Abelmoschus esculentus*
Onion	*Allium cepa*
Parsnip	*Pastinaca sativa*

Fruit and Nut Crops

Almond	*Prunus dulcis*
Apple	*Malus sylvestris*
Apricot	*Prunus armeniaca*
Avocado	*Persea americana*
Blackberry	*Rubus sp.*
Boysenberry	*Rubus ursinus*
Cherimoya	*Annona cherimola*
Cherry, sweet	*Prunus avium*
Cherry, sand	*Prunus besseyi*
Currant	*Ribes sp.*
Gooseberry	*Ribes sp.*
Grapefruit	*Citrus paradisi*
Lemon	*Citrus limon*
Lime	*Citrus aurantiifolia*
Loquat	*Eriobotrya japonica*
Mango	*Mangifera indica*
Orange	*Citrus sinensis*
Passion fruit	*Passiflora edulis*
Peach	*Prunus persica*
Pear	*Pyrus communis*
Persimmon	*Diospyros virginiana*
Plum: Prume	*Prunus domestica*
Pummelo	*Citrus maxima*
Raspberry	*Rubus idaeus*
Rose apple	*Syzgium jambos*
Sapote, white	*Casimiroa edulis*
Strawberry	*Fragaria sp.*
Tangerine	*Citrus reticulata*

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[1] Data taken from Maas (1984).

[2] These data serve only as a guide to the relative tolerances among crops. Absolute tolerances vary with climate, soil conditions and cultural practices.

[3] The relative tolerance ratings are defined by the boundaries in Figure 10. Detailed tolerances can be found in Table 4 and Maas (1984).

Appendix 2: Raw analysis results of collected ADW samples

Table A1: Physical, chemical and microbiological parameter results of the ADW

Sample Date	Station Name	pH	Temp	EC	TDS	Na	Mg	Ca	Mn	Fe	Cu	Pb	Cl	SO4	HCO3	NO3	Sal	E.coli	Faecal coliform	Total coliform
21/04/22	D1	7.94	24.80	129.80	95.50	7.97	3.94	16.70	ND	0.10	ND	ND	0.88	6.31	20.00	18.80	60.80	1750.00	2120.00	3000.00
21/04/22	D2	8.26	27.70	133.40	96.50	3.66	4.59	28.00	ND	0.40	ND	0.01	0.70	2.31	24.00	12.14	58.50	ND	ND	ND
21/04/22	D3	8.12	23.40	91.50	61.00	5.63	2.92	11.40	ND	0.01	ND	0.01	0.68	4.80	27.00	4.93	36.40	560.00	640.00	2300.00
23/05/22	D3	7.75	15.60	102.50	75.60	7.33	3.70	16.35	ND	0.16	ND	0.01	0.22	4.32	14.00	2.15	45.10	ND	5400.00	20000.00
13/07/22	D3	6.76	17.00	137.00	101.20	5.98	4.91	24.16	ND	ND	ND	ND	0.34	3.56	20.00	3.78	62.80	390.00	410.00	51000.00
31/08/22	D3	7.52	24.90	136.80	101.10	19.73	12.22	31.65	ND	ND	ND	ND	0.57	2.84	31.50	4.54	62.50	290.33	1090.00	69300.00
21/04/22	D4	8.20	23.40	80.80	60.70	4.73	2.44	9.17	ND	0.04	ND	ND	0.53	4.51	20.00	28.12	36.50	ND	ND	ND
23/05/22	D4	7.78	15.80	97.90	72.50	7.38	3.75	18.86	ND	0.06	ND	ND	0.14	4.32	14.00	0.24	43.00	ND	1600.00	17200.00
13/07/22	D4	6.54	18.40	164.60	121.20	7.55	5.63	15.40	ND	ND	ND	ND	0.38	4.05	24.00	25.76	76.30	650.00	670.00	11200.00
31/08/22	D4	7.43	25.80	138.00	101.90	5.53	2.04	12.46	ND	ND	ND	ND	0.26	4.57	24.00	30.20	63.10	220.00	320.00	5400.00
21/04/22	D5	8.28	23.10	114.40	84.70	3.10	3.75	21.10	ND	0.19	ND	ND	0.94	2.27	20.00	6.61	51.20	1720.00	2060.00	2940.00
23/05/22	D5	7.67	12.90	160.20	119.10	11.58	6.98	28.03	0.01	66.30	ND	ND	0.98	9.47	27.00	16.51	74.80	4000.00	4100.00	20000.00
13/07/22	D5	6.74	21.30	422.00	313.00	19.20	18.12	39.17	ND	ND	0.01	ND	1.04	21.05	60.50	32.43	203.00	14400.00	15200.00	18000.00
31/08/22	D5	7.31	25.60	264.00	195.30	7.64	3.72	49.84	ND	ND	ND	ND	1.11	32.12	20.50	47.66	125.40	21400.00	22400.00	28700.00
21/04/22	D6	8.21	21.40	112.20	83.00	7.15	3.47	14.90	ND	0.03	ND	ND	0.81	6.50	23.00	9.35	50.10	ND	ND	ND
23/05/22	D6	7.62	13.70	161.60	119.70	11.73	7.34	30.15	0.01	50.60	ND	ND	0.93	9.22	27.00	13.29	74.40	1900.00	2600.00	8500.00
13/07/22	D6	7.26	20.60	431.00	319.00	18.17	18.08	54.67	ND	ND	ND	ND	1.12	13.59	33.43	19.62	206.00	8200.00	10800.00	17000.00
31/08/22	D6	7.36	25.50	266.00	195.70	21.06	11.57	78.13	ND	ND	ND	ND	1.31	17.78	39.59	25.69	125.70	14200.00	18600.00	25100.00
21/04/22	S3	7.55	20.30	92.20	67.30	5.22	4.01	10.20	0.02	0.27	ND	ND	1.44	1.82	27.00	17.91	40.90	520.00	890.00	1800.00
23/05/22	S3	7.38	13.50	213.00	156.50	11.87	13.75	37.12	ND	0.05	0.01	ND	3.02	ND	28.00	0.94	100.40	ND	1500.00	19400.00
21/04/22	S4	7.70	23.70	140.00	102.40	5.82	5.24	20.10	0.01	0.22	ND	ND	1.44	2.16	27.00	4.75	62.70	1000.00	1060.00	2150.00
BOS 463:2011		8.40	-	3000.00	2000.00	230.00	-	-	0.20	5.00	0.20	2.00	350.00	200.00	92.00	30.00	-	77.00	1000.00	-
BOS 93:2012		9.00	-	-	2000.0	400.00	-	-	0.10	2.00	1.00	0.05	600.00	-	-	50.00	-	-	1000.00	20,000.00

Appendix 3: Geological information of sampling stations

Table A2: Geological information of sampling stations

Station Name	Geology	Latitude	Longitude	Elevation
D1	vertisols	-18.5732	25.4661	1073
D2	vertisols	-18.5724	25.4660	1072
D3	vertisols	-18.4611	25.5095	1058
D4	vertisols	-18.4602	25.5113	1058
D5	vertisols	-18.4519	25.5259	1057
D6	vertisols	-18.4511	25.5274	1057
S3	vertisols	-18.5324	25.5209	1080
S4	vertisols	-18.5224	25.4925	1059