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The Characterisation of Borehole Water Properties and Soil Salinity Across Seasons for the Period 2016-2020 with Some Links to Rainfall and Sugarcane Yield in the Makhathini Irrigation Scheme, KwaZulu-Natal

by

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DECLARATION

I hereby declare that this work is my own. It is being submitted for the research report component of the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

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____09th____ day of ____May____ 2023____ at ____Pretoria____

ABSTRACT

The sugar business in South Africa has a strong socioeconomic development focus in rural regions, creating jobs, giving a source of revenue, and constructing transportation and communication networks. Despite its benefits, the sugar sector has faced several obstacles mostly by Small-Scale Growers (SSGs), which have led to a decline in sugarcane production. This study analysed borehole water properties such as electrical conductivity, water levels, and temperature at the Makhathini Irrigation Scheme in KwaZulu-Natal. The quality of water from the Jozini/Pongola Dam used for irrigation was also analysed, in addition to the salinity levels of the soil at the irrigation scheme. Water from nineteen (19) boreholes within the irrigation scheme between 2016 and 2020 was collected every three months from January and tested. Annual water quality data collected upstream (PR1) and downstream (PR2) of the dam were obtained from the Department of Water and Sanitation. One kilogram of soil was collected from six sampling points, respectively, within the Makhathini Irrigation Scheme and sent for testing at the Agricultural Research Council Institute of Soil Water and Climate. Rainfall data and annual sugarcane yield data were obtained and analysed. The ANOVA results showed a significant ($p < 0.05$) difference in electrical conductivity (EC) between all 19 boreholes in the five-year data. The Tukey test also confirmed the electrical conductivity's significant ($p < 0.05$) variation across all boreholes during dry and wet seasons. The borehole water level analysis shows that no significant ($p > 0.05$) difference was observed in dry seasons, but there was a significant difference in the wet seasons. The Tukey test also confirmed that the borehole water levels varied significantly during the wet season for the five-year study period, suggesting that the water levels were shallow in the wet seasons compared to the dry season. The borehole water temperature analysis indicates no significant ($p > 0.05$) difference for all seasons from 2016 to 2020. The water collected at PR1 suggests that the water from the dam is of acceptable quality for irrigation, while the return flow to the Pongola River at sampling point PR2 had high SAR, EC, and PO_4^- concentrations. Samples collected downstream (PR2) show signs of pollution. This suggests that water contamination occurs when water passes through the Makhathini Irrigation Scheme. A *t*-test analysis reveals that pH, NO_3^-, and NO_2 have no significant ($p > 0.05$) difference, but SAR, EC and PO_4^- were significant ($p < 0.05$). The measured parameters were compared to the Department of Water Affairs and Forestry standards for the quality of water used in agricultural irrigation. The correlation analysis between rainfall, borehole electrical conductivity, borehole water levels, and sugarcane yields revealed that while rainfall influenced borehole electrical conductivity, water levels, and sugarcane yield, the effect was minimal, possibly due to irrigation volumes. Rainfall had a positive effect on sugarcane production and EC but a negative effect on water levels. Soil salinity analysis demonstrated an increase in the soil's electrical conductivity with each passing year. The ANOVA analyses for sugarcane yield and soil salinity reveal statistically significant differences ($p < 0.05$). The accumulation of salts in the soil at the Makhathini Irrigation Scheme, also seen by the contaminated return flow to the Pongola River, reduces sugarcane yields. Water properties of the sugarcane irrigation water affect the soil salinity in the irrigation scheme and, consequently, the decline in sugarcane production by small-scale growers.

Keywords: Makhathini Irrigation Scheme; Salinity; Waterlogging; Electrical Conductivity; Water Level; Irrigation Water Quality; Rainfall; Sugarcane; Yield.

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LIST OF ABBREVIATIONS

Acronym	Description
AMJ	April May June
ANOVA	Analysis of Variance
ARC-ISWC	Agricultural Research Council - Institute of Soil Water and Climate
BH-EC	Borehole Electrical Conductivity
BH-WL	Borehole Water Level
Ca^{2+}	Calcium
Cl^{-}	Chlorine
CO_3^{2-}	Carbonate
CV	Coefficient of Variation
DAFF	Department of Agriculture Forestry and Fisheries
DALRRD	Department of Agriculture Land Reform and Rural Development
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
ET	Evapotranspiration
GDP	Gross Domestic Product
HCO_3^{-}	Bicarbonate
JAS	July August September
JFM	January February March
K^{+}	Potassium
KZNDARD	KwaZulu-Natal Department of Agriculture and Rural Development
M	Metre
Mg^{2+}	Magnesium
Mm	Milimetre
mS/m	milliSiemens per metre
Na^{+}	Sodium
NH_4^{+}	Ammonium
NO_2	Nitrite
NO_3^{-}	Nitrate
OND	October November December
PO_4^{-}	Phosphate
PR	Pongola River
SAR	Sodium Adsorption Ratio
SASA	South African Sugar Association
SASRI	South African Sugarcane Research Institute
SAWQ	South African Water Quality
SD	Standard Deviation
SO_4^{2-}	Sulphate
SSGs	Small-Scale Growers
TLC	Temperature Level and Conductivity Meter
USDA	United States Department of Agriculture

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Sugarcane is recognised as a vital crop worldwide because of its widespread usage in people's daily lives and its industrial application for gastronomic and economic sustenance (SASA, 2012). All around the world, in the tropics and subtropics, sugarcane is grown as an important cash crop. (Moore and Botha, 2013). According to the Fair Labour Association (2012), sugarcane is planted on roughly 28.3 million hectares in over 90 countries, with a total production of nearly 1.69 billion tonnes. The sugar business in South Africa has been described as having a strong socio-economic development focus in rural regions, creating jobs, giving a source of revenue, and constructing transportation and communication networks (Sibiya and Hurly, 2011). According to the Department of Agriculture, Forestry and Fisheries (DAFF) (2014), South Africa is the continent's biggest sugarcane producer, with less than 400 000 hectares of land producing around 20 million tonnes of sugarcane yearly (Muir *et al*., 2010). Sugarcane growers in South Africa number around 26400 and are spread across KwaZulu-Natal, Mpumalanga, and the Eastern Cape provinces. Over 25000 of the 26400 sugarcane growers are small-scale, generating around 10% of the total crop. Large-scale growers (about 1400) account for roughly 83 percent (%) of the overall sugarcane harvest, while milling businesses with their sugar estates account for about 7%. Most of the sugar belt receives enough rainfall to grow sugarcane without irrigation; however, about 30% of the total production is produced with irrigation in sections of northern KwaZulu-Natal and Mpumalanga (DAFF, 2014).

Drought harms crop productivity, putting global food security in jeopardy. On the other hand, irrigation has stabilised food production, yet, agricultural water resources have been abused and exploited, resulting in widespread waterlogging and salinity (Northey *et al*., 2006). Irrigation is presently in jeopardy because of poor salinity management, resulting in the loss of productive lands worldwide (Dandekar and Chougule, 2010; Stirzacker, 2011). Waterlogging is caused by excessive water application, which raises the water table in farms and nearby fields (Deng and Bailey, 2020; Northey *et al*., 2006). As a result, salts rise to the surface, causing salinity, which impacts the physical and chemical qualities of the soil (Malota and Senzanje, 2016).

Waterlogged soils are soils that have been saturated with water for a long time. They have slower organic matter oxidation and mineralisation of NH_4^+ to NO_2, and the transition of NO_2 to NO_3^- is impeded owing to a shortage of oxygen in the soil, since mineralisation happens best when there is adequate diffusion of oxygen (Rietz and Haynes, 2003). All the pore spaces in submerged soils are filled with water, decreasing aeration of the root zone, and causing crop senescence, which reduces yields. Because wet soils have a higher specific heat capacity than dry soils, the temperature of the soil is increased when it is waterlogged (Gustafson *et al.*, 2020). Furthermore, the longer soil is submerged, the more likely the soil structure will be compromised. This is because the longer the soil remains saturated, the more likely it is that organic matter may be leached deeper into the profile, leaving the inorganic components without binding surfaces (Dal Ferro *et al.*, 2010). Waterlogged soils also show nitrogen deficiencies, and there have been reports of soil pH reversal in these soils. This is the point at which pH rises in acidic soils and falls in alkaline soils. Except for rice, all these characteristics significantly influence field crops due to inadequate aeration and nutrient availability (Nishiuchi *et al*., 2012).

In addition, plant development is stunted or even prevented in salinized soils due to excess salt (Machado and Serralheiro, 2017). Soil salinity reduces the soil's osmotic potential, making water less available for crop absorption (Sheldon *et al.*, 2017). Soil salinity is often caused by excessive water application. Irrigation water, which contains dissolved salts, is one such source of applied water. Salts persist in the soil after evaporation of water from the surface of irrigated crops. Salinity is a big concern in poorly drained soils, depending on the soil type and when groundwater is within 3 m or less of the surface (Rietz and Haynes, 2003; Malota and Senzanje, 2016). In such cases, the water rises to the surface by capillary action and then evaporates off the soil surface instead of percolating through the full soil profile (Marthews *et al.*, 2014). This is especially true in semi-arid areas where there is not enough rainfall to wash the salts deeper in the soil profile, which is common in the lower-lying sections of irrigation schemes (Okur and Örçen, 2020). A study by Chaieb *et al.* (2019) showed that at the lowest points of the depressions, salinity rose as aridity expanded, while as aridity increased at the highest points, salinity reduced. Apart from the natural processes of rock or parent matter weathering, which causes salinity, seawater intrusion around coastal areas and restricted surface evaporation all increase the salinity of the soil. Anthropogenic activities such as using brackish water for irrigation and distorting natural drainage systems contribute to salinity (Shahid *et al.*, 2018a; Choudhary and Kharche, 2018).

1.2 Rationale

South Africa produces some of the world's most competitively priced refined sugar and is the world's sixth-largest net exporter of raw sugar (Muir *et al.*, 2010). Exporting raw sugar from South Africa contributes substantially to unemployment alleviation, mainly in rural areas, sustainable development, and regional and national (Muir *et al.*, 2010). Because of the various links between the sugar sector and the core businesses that serve the sugar industry, the South African sugar industry creates both direct revenue and employment in the regions and indirect economic activity. Connections to downstream businesses provide considerable job prospects. A total of 65 000 persons are employed directly, and 270 000 are indirectly employed by the sugar industry (SASA, 2020). The industry produced 19.24 million tons of cane from an estimated 262 221 ha during the 2019/20 seasons, resulting in an estimated average cane yield of 73.4 t/ha. In 2019/20, the cane-to-sugar ratio was 8.64, with sugar output reaching 2.23 million tons (Singels *et al*., 2020). For the fiscal year 2019/20, the sugar industry earned R25.8 billion toward the gross domestic product (GDP) (Mvelase, 2021).

However, according to Garside and Bell (2007), despite the benefits of sugarcane production, the sugar sector has faced several obstacles mostly by Small-Scale Growers (SSGs). In South Africa, the sugar sector has been seeing a decline in sugarcane production, notably by SSGs (Garside and Bell, 2007; Dubb, 2016). As a result, there are fewer SSGs, and their commercialization potential is limited. Due to poor net-farm revenue, SSGs have become more reliant on government social payments, such as old-age pensions and child support, as sugarcane output has declined. Although it is widely accepted that the number of farmers has declined because of reduced output and farm revenue, it is unclear what has caused the decrease in productivity, which has resulted in lower income and, ultimately, fewer farmers (Zulu *et al*., 2019).

Irrigated croplands can be affected by waterlogging and salinity. Waterlogging and soil salinisation as a consequence of irrigation are problems in South Africa since the country is located in a semi-arid climatic zone (Reinders *et al*., 2016c). Fifteen to eighteen percent (15–18%) of South Africa's irrigated land is believed to be waterlogged and salinised due to drainage costs (Reinders *et al.*, 2016a;

Malota and Senzanje, 2016). These lands include sugar cane fields. The above-mentioned constraints can negatively impact the reduction in sugar cane production. However, research has not been conducted to confirm the effects of waterlogging and soil salinisation in irrigated sugar cane fields in the KwaZulu Natal sugar belt region.

1.3 Aim

This study aims to characterise the borehole water and soil properties across seasons for the period 2016-2020 and to make links to rainfall and sugarcane yield in the Makhathini Irrigation Scheme, KwaZulu-Natal in order to identify areas prone to waterlogging and salinisation.

1.4 Research questions

Questions this research aimed to address include the following:

- How do borehole water properties, electrical conductivity (EC), water levels and temperatures change over the different seasons from 2016 to 2020?
- How does water quality for irrigation from the Jozini/Pongola Dam change over the seasons from 2016 to 2020?
- How does rainfall influence the boreholes’ electrical conductivities, water levels, and yield in the Makhathini Irrigation Scheme from 2016 to 2020?
- How does the Makhathini Irrigation Scheme's soil salinity change from 2016 to 2020, and does this impact the yield?

CHAPTER 2: LITERATURE REVIEW

2.1 Salinity and waterlogging

Semi-arid areas' irrigation systems have significant challenges due to soil salinity and water accumulation in saturated areas, which affect agricultural production (Materechera, 2011). Worldwide, 34 million hectares of land have been salinised, causing poor soil drainage. As a result, valuable agricultural land between 250 000 and 500 000 hectares is lost annually, resulting in a decline in crop yields (Dubois, 2011; Qadir *et al.*, 2013). Soil salinisation is a multi-factorial process, including evaporation, salt precipitation and dissolution, salt transport, and ion exchange (Bui, 2017). Water and dissolved salts rise to the soil's surface by capillary action in areas with shallow groundwater. The salts remain after the water has evaporated from the surface, and this is referred to as salinisation (Li *et al.*, 2014; Wannakomol, 2005). Irrigated agriculture in semi-arid and arid areas is particularly vulnerable (Connor *et al.*, 2012), like in South Africa, where irrigation has a direct impact (Freisem and Scheumann, 2001).

Waterlogging (excess water in the soil) and salinisation (excess salts in the soil) in the root zone of plants are symptoms of inadequate drainage in semi-arid and dry climates. These two events occur in conjunction with one another (Hailu and Mehari, 2021; Madramootoo *et al*., 1997). They negatively impact the root zone's air, water, and salt conditions. As a result, plant development is stunted in these environments, reducing agricultural yield. Therefore, artificial drainage is necessary for agricultural areas with poor drainage to avoid these problems (Dikeogu *et al.*, 2021; Shahid *et al.*, 2018b; Madramootoo *et al*., 1997).

Agricultural (artificial) drainage is a crucial method of water management that plays an essential role in creating sustainable and effective agricultural production systems (Khwidzhili and Worth, 2016; Van der Molen *et al*., 2007). According to Malota and Senzanje (2016), physical assessment is often used for constructing subsurface drainage systems, but it is costly, time-consuming, and may inhibit decision-making. Complexity and nonlinearity are features shared by the soil system and the activities that occur within it (Ali, 2011). For instance, soil properties, like its saturated hydraulic conductivity, shift across time and space (Oosterbaan and Nijland, 1994). To correctly manage agricultural water systems, one must be thoroughly familiar with the processes involved (Bastiaanssen *et al.*, 2007).

2.2 Factors that contribute to soil salinisation

Sodic soils, which are high in salt, are often created by a combination of geological, hydrological, and pedological processes (Leogrande and Vitti, 2019; Bui, 2017). In low-lying regions, soluble salts build up in the soil when evaporation dominates rainfall, and the salts are not washed away. Primary salinisation refers to the natural process through which dry and semi-arid soil becomes more saline. Soil that has been salinised due to direct human activity is referred to as having secondary salinisation (Choudhary and Kharche, 2018).

Soil toxicity, decreased soil fertility, less water availability to plants as a result of a decrease in the osmotic potential of the soil solution, and a noticeable shift in the hydraulic characteristics of soil are all effects of soil salinity that exceeds safe levels (Sheldon *et al.*, 2017; Machado *et al.*, 2017). The soil salinity is also affected by the irrigation water quality (Vengosh, 2003). Soil salinity directly results from irrigation with marginal water, such as brackish water or wastewater, which has a high concentration of soluble salts (Rahman *et al.*, 2022).

In many cases, salinisation of the soil is a result of having sodic soil. Na^+ gradually replaces divalent cations on the clay mineral exchange complex as a result of either natural or artificial sodium build-up in the system (Stavi *et al.*, 2021). An increase in adsorbate Na^+ induces soil fragmentation, decreasing soil porosity and permeability. Due to this, unsaturated zone drainage of soil water and salt flush is greatly impeded. High levels of Na^+ in the soil water and the subsequent precipitation of Ca^{2+} and Mg^{2+} as calcium carbonate and calcium sulphate minerals cause Na^+ to dominate the exchanger phases (Osman, 2018).

2.3 Impact of salinity on Sugarcane

In the field of agriculture, salinity is a common problem that is often brought on by irrigation. Hopmans *et al*. (2021) urge that, according to estimates, salt has a negative impact on approximately forty percent of irrigated land globally. This problem is common in soils used for irrigating sugarcane, especially in areas with low precipitation and high demand for water lost to evaporation (Dominy *et al*., 2002). Capillary action draws salts dissolved in groundwater to the soil's surface as the water table rises. Poor irrigation and drainage management are frequently the major causes of salinisation (George *et al*., 2012). This problem is made much worse if the area is subjected to high temperatures, accelerating the evaporation rate and leaving salt crystals or crusts on the surface or in the top few centimetres of the soil (Zhao *et al.*, 2019). Accumulating neutral soluble salts inhibit soil fertility and plant development because the ions inhibit water intake and may be phytotoxic (Rietz *et al*., 2001). Several researchers demonstrated that salinity and sodicity caused considerable reductions in harvested sugarcane amounts (Singh and Sengar, 2020; Meyer and Van Antwerpen, 2001; Nelson and Ham, 2000).

According to the findings of some studies, salt and sodicity have a detrimental influence on the amount of sugarcane produced (Houk *et al*., 2006; Rietz and Haynes, 2002; Nelson and Ham, 2000; Rozema, 1994; Nour *et al*., 1989; Dev and Bajwa, 1972; von der Meden, 1966; Bernstein *et al*., 1966; Richards, 1954). Sugarcane is ranked as a crop susceptible to damage on the USDA scale of soil salinity developed by Richards in 1954. Rozeff (1995) concluded, after reviewing the relevant literature, that sugarcane is somewhere between moderately sensitive and sensitive to salt. According to the findings of this author, electrical conductivity (EC) values that were less than 200 milliSiemens per metre (mS/m) had little to no influence on the development and output of sugarcane. Sugarcane yields decreased between 200 and 400 mS/m, with 300 mS/m being the likely threshold for a higher drop, and between 520 and 700 mS/m, yields decreased by at least 50 percent.

There is a possibility that the stools of certain cultivars may die at an EC value of 800 mS/m, and at values between 1000 and 1500 mS/m, no stools will be able to survive. Barnes (1974) states that sugarcane suffers developmental and aesthetic harm when exposed to high saltwater concentrations. When crops are allowed to develop in saline conditions, the juice processing becomes more difficult, the amount of sugar that can be recovered decreases, and the amount of molasses that can be produced increases. An excess of salt may cause the discolouration of the leaves on sugarcane. When conditions are adverse, the leaves may become white with regions of blackish tissue (Barnes, 1974). Sugarcane exposed to excessive salt would grow unevenly and poorly, with short, thin canes, small intervals between them, and a poor structure (Dev and Bajwa, 1972). Maas and Hoffman (1977), as well as Rozeff (1995), state that since the effect of salts on yield is contingent upon the composition of the salts, the amount and pattern of rainfall, the technique of irrigation, and the type of soil, no one EC value can be considered to be universally applicable as the crucial threshold for salinity damage. In the study by Bernstein *et al*. (1966), findings show that the harmful effects of salt become more obvious with each sugarcane cycle; for example, ratoon crops are more severely damaged than plant crops, mostly as a result of poor sprouting and lower shoot counts. This is the case because ratoon crops are more susceptible to salt. Studies by Nelson and Ham (1998, 2000) show that the yield of irrigated sugarcane grown on sites with variable salinity and sodicity was negatively correlated with the levels of salinity and sodicity, even at levels normally deemed too low to be detrimental, indicating that the combination of salinity and sodicity decreased the crop's access to water.

2.4 Electrical Conductivity

The ability of water to carry an electric current is measured by a property called its electrical conductivity (EC). It depends on the kind, charge, and motion of the ions found in the water. Concentrations of dissolved salts are used to categorise irrigation water. Many positive (cations) and negative (anions) ions are produced when salts dissolve in water (anions). Sodium (Na^+), calcium (Ca^{2+}), chlorine (Cl^-), magnesium (Mg^{2+}), bicarbonate (HCO_3^-) and sulphate (SO_4^{2-}) are the most prevalent ions (Fourie, 2017). Ehlers *et al.* (2007) urges that some of the other ions that contribute to the overall charge in these water systems include potassium (K^+), nitrate (NO_3^-), and carbonate (CO_3^{2-}). The amount of charge that moves through water is known as its electrical conductivity (EC), measured in (mS/m).

Table 1: South African water quality guidelines for irrigation as related to electrical conductivity

Target water quality range EC (mS/m)	Recommendations
00 – 40	Low-frequency irrigation is required for salt-sensitive crops.
40 – 90	Low-frequency irrigation is required for moderately salt-sensitive crops.
90 – 270	Medium-frequency irrigation is required for moderately salt-sensitive crops.
270 – 540	High-frequency irrigation is required for salt-sensitive crops.
>540	High-frequency irrigation is required for selected salt-tolerant crops (DWAF, 1996).

Source: DWAF, 1996.

2.5 Effect of a shallow water table on irrigation schemes

Several studies have shown that a shallow groundwater table may provide up to sixty percent of a crop's water demands. However, the benefits to agriculture from underground water sources are conditional on factors such as crop type, soil type, depth to the groundwater table, groundwater salinity, and climatic circumstances (Gowing *et al*., 2009; Ayars *et al*., 2006; Ghamarnia *et al*., 2004; Ehlers *et al*., 2003; Wallender *et al*., 1979). A shallow water table does not always contribute to soil degradation, unlike salinisation or acidification; at times, groundwater tables may be beneficial as a potential water source for crops (Streutker *et al*., 1981). According to Kahlown and Ashraf (2005), the recommended water level for irrigation and irrigated crops lies within the range of 1.5 m to 2.0 m. Anything above 1.5 m is considered shallow and susceptible to waterlogging.

Groundwater may be shallow, and the upward flow rate is determined solely by environmental conditions that affect soil evapotranspiration (ET). Soil characteristics limit upward movement when the groundwater table is deep. The percentage of silt and clay in the soil is inversely related to the amount of capillary rise, as shown by Ehlers *et al*. (2003). According to Backeberg *et al. (*1996), around 20% of South Africa's irrigated soils are predicted to have groundwater levels too shallow to support the rooting depth of annual crops. Root zone salinisation and flooding may result from poorly managed shallow groundwater levels (Hornbuckle *et al*., 2005; Meyer *et al*., 1998; Streutker *et al*., 1981). Changing the irrigation schedule to enhance crop water intake from shallow groundwater tables raises the risk of increased soil salinisation due to reduced leaching and the build-up of salts within the groundwater; for this reason, soil salinity should be monitored regularly (Ehlers, 2007).

2.6 Management of salinity and waterlogging conditions

Soil salinisation and waterlogging conditions are two phenomena that contribute to soil degradation and yield loss. Soil salinisation refers to the degree to which water or soil contains salt. Other crops can tolerate high salt concentrations in soil, but the accumulation of salts in the soil profile can harm crop production (Machado and Serralheiro, 2017). Soil management strategies such as leaching are recommended for soil with higher electrical conductivity. Soil salinisation is caused in part by groundwater and by irrigation water.

On the other hand, waterlogging is caused by over-irrigation that brings water from underground levels to the surface (Basu and Meter, 2014). In poorly drained agricultural areas, artificial drainage is required to prevent waterlogging and salinisation in order to provide adequate air, water, and salt conditions in the root zone (Singh, 2019). Consequently, agricultural drainage is a crucial part of irrigation water management that plays an important role in achieving sustainable and effective agricultural production (Gany *et al.*, 2019).

2.6.1 Methods of leaching saline soils

Good quality irrigation water is essential to leach salty soils by ponding water on the soil surface either continuously or intermittently (Ehlers *et al.*, 2007). There are various types of leaching: continuous ponding, intermittent ponding method, and rainwater leaching.

2.6.1.1 Continuous ponding method

Continuous ponding is a kind of surface irrigation in which water is continuously impounding on the surface. The technique has all the benefits and drawbacks of flood irrigation. Facilitating consistent water application and infiltration is essential for optimal salt leaching during continuous ponding (Cherchian, 2019).

2.6.1.2 Intermittent ponding method

In areas lacking drainage provision, the intermittent ponding method is appropriate since it allows the subsequent increase in the water table to settle before the next application. Studies show that salt leaching is more efficient when water pools occasionally (Chhabra, 2021). Due to large evaporation losses, any benefits from improved leaching efficiency would be nullified by this approach (Okur and Örçen, 2020). Under poor drainage rates and a high-water table, mulched intermittent ponding is very beneficial (Shankar and Evelin, 2019).

2.6.1.3 Rainwater leaching

Where poor irrigation water quality is scarce, leaching with rainfall is often used (Minhas *et al.,* 2019). During the monsoon season, salt leaching may be enhanced by adopting adequate moisture conservation strategies and increasing the permeability of soils. Even leaching with rainfall may be carried out over a large area if the ground is properly levelled and bunched (Cucci *et al.*, 2019). During the dry season, mulching the field with a plough will save water. Regardless of rainfall frequency, intensity, or length, salt removal from soils of varying textures was seen to provide the same benefit (Devkota *et al.,* 2022).

Scientists in India determined that 300 mm of monsoon rain was sufficient to leach most of the salts from the soil's surface; 400 mm of loamy sand and approximately 80% of the salts from the medium-textured soils were also washed away. Research has revealed that the effectiveness of rainfall for salt leaching may be considerably increased by raising the soil moisture content with saline irrigation as the rainy season approaches (Gupta and Abrol, 1990).

2.6.2 Surface Drainage

Man-made drainage may be either underground or surface-based. Surface drainage systems remove surplus water from the soil's surface, while underground drainage systems regulate water table levels and salt balances inside the soil profile (Darzi-Naftchali *et al.,* 2013; Yannopoulos *et al.,* 2020).

2.7 Irrigation water quality

Good irrigation water quality is essential for the success and longevity of irrigated agriculture. In many regions of South Africa, however, agriculture is one of the primary sources of water quality deterioration due primarily to a high nitrate content because of both direct and indirect impacts on the quality of surface water and groundwater (Shabalala *et al.*, 2013). Zalidis *et al.* (2002) found that agricultural activities contribute to water pollution and that this pollution may have long-term, cumulative consequences that degrade water quality. Salty water used for irrigation may drastically diminish harvests, particularly in areas with poor drainage. When plants use irrigation water, they leave behind salts that will accumulate over time. In order to avoid salinity issues and sustain crop production, it is important to export salt from the plant root zone periodically. This may be accomplished naturally by rainwater seepage or artificially by applying irrigation quantities in excess of the soil water holding capacity, often known as the "leaching requirement" (Rhoades, 1974). The salt concentration in the runoff water and the need for leaching increase as the amount of salt applied to the irrigation water increases. The condition of the streams that receive these salts after being rinsed off agricultural fields is projected to decline. Sodicity is another issue that arises when irrigation water contains a lot of sodium ($Na^{+)}$ cations compared to other cations like magnesium (Mg^{2+}) and calcium (Ca^{2+}). High Na^+ levels may cause clay particles to deflocculate and hinder infiltration (Suarez *et al.*, 2006).

The salinity of water and the types of irrigation water that may be distinguished by it are most often indicated by the electrical conductivity of that water. Sodium causes the clay to disperse, which may lead to sodic soils and water infiltration issues. When evaluating the potential for sodicity, the sodium adsorption ratio (SAR) provides information on the concentrations of Na^+ cations in relation to Ca^{2+} and Mg^{2+} cations. Since nitrogen and phosphorus are often the limiting factors for algal development, they are the principal nutrients responsible for eutrophication. Oligotrophic (low nutrient levels, no quality problems), mesotrophic (intermediate nutrient levels, emerging quality problems), eutrophic (high nutrient levels, frequent quality problems) and hypertrophic (excessive nutrient levels, almost continuous quality problems) are the four categories of enriched water bodies (Walmsley, 2000). Concentrations of nitrogen between 0.4 to 1.0 mg/L are typically considered low enough to minimize eutrophication, while this value is highly dependent on site-specific variables (MacKay *et al*., 1995). Phosphorus is a key nutrient in freshwater because it controls both rate processes and total biomass, whereas nitrogen (N) availability in marine settings controls the dominant species composition of algal blooms (Young *et al*., 1996). Phosphorus (P) levels are used for trophic status categorisation, and it is widely acknowledged that reducing P availability in surface waters is the only effective approach to prevent eutrophication (Walmsley, 2000). In a source-directed strategy for eutrophication control, the South African DWAF has established effluent discharge standards (DWAF, 1996; Walmsley, 2000). There is a well-established link between NO_3^- in rivers, and the human population in that catchment, and NO_3^- levels are a good reflection of the degree of watershed development and disturbance (Van der Laan *et al.*, 2012).

CHAPTER 3: STUDY AREA AND METHODOLOGY

3.1 Study area

The Makhathini Irrigation Scheme is in the Jozini Local Municipality in the uMkhanyakude District Municipality, 15 km east of Jozini Town, 105 km north of Hluhluwe town and 100 km southeast of Pongola. It is located on the flood plains of the Pongola River, below the Jozini Dam in the KwaZulu-Natal Province. According to the Mjindi farming records, the scheme covers an area of approximately 3950 hectares (ha) (KZNDARD, 2016). The Irrigation scheme was established in 1979 with a 600-hectare commercial project to serve as a nucleus for growth in the area. In 1984, the first small-scale farmers were introduced to the scheme. There are currently 3927 hectares developed using irrigation for smallholder farmers. The scheme is subdivided into 278 plots of approximately 5 to 10 ha each (Mjindi, 2020).

The main crop grown at the Makhathini Irrigation Scheme is sugarcane, which is used as raw material for sugar production. Figure 1 shows the Map of KwaZulu-Natal highlighting Jozini, where the research is being carried out. Figure 2 shows the salinisation and waterlogging conditions at the Makhathini Irrigation Scheme in KwaZulu-Natal.

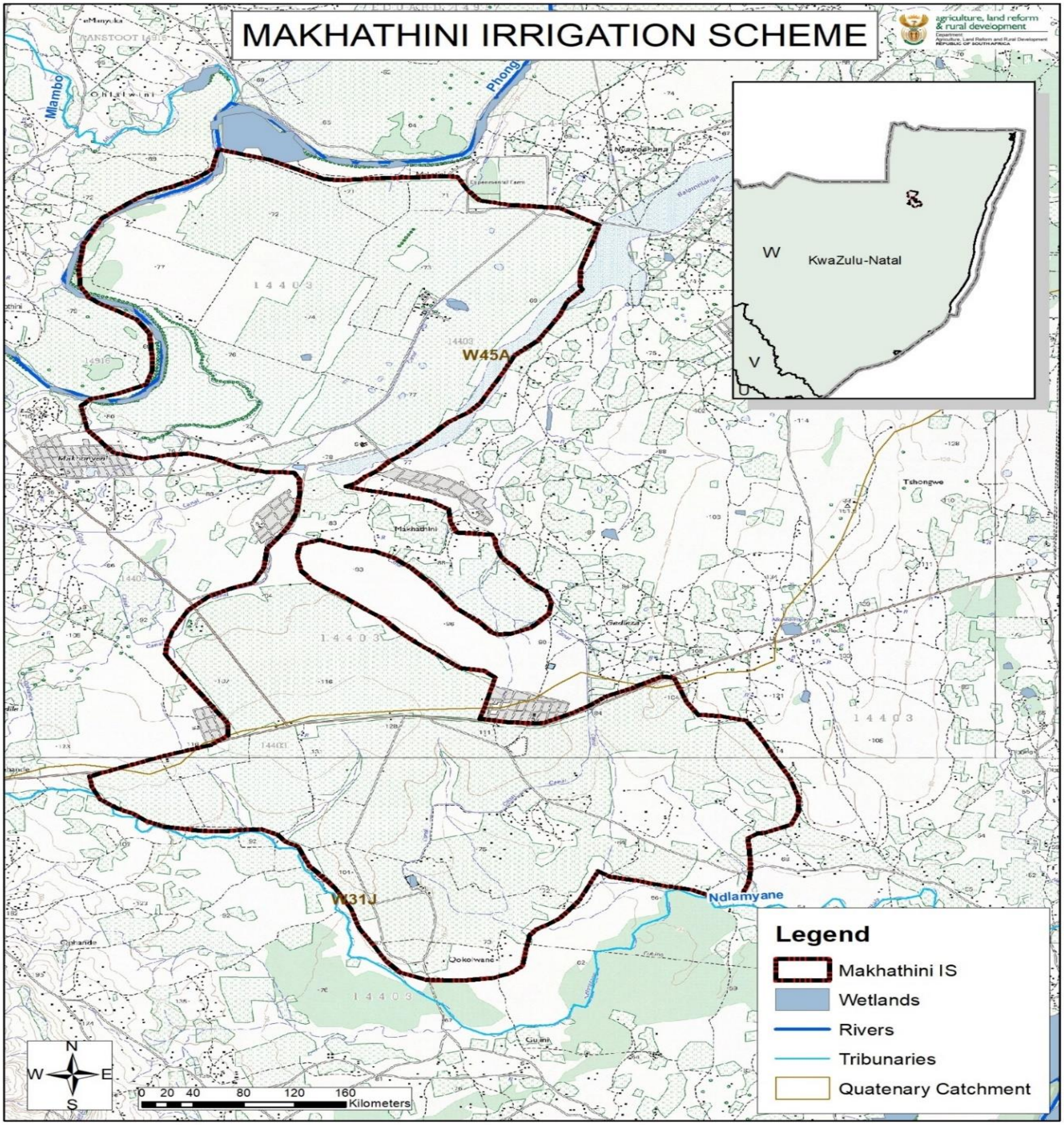

Figure 1: Topographical Map showing the location of the Makhathini Irrigation scheme, KwaZulu-Natal Province

Source: DALRRD, 2022

a) b)

Figure 2: The soil (a) salinisation and (b) waterlogged condition for Makhathini Irrigation Scheme in KwaZulu-Natal

Source: DALRRD, 2019

3.2 Methodology

The aim and questions of this study were addressed using a quantitative approach. Data from 2016 – 2020 were analysed and reported below.

3.2.1 Water table monitoring using boreholes

Nineteen (19) boreholes, namely, B1 to B19, were drilled and installed in two blocks (South and North blocks) of the Makhathini Irrigation scheme by the Department of Agriculture Land Reform and Rural Development (DALRRD) to monitor electrical conductivity, water levels, and temperature. Figure 3 shows the Makhathini boreholes used as monitoring points for electrical conductivity, water levels and water temperature.

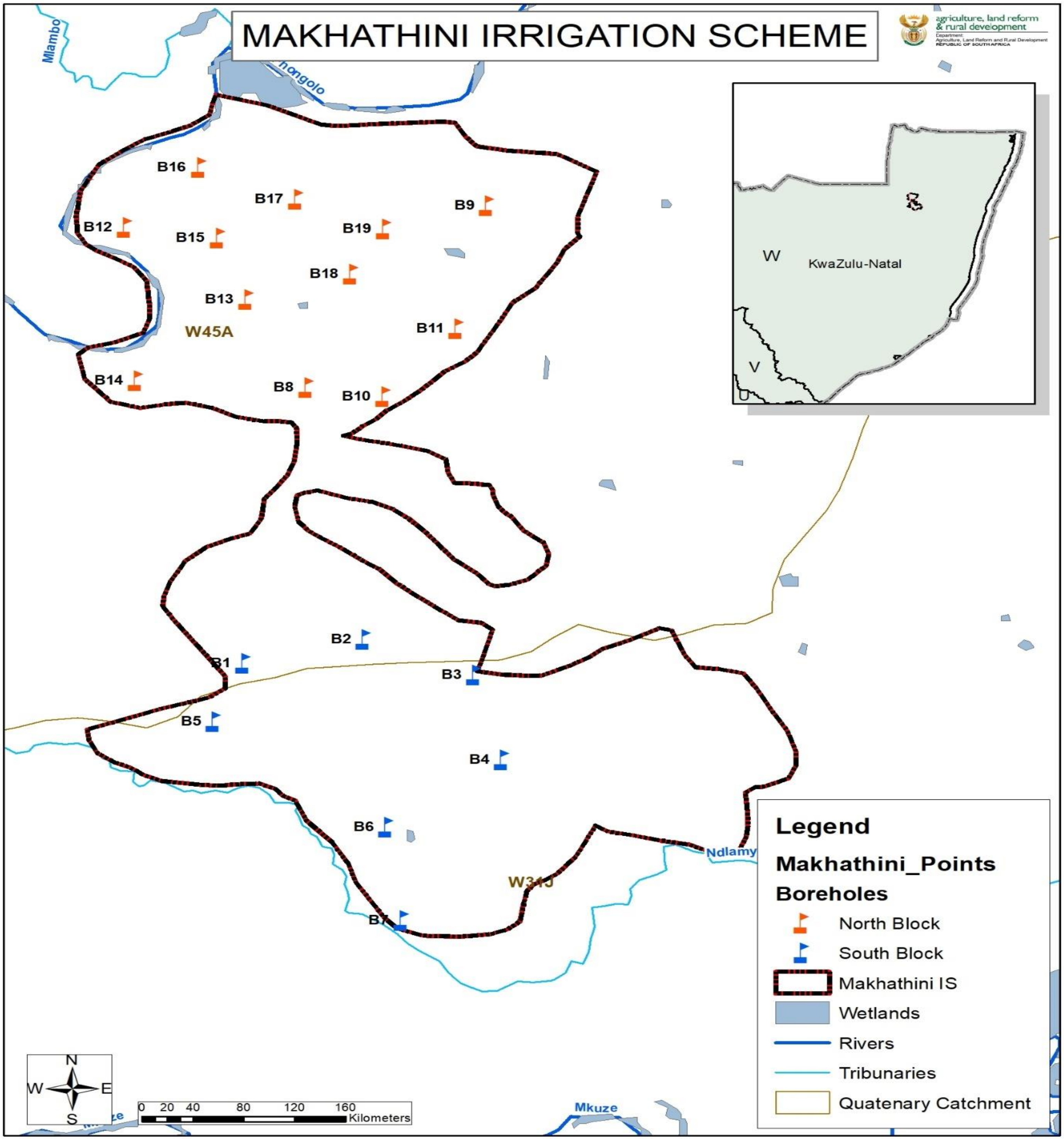

Figure 3: Makhathini Irrigation Scheme with nineteen (19) boreholes used for monitoring

Source: DALRRD, 2022

Seven (7) boreholes are located in the southern block, while twelve (12) are located in the northern block, respectively (Table 2).

Table 2: Elevation of 19 boreholes in the Makhathini Irrigation Scheme

Field Number	Borehole Number	Latitude	Longitude	Elevation (m)
South Block	B1	-27.49186994	32.14415953	127
	B2	-27.48772291	32.16115418	199
	B3	-27.49383193	32.17676075	112
	B4	-27.50851094	32.18068973	92
	B5	-27.50186079	32.13997139	117
	B6	-27.52006725	32.16435322	91
	B7	-27.53616061	32.16647704	84
North Block	B8	-27.44436937	32.15305108	81
	B9	-27.41297935	32.17859575	75
	B10	-27.44593796	32.16398148	81
	B11	-27.43421928	32.17430656	78
	B12	-27.41675532	32.12741601	77
	B13	-27.4292189	32.14462162	78
	B14	-27.44315256	32.12900167	77
	B15	-27.41857106	32.1405506	78
	B16	-27.40641633	32.13788414	77
	B17	-27.41193445	32.15165238	74
	B18	-27.4247604	32.15942499	76
	B19	-27.41703382	32.16407815	77

Source: DALRRD, 2021

The boreholes have pipes (in steel casing) of 40 mm in diameter and are 18 m deep. Each borehole casing is installed to a depth of 18 m with 0.5 m of the borehole above the ground and fitted with a screw cap so that, during waterlogging conditions or surface runoff, water is prevented from entering the borehole. The ground elevations of each borehole were surveyed using a dumpy level. The electrical conductivity, water levels, and temperature of water in the borehole were measured in the dry season: April, May, and June (AMJ); July, August, and September (JAS) and in the wet season: October, November, and December (OND); January, February, and March (JFM), using a Temperature Level and Conductivity (TLC) Meter. This was done once each season at the 19 boreholes by lowering the sensor into each borehole until a sound was heard. The sound indicated that the TLC meter has successfully measured the water level, electrical conductivity and temperature in the borehole. The readings were recorded for each borehole.

3.2.2 Surface Water Quality Data

The Department of Water and Sanitation provided the historical water quality data comprising 60 samples collected monthly for five years. The following parameters were measured EC, pH, Sodium Absorption Ratio (SAR), Nitrate, Nitrite and Phosphate from 2016 – 2020. The irrigation water in Makhathini Irrigation Scheme comes from the Jozini/Pongola Dam. The water samples were collected at two sampling points: the dam release point (S27 25 19.96 E32 04 49.07), known as "PR1" GPS and downstream of Pongola River (S27 19 47.97 E32 13 17.80), known as "PR2" GPS.

3.2.3 Soil Salinity Data

The soil samples were taken from six sampling points: 6A and 6B, which fall in the South block and 15A, 15C, 15E, and 19A, which fall in the North block within the Makhathini Irrigation Scheme. One kilogram of soil was collected at each sampling point and stored in separate ziplock bags. The samples were transported to the Agricultural Research Council Institute of Soil Water and Climate three days after collection, where they were analysed. The serial method for soil salinity analysis was used to analyse the electrical conductivity of each sample at the laboratory. The analysis results determined the salinity changes from 2016 to 2020.

3.2.4 Climatic Data

The daily historical rainfall data from the Makhathini ARC Farm Weather Station were provided by the South African Sugarcane Research Institute (SASRI), which owned the weather station from 2016 to 2020. The data were used to understand the relationship between rainfall and borehole electrical conductivity as well as borehole water levels in the Makhathini Irrigation Scheme. Rainfall was also correlated with sugarcane yield.

3.2.5 Sugarcane Yield data

The annual average sugarcane yields (ton/ha) from the small-scale irrigation sugar cane growers in the Makhathini Irrigation Scheme for 2016 – 2020 were provided by Mjindi Farming (Pty) Ltd in KwaZulu Natal.

3.3 Data Analyses

This section gives an overview of how the results are presented and statistics used to analyse the data for the key research questions:

- How do borehole water properties EC, water levels and temperatures change in different seasons between 2016 to 2020?
- How does the quality of the water used for irrigation from the Jozini/Pongola Dam vary across the seasons from 2016 to 2020?
- How does rainfall influence boreholes' electrical conductivities, water levels, and yield in the Makhathini Irrigation Scheme from 2016 to 2020?
- How does the Makhathini Irrigation Scheme's soil salinity change from 2016 to 2020, and does this impact crop yield?

Question 1

The data were analysed using the statistical software R version 4.2.0 and MS Excel for graphical presentation in the form of tables and graphs. The data were analysed using descriptive statistics such as mean, standard deviation (SD), and coefficient of variation (CV).

Results were also subjected to inferential analysis of variance (ANOVA) to determine the significance of differences in ECs, water levels and temperatures of the 19 boreholes across the five-year period. When the ANOVA was performed, Tukey's honestly significant difference test (Tukey's HSD) was conducted to determine the differences between EC, water levels, and sampling period (dry and wet season) of the 19 boreholes across the five-year period. In order to establish whether or not the irrigation water was suitable for use, the measured parameters were compared to the standards set out by the Department of Water Affairs and Forestry for the quality of water used in agricultural irrigation (DWAF, 1996).

Question 2

The data were analysed using statistical software Statistica 10 and MS Excel for graphical presentation in the form of tables and graphs. The data were analysed using descriptive statistics such as mean and standard deviation (SD). Results were also subjected to a two-tailed t-test to determine the significance of differences in pH, SAR, EC, NO_3^- and NO_2 and PO_4^-. The t-test was used to analyse differences in chemical concentrations between two sampling points, the PR1 and PR2 scheme, and between the chemical concentrations of samples between 2016 and 2020. In order to establish whether or not the irrigation water was suitable for use, the measured parameters were compared to the standards set out by the Department of Water Affairs and Forestry for the quality of water used in agricultural irrigation (DWAF, 1996).

Question 3

The data were analysed using the statistical software MS Excel for graphical presentation in the form of tables and graphs. The data were also subjected to an inferential correlation analysis (the Pearson Test). The test was used to understand the relationship between annual accumulative rainfall and annual average borehole electrical conductivity, annual average borehole water levels, and annual yield in the Makhathini Irrigation Scheme. A linear regression model was used to determine the significant difference between annual accumulative rainfall and borehole electrical conductivity, annual average borehole water levels, and annual yield.

Question 4

The data were analysed using the software MS Excel for graphical presentation in the form of tables and graphs. The data were analysed using the annual average of soil electrical conductivity and annual yield. Results were subjected to inferential factorial analysis of variance (ANOVA) to determine the significance of differences in annual average soil electrical conductivity (EC) from 2016 to 2020. The Agricultural Research Council Institute of Soil Water and Climate analysed soil salinity data. The laboratory analysed each sample's electrical conductivity using the series method. A linear regression model was used to determine the relationship between annual yield and average soil electrical conductivity.

CHAPTER 4: RESULTS

The following section of the research report presents the results of the analysis of borehole water properties such as electrical conductivity, water level, and temperature. The analysis focused on four sampling periods categorised into the dry season: April, May, and June (AMJ); July, August, and September (JAS) and the wet season: October, November, and December (OND); January, February, and March (JFM). Furthermore, the following parameters were considered when analysing irrigation water quality: pH, Sodium Adsorption Ratio, Electrical Conductivity, Nitrate and Nitrite, and Phosphate. The study also analysed the correlation between annual cumulative rainfall, annual average borehole electrical conductivity, annual average borehole water level, and annual sugarcane yield. Finally, analyses of the Makhathini Irrigation scheme's soil salinity were conducted.

4.1 Borehole water properties, electrical conductivity, water level, and temperatures analyses

4.1.1 Borehole Electrical Conductivity

4.1.1.1 Electrical conductivity for April, May, and June

The mean electrical conductivity (± standard deviations (SD)) across all 19 boreholes in the months of April, May and June are shown in Table 3. The overall mean and standard deviation for the five years were 45.01 mS/m ± 37.57. The ECs varied over the months but remained within a range of 20 - 200 mS/m. The two highest values were recorded in 2020 for Boreholes 10 and 19, shown in Figure 4a. The mean values obtained in 2016 and 2018 were within the South African Water Quality Guidelines for irrigation, whereas those obtained in 2017, 2019, and 2020 were above the South African Water Quality Guidelines for Irrigation, making the water saline (DWAF, 1996). The results of the ANOVA for EC for the months of April, May, and June showed a significant difference in electrical conductivity between boreholes ($p < 0.001$) in the five years (Table 8).

4.1.1.2 Electrical conductivity for July, August, and September

Table 3 presents the mean electrical conductivity and standard deviations across all 19 boreholes in the months of July, August, and September. The overall mean and standard deviation for the five years was 45.67 mS/m ± 49.41. The ECs varied over the months but remained within a range of 10 - 400 mS/m. The two highest values were recorded in 2017 for Borehole 19 and 2020 for Borehole 6, shown in Figure 4b. The mean values obtained in 2016 and 2018 were within the South African Water Quality Guidelines for Irrigation, whereas the means obtained in 2017, 2019, and 2020 were above the South African Water Quality Guidelines for Irrigation and would be considered to be saline (DWAF, 1996). The 19 boreholes' electrical conductivity significantly varied between 2016 and 2020, according to the ANOVA results ($p = 0.004$) (Table 8).

4.1.1.3 Electrical conductivity for October, November, and December

In October, November, and December, the overall EC mean and standard deviation for the five years was 53.29 mS/m ± 47.41 (Table 3). Even though the EC measures varied over the months, they remained within a range of 10-350 mS/m. The highest values were recorded in 2017 for Boreholes 9 and 11, in 2019 for Borehole 1, and in 2020 for Boreholes 10 and 14, as shown in Figure 4c. The mean values obtained in 2016 and 2018 were within the South African Water Quality Guidelines for Irrigation, whereas the means obtained in 2017, 2019, and 2020 were above the South African Water Quality Guidelines for Irrigation and would be considered to be saline

(DWAF, 1996). The electrical conductivity of the 19 boreholes varied significantly between 2016 and 2020, according to the ANOVA results (p = 0.004) (Table 8).

4.1.1.4 Electrical conductivity for January, February, and March

The mean EC and standard deviations across all 19 boreholes in the months of January, February, and March are shown in Table 3. The overall mean and standard deviation for the five years was 76.07 ± 98.56. The ECs varied over the months but remained within a range of 10-550 mS/m. The highest values were recorded in 2017 for Boreholes 9 and 14, in 2019 for Boreholes 2, 3, 8, and 9 and in 2020 for Boreholes 1, 2, 3, 5, and 14, shown in Figure 4d. The mean values obtained in 2016 were within the South African Water Quality Guidelines for Irrigation, whereas the means obtained in 2017, 2018, 2019, and 2020 were above the South African Water Quality Guidelines for Irrigation and would be considered to be saline (DWAF, 1996). The results of the ANOVA for the 19 boreholes showed a significant difference, as the p-value was 0.004 (Table 8).

Table 3: Descriptive statistics of borehole electrical conductivity from 2016 to 2020 for the Makhathini Irrigation Scheme

Electrical conductivity (mS/m)							
Dry seasons	AMJ	**Years**	**2016**	**2017**	**2018**	**2019**	**2020**
		Mean	22.54	51.92	28.13	51.80	70.64
		SD	11.82	36.26	25.91	20.75	56.47
		CV	0.52	0.70	0.92	0.40	0.80
	JAS	Mean	23.86	78.94	27.69	49.28	48.58
		SD	14.54	82.52	25.99	37.37	40.31
		CV	0.61	1.05	0.94	0.74	0.83
Wet seasons	OND	Mean	24.95	72.70	39.41	70.74	58.66
		SD	12.50	83.25	20.74	27.00	41.13
		CV	0.50	1.15	0.53	0.38	0.70
	JFM	Mean	26.04	75.16	43.38	132.95	102.81
		SD	25.94	79.32	23.94	150.59	112.15
		CV	1.00	1.06	0.55	1.13	1.09

Mean = Average, SD = standard deviation, CV = coefficient of variation

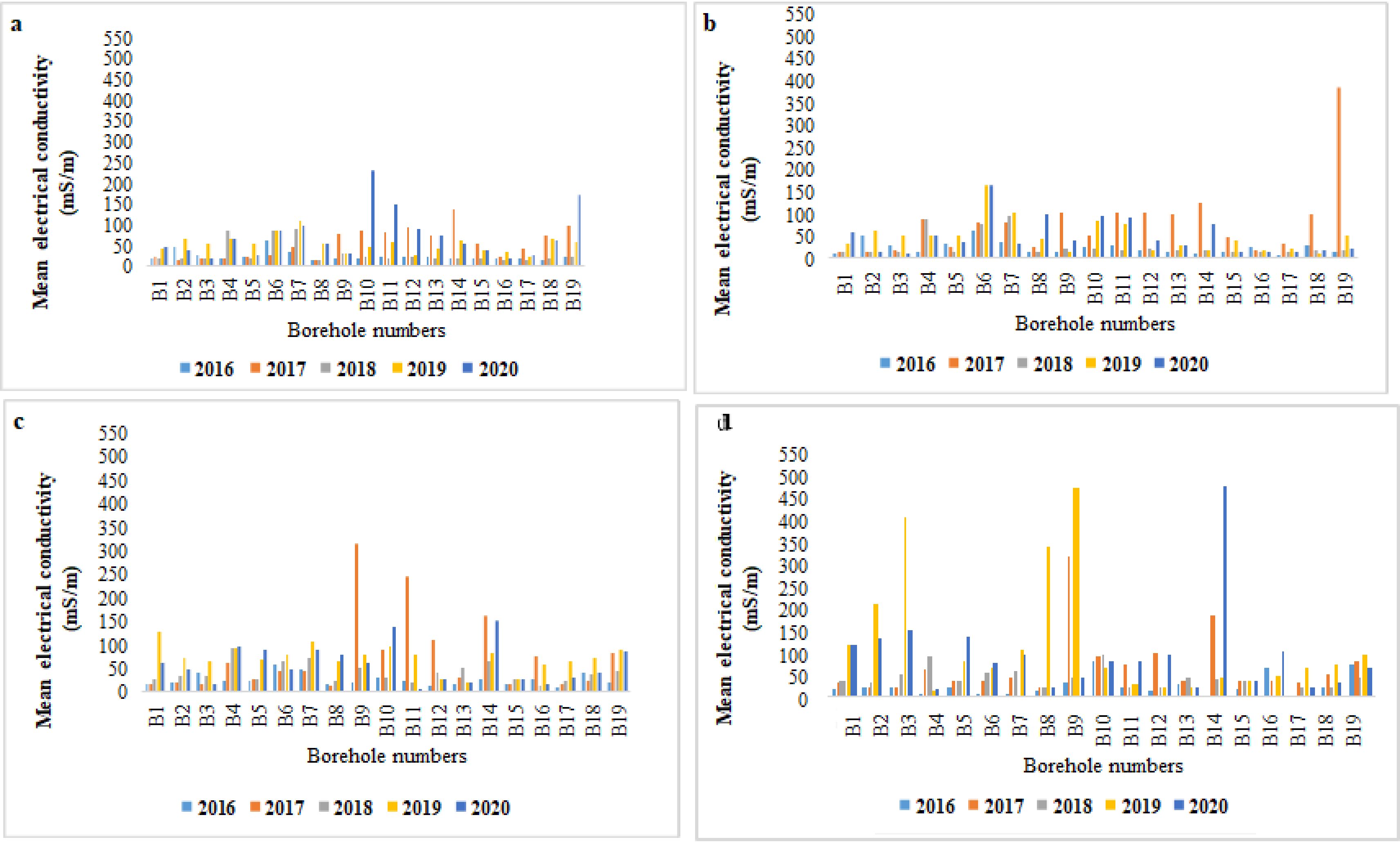

Figure 4: Mean electrical conductivity (mS/m) values in data collection periods (a) April, May, June, (b) July, August, September, (c) October, November, December, and (d) January, February, March (d) from 2016 to 2020.

4.1.1.5 Tukey HSD test for electrical conductivity

The Tukey test results for electrical conductivity are shown in Table 4, showing a statistically significant difference ($p = 0.049$) between boreholes B9 and B17 throughout all sample seasons and years. The Tukey test also confirmed that the EC varied significantly ($p = 0.002$) across all boreholes during dry and wet seasons. A Tukey HSD analysis of the EC across the years only indicated that there was a significant difference in EC between 2017 and 2016 ($p = 0.02$), 2019 and 2016 ($p < 0.001$); 2020 and 2016 ($p < 0.001$); 2019 and 2018 ($p < 0.001$); and 2020 and 2018 ($p = 0.003$).

Table 4: Tukey HSD test for electrical conductivity

Source	Diff	Lwr	Upr	p-value
B9 – B17	69. 8100	0. 1354449	139. 484555	0. 049
Wet – dry	19. 34174	7. 082466	31. 60101	0 .002
2017 – 2016	32. 010940	4. 103286	59. 918595	0. 015
2019 – 2016	49. 182956	19. 996433	78. 369480	<0. 001
2020 – 2016	43. 163219	13. 976696	72. 349743	<0. 001
2019 – 2018	41. 538158	14. 516688	68.5 59628	<0. 001
2020 – 2018	35. 518421	8. 496951	62. 539891	0. 003

4.1.2 Borehole water levels

The smaller the value of the water level, the more shallow the water level (water is closer to the soil surface), and vice versa.

4.1.2.1 Borehole water levels for April, May, and June

In the months of April, May, and June (AMJ), the mean water level and standard deviations (SD) for all 19 boreholes are shown in Table 5. The five-year overall mean and standard deviation were recorded as 4.64 m and ±0.47, respectively. The water levels from 2016 to 2020 ranged from 0.63 m to 13.60 m. The average water levels were stable from the year 2016 to 2018 and gradually increased in 2019 and 2020, as shown in Table 5. Borehole B12 continuously had shallow water levels throughout the five years, whereas B10 and B9 had deep water levels (Figure 5a). The results of the ANOVA single factor with a p-value of 0.232 indicate no significant difference in the water levels of boreholes in the months AMJ from 2016 to 2020 (Table 8).

4.1.2.2 Borehole water levels for July, August, and September

Table 5 presents the mean water level and standard deviations (SD) for all 19 boreholes in July, August, and September (JAS). The overall mean and standard deviation were 4.39 m ± 3.46, respectively. The average water levels for JAS from 2016 to 2020 ranged from 2.64 m to 5.37 m (Table 5). The average water levels were considerably deep from 2016 to 2019 and significantly increased in 2020 (Table 5). Figure 5b shows that boreholes B12 and B5 had shallow water levels, while B10 and B11 had deep water levels from 2016 to 2020. The findings of the ANOVA single factor, with a p-value of 0.151, show that the borehole water levels in the months JAS from 2016 to 2020 were not significantly different (Table 8).

4.1.2.3 Borehole water levels for October, November, and December

The mean water level and standard deviations (SD) for all 19 boreholes in October, November, and December (OND) are shown in Table 5. The overall mean and standard deviation results were 3.36 m and ± 2.99, respectively. The average water levels in 2016 were very deep; however, as the years progressed until 2020, a rise in the water level could be detected (Table 5). In the OND months, borehole B12 recorded shallow water levels, while B10 had deep water levels during the five years (Figure 5c). The results of the ANOVA single factor, a p-value of <0.001, indicate a significant variation in water levels for the months of OND in the five years (Table 8).

4.1.2.4 Borehole water levels for January, February, and March

In January, February, and March (JFM), the mean water level and standard deviations (SD) for all 19 boreholes are presented in Table 5. The overall mean and standard deviation for the five years were 2.90 m and ±2.76, respectively. The average water levels across the five years were deep in 2016 at 6.27 m and shallow in 2020 at 1.10 m (Table 5). The mean water levels were above the target of 1.5 m to 2.0 m in 2016, 2017 and 2019; however, they rose to extremely shallow levels in 2017 and 2020. Borehole B11 recorded shallow water levels value, while B8 and B9 recorded deep water levels (Figure 5d). The results of the ANOVA single factor, a p-value of 8.42E-16, indicate a significant variation in water levels for the months of JFM in the five years (Table 8).

Table 5: Descriptive statistics of borehole water levels from 2016 to 2020 for the Makhathini Irrigation Scheme

Water levels (m)							
Dry seasons	AMJ	**Years**	**2016**	**2017**	**2018**	**2019**	**2020**
		Mean	4.99	4.89	4.88	3.34	3.45
		SD	3.80	3.66	3.41	2.07	1.71
		CV	0.76	0.75	0.70	0.62	0.49
	JAS	Mean	5.37	4.48	4.73	4.70	2.64
		SD	4.82	2.56	3.18	3.90	1.77
		CV	0.90	0.57	0.67	0.83	0.67
Wet seasons	OND	Mean	5.63	2.75	1.20	1.41	1.66
		SD	3.59	1.47	0.50	0.66	1.17
		CV	0.64	0.54	0.42	0.47	0.71
	JFM	Mean	6.27	1.60	1.04	1.57	1.10
		SD	3.65	0.93	0.43	1.06	0.47
		CV	0.58	0.58	0.41	0.68	0.43

Mean = Average, SD = standard deviation, CV = coefficient of variation

4.1.2.5 Tukey HSD test for water levels

The Tukey test results for the water levels are shown in Table 6, and they show no statistically significant difference (p = 0.31) between the boreholes and the water dep throughout all sample periods. The Tukey test also confirmed that the water levels varied significantly during the wet season across, which means that in wet seasons the water level depths were shallow than in the dry season in all boreholes between 2017 and 2016 (p = 0.001); 2019 and 2016 (p < 0.001); 2020 and 2016 (p < 0. 001); 2019 and 2017 (p = 0.001); 2020 and 2017 (p < 0.001); 2019 and 2018 (p < 0.001); and 2020 and 2018 (p < 0.001).

Table 6: Tukey HSD test for water levels in the wet season

Source	**Diff**	**Lwr**	**Upr**	**p-value**
Boreholes				0. 31
2017 – 2016	-2. 0921053	-3. 888457	-0. 295739	0. 013
2019 – 2016	-4. 1431579	-6. 048476	-2. 2378395	<0. 001
2020 – 2016	-4. 2534211	-6. 158739	-2. 3481027	<0. 001
2019 – 2017	-2. 0510526	3. 471193	-0. 6309299	<0. 001
2020 – 2017	-2. 1613158	-3. 581456	-0. 7411753	<0. 001
2019 – 2018	-3. 2618421	-4. 817528	-1. 7061562	<0. 001
2020 – 2018	-3. 3721053	-4. 927791	-1. 8164193	<0. 001

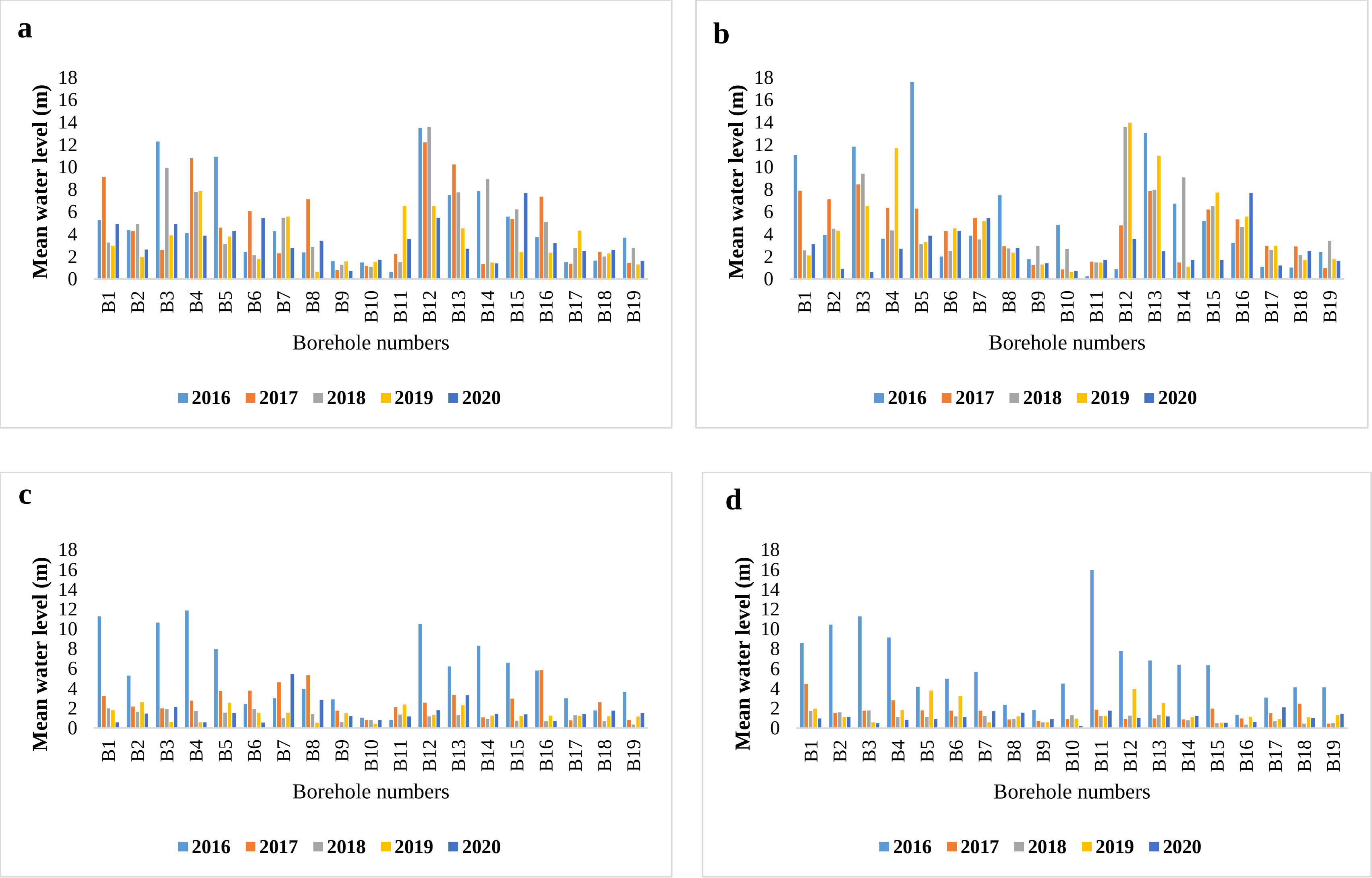

Figure 5: Mean water levels (m) change in different seasons April, May, June (a), July, August, September (b), October, November, December (c), and January, February, March (d) over the period of 2016 to 2020.

4.1.3 Borehole Temperature

4.1.3.1 Borehole water temperatures for April, May, and June

Table 7 shows the mean water temperatures and standard deviations in the months of April, May, and June, the mean water temperatures and standard deviations (SD) for all 19 boreholes from 2016 to 2020. The five-year overall mean and standard deviation were recorded as 25.01°C and ± 1.29, respectively. The highest temperature recorded for these months of AMJ was 25.58 °C in 2017 and 2018. The lowest temperature for these months was 24.14 °C, captured in 2020. Figure 6a shows similar values across all the borehole water over the five years; however, borehole B13 had the greatest water temperature, and B1 had the lowest over that time. The results of the ANOVA single factor with a p-value of 0.075 indicate no significant difference in the water temperatures of boreholes in the months AMJ from 2016 to 2020 (Table 8).

4.1.3.2 Borehole water temperatures for July, August, and September

The mean water temperatures and standard deviations (SD) for all 19 boreholes in July, August and September for the period of the study are shown in Table 7. The five-year overall mean temperature and standard deviation were 25.32 ˚C ± 1.74, respectively. The highest temperature recorded for the months of JAS was 27.12 ˚C in 2016, and the lowest temperature was 24.19 ˚C which was recorded in 2018. Figure 6b shows similar temperatures s across all the borehole water over the five years. Borehole B2 had the highest water temperatures, while B1 had the lowest in the JAS months over 5 five years (Figure 6b). The results of the ANOVA single factor with a p-value of 0.098 indicate no significant difference in the water temperatures of boreholes in the months JAS from 2016 to 2020 (Table 8).

4.1.3.3 Borehole water temperatures for October, November, and December

Table 7 shows the mean water temperatures and standard deviations (SD) for all 19 boreholes during 2020. The five-year overall mean and standard deviation were 24.68 ˚C ± 1.36, respectively. The highest temperature recorded for the months of JAS was 25.14 ˚C in 2020, and the lowest temperature was 23.77 ˚C which was recorded in 2017. Figure 6c depicts similar water temperatures across all boreholes over the five years. Borehole B10 had the highest water temperatures, while B3 had the lowest in the OND months over the five years (Figure 6c). The results of the ANOVA single factor with a p-value of 0.090 indicate that there was no significant difference in the borehole water temperatures in the months OND from 2016 to 2020 (Table 8).

4.1.3.4 Borehole water temperature for January, February, and March

The mean water temperatures and standard deviations (SD) in January, February, and March for all 19 boreholes are shown in Table 7. The overall mean and standard deviation for the five years was 24.77 ˚C ± 1.64, respectively. The highest temperature recorded for the months of JFM was 25.50 ˚C in 2020, and the lowest temperature was 24.19 ˚C which was recorded in 2017. Figure 6d also depicts a prolonged rise in the borehole water temperatures over the five years. Borehole B15 had the highest water temperatures, while B9 had the lowest in the JFM months over the five years (Figure 6d). The results of the ANOVA single factor with a p-value of 0.062 indicate that there was no significant difference in the water temperatures of boreholes in the months JFM from 2016 to 2020 (Table 8).

Table 7: Descriptive statistics of borehole temperatures from 2016 to 2020 for the Makhathini Irrigation Scheme

Temperature (˚C)							
Dry seasons	AMJ	**Year**	**2016**	**2017**	**2018**	**2019**	**2020**
		Mean	25.01	25.58	25.58	24.79	24.14
		SD	1.02	1.55	1.55	0.46	1.08
		CV	0.04	0.06	0.06	0.02	0.04
	JAS	Mean	27.12	24.89	24.19	24.47	25.91
		SD	0.45	1.70	1.64	1.48	1.28
		CV	0.02	0.07	0.07	0.06	0.05
Wet seasons	OND	Mean	24.98	23.77	25.01	24.49	25.14
		SD	1.02	1.62	1.02	1.20	1.48
		CV					
	JFM	Mean	25.29	24.19	24.51	24.37	25.50
		SD	1.25	1.64	1.42	1.96	1.57
		CV	0.05	0.07	0.06	0.08	0.06

Mean = Average, SD = standard deviation, CV = coefficient of variation

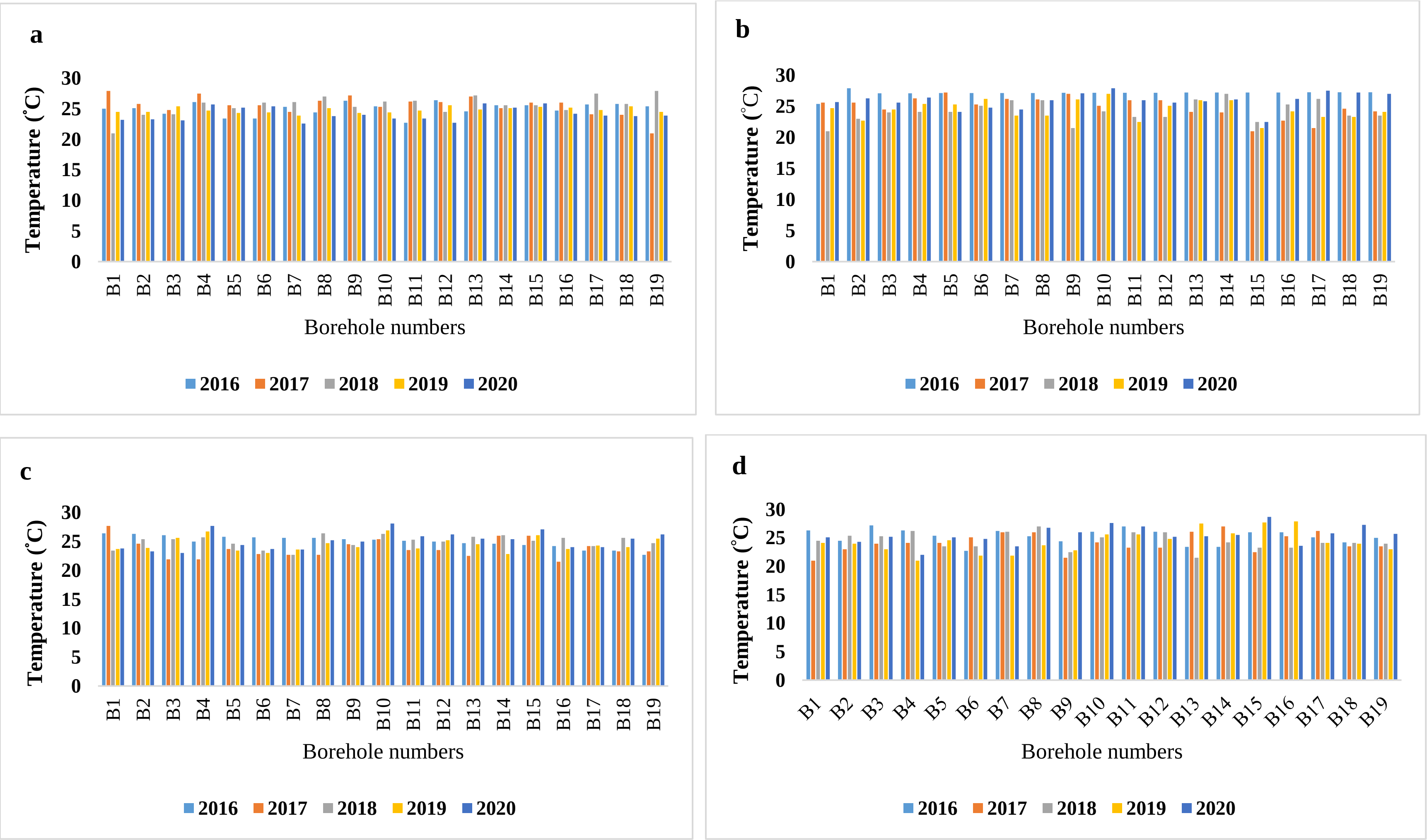

Figure 6: Mean temperature (°C) change in different data collection seasons (a) April, May, and June; (b) July, August, and September; (c) October, November, and December; and (d) January, February, and March from 2016 to 2020.

Table 8: Analysis of variance (ANOVA) results for borehole electrical conductivity, water depth, and temperature

		p-value		
SEASON	MONTHS	EC	WL	Temperature (°C)
Dry seasons	April, May, and June	<0.001	0.232	0.075
	July, August, and September	0.003	0.151	0.098
Wet seasons	October, November, and December	0.004	<0.001	0.090
	January, February, and March	0.004	< 0.001	0.063

EC = electrical conductivity, WL = water levels, p-value < 0.05 is significant

4.2 Irrigation water quality analysis

The section presents the results for water quality for irrigation from the Jozini/Pongola Dam sampled from upstream (PR1) and downstream (PR2) over the different data collection seasons from 2016 to 2020. The parameter sampled were pH, Sodium adsorption Ratio (SAR), Electrical conductivity (EC), Nitrate (NO_3^-) and Nitrite (NO_2), as well as Phosphate (PO_4^-).

4.2.1 pH

The pH values at both sampling points (PR1 and PR2) in all seasons were within the "good" class, which indicates that the pH values met the standards (Figure 7a and Tables 9 and 10). The p-value for the two-tailed t-test version was used for the results. As shown in Table 11a, the p-value (0.159) is greater than the standard significance level of 0.05. The pH values at the two sampling points show that there is no significant difference between pH PR1 and pH PR2 (Table 11a). In particular, the means of pH PR1 and pH PR2 are similar, as shown in Table 9.

4.2.2 Sodium Adsorption Ratio

The average sodium adsorption ratio (SAR) for all seasons (summer, autumn, winter, and spring) of PR1 ranged from 0.72 to 1.04, which is classified as "good" (Tables 9 and 10); these values have been similar from the year 2016 to 2020, as shown in Figure 7b. For all sampling seasons, SAR increases at PR2 and is classified as "fair" (Table 9 and Figure 6b). To determine the difference between the SAR of the two sampling points (PR1 and PR2), a t-test was used. The p-value (<0.001) confirmed a significant difference between the two sampling points (Table 11b). The significant difference between SAR values for the two sampling points accepts the assumption that the SAR vary from one sampling point to another. Specifically, SAR-PR2 have a greater mean than SAR-PR1, as shown in Table 9.

4.2.3 Electrical conductivity

At PR1, upstream of the Makhathini Irrigation Scheme, the electrical conductivity of the irrigation water quality is classified as "good" for all four seasons. These values are similar over the five years (Tables 9 and 10, and Figure 7c). However, PR2 is categorised as “fair” due to increased EC across all four seasons (Tables 9 and 10 and Figure 6c). The p-value (0.002) from the t-test analysis indicated a significant difference between the sampling points (Table 11c). These results support the notion that the EC values vary considerably from one sampling point to another. According to Table 9, the EC average for PR2 is significantly greater than EC mean for PR1.

4.2.4 Nitrate and Nitrite

The seasonal increases in inorganic N concentrations from PR1 to PR2 are shown in Table 9. At PR2, nitrate and nitrite levels are only considered "good" during winter (Table 9). Figure 7d shows a consistent pattern for PR1 over five years, while PR2 fluctuated from 0.38 mg/L to 2.48 mg/L from 2017 to 2019, respectively. The results of the p-value (0.05634) obtained from the *t*-test indicated a significant difference at 0.05, as shown in Table 11d. The NO_3^- and NO_2 values for the two sampling points support the notion that the means vary across sampling points. As shown in Table 9, the mean of NO_3^- and NO_2 PR2 is greater than that of $NO_3^-+NO_2$ PR1.

4.2.5 Phosphate

At the PR1 sampling point, the PO_4^- was rated as "good" throughout the summer, autumn, and winter seasons and "fair" only during the spring season (Tables 9 and 10). At PR2, the PO_4^- concentration was deemed unacceptable. Figure 7e shows the PR1 PO_4^- were good from 2016 to 2020, while PR2 shows a substantial increase in phosphate levels from 2017 to 2020. The *t*-tests indicated a significant difference (p-value = 0.006) of PO_4^- values across sampling points (Table 11e). The PO_4^- values for the two sampling points accept the notion that the means are different across sampling points. Specifically, the PO_4^- PR2 mean is greater than the PO_4^- PR1 mean, as shown in Table 9.

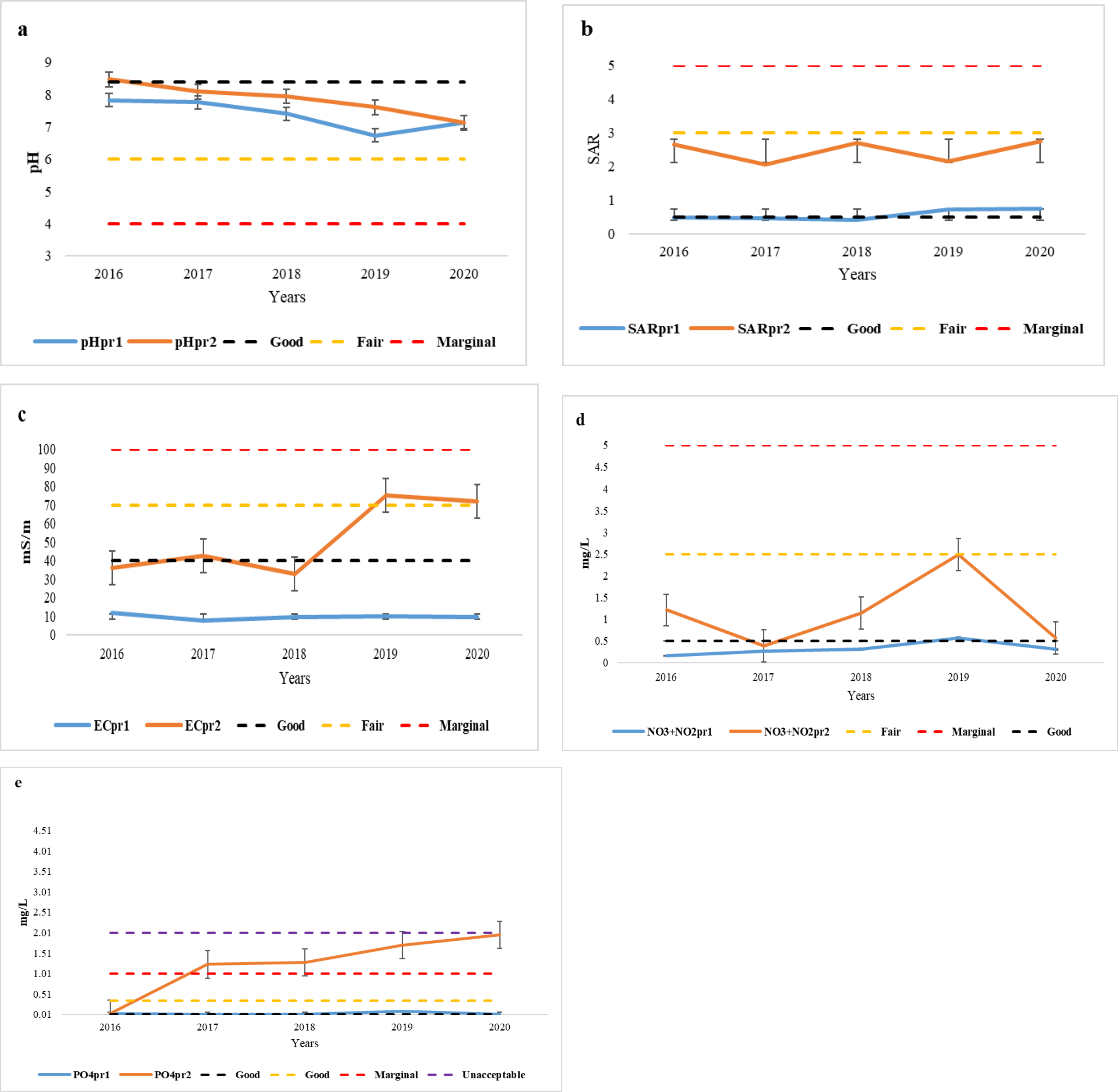

Figure 7: Average concentration of (a) pH, (b) SAR, (c) EC, (d) Nitrate and Nitrite, and (e) Phosphate for upstream (PR1) and downstream (PR2) of Makhathini Irrigation Scheme

Table 9: Descriptive statistics of surface water quality from the Jozini/Pongola Dam used for irrigation

Parameters		**Pongola Catchment**							
		Upstream Makhathini Irrigation Scheme "PR1"				**Downstream Makhathini Irrigation Scheme "PR2"**			
		Summer	**Autumn**	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**	**Spring**
pH	Range	6.86 - 8.10	6.14 - 7.50	6.40 - 8.10	6.00 - 8.14	7.45 - 8.70	7.16 - 8.70	5.40 - 8.80	6.00 - 8.90
	Mean	7.45	7.29	7.30	7.35	8.00	7.92	7.73	7.79
	S.D.	0.41	0.48	0.50	0.67	0.37	0.37	0.91	0.80
Irrigation Class		"Good"	"Good"	"Good"	"Good"	"Good"	"Good"	"Good"	"Good"
SAR	Range	0.19 - 4.55	0.20 - 4.61	0.20 - 2.87	0.20 - 1.57	1.19 - 4.49	1.62 - 4.68	1.52 - 4.55	1.49 - 4.83
	Mean	0.95	1.04	0.72	0.76	2.67	2.72	2.84	2.76
	S.D.	1.45	1.42	0.73	0.71	1.09	1.09	1.28	1.26
Irrigation Class		"Good"	"Good"	"Good"	"Good"	"Fair"	"Fair"	"Fair"	"Fair"
EC (mS/m)	Range	7.77 -13.76	7.10 -15.50	7.77 -12.10	8.06 -14.00	19.40 -90.10	30.40 -79.40	25.30 - 105.70	20.50 -107.40
	Mean	10.21	9.51	9.26	10.21	44.75	48.66	60.13	53.37
	S.D.	2.74	2.51	1.52	2.32	19.88	19.88	28.49	27.68
Irrigation Class		"Good"	"Good"	"Good"	"Good"	"Fair"	"Fair"	"Fair"	"Fair"
NO_3^- $+NO_2$ (mg/L)	Range	0.05 - 1.06	0.05 - 1.17	0.0 - 0.80	0.05 - 1.03	0.05 - 5.60	0.14 - 4.00	0.05 - 1.11	0.05 - 13.99
	Mean	0.41	0.33	0.34	0.31	1.41	0.96	0.50	1.65
	S.D.	0.32	0.34	0.26	0.31	1.76	1.76	0.33	3.47
Irrigation Class		"Good"	"Good"	"Good"	"Good"	"Fair"	"Fair"	"Good"	"Fair"
PO_4^- (mg/L)	Range	0.01 - 0.10	0.01 - 0.10	0.01 - 0.10	0.01 - 2.59	0.01 - 2.60	0.01 - 2.53	0.01 - 3.02	0.01 - 5.60
	Mean	0.003	0.004	0.003	0.033	0.88	0.82	1.34	1.72
	S.D.	0.004	0.004	0.003	0.080	1.07	1.07	0.99	1.59
Irrigation Class		"Good"	"Good"	"Good"	"Fair"	Unacceptable	Unacceptable	Unacceptable	Unacceptable

Table 10: South African Water Quality Guidelines Irrigation Water Classes

Parameters	**Fitness for use**			
	Good	**Fair**	**Marginal**	**Unacceptable**
pH	6.5 – 8.4	<6.0	<5.0	<4.0
SAR	0 – 1.5	1.5 – 3.0	3.0 – 5.0	> 5.0
EC (mS/m)	0 – 40	40 – 90	90 – 270	>270
NO_3^-+NO_2 (mg/L)	0 – 0.5	0.5 – 2.	2.5 – 10	>10
PO_4^- (mg/L)	0-0.010	0.010-0.035	0.035-0.100	>0.100

Source: DWAF, 1996

Table 11: T-test results for pH, SAR, EC, NO_3^- and NO_2 and PO_4^-

a)	**pH PR1**	**pH PR2**	**b)**	**SAR PR1**	**SAR PR2**
Mean	7.377533	7.851332	Mean	0.573716667	2.468856
Variance	0.204326	0.260123	Variance	0.024431488	0.112529
Observations	5	5	Observations	5	5
df	8		df	8	
t Stat	-1.55457		t Stat	-11.45061102	
P(T<=t) one-tail	0.079328		P(T<=t) one-tail	1.53079E-06	

t Critical one-tail	1.859548		t Critical one-tail	1.859548038	
P(T<=t) two-tail	**0.158657**		P(T<=t) two-tail	**3.06E-06**	
t Critical two-tail	2.306004		t Critical two-tail	2.306004135	
c)	**EC PR1**	**EC PR2**	**d)**	**NO_3^-+NO_2 PR1**	**NO_3^-+NO_2 PR2**
Mean	9.81225	51.75882	Mean	0.327133333	1.159785
Variance	1.90554	411.8409	Variance	0.021961408	0.675437
Observations	5	5	Observations	5	5
df	8		df	8	
t Stat	-4.6112		t Stat	-2.229501351	
P(T<=t) one-tail	0.000865		P(T<=t) one-tail	0.028170398	
t Critical one-tail	1.859548		t Critical one-tail	1.859548038	
P(T<=t) two-tail	**0.00173**		P(T<=t) two-tail	**0.056340796**	
t Critical two-tail	2.306004		t Critical two-tail	2.306004135	
e)	**PO_4^- PR1**	**PO_4^- PR2**			
Mean	0.03145	1.243485			
Variance	0.001231	0.547713			
Observations	5	5			
df	8				
t Stat	-3.65794				
P(T<=t) one-tail	0.00321				
t Critical one-tail	1.859548				
P(T<=t) two-tail	**0.00642**				
t Critical two-tail	2.306004				

4.3 Analysis of the correlation between annual accumulative rainfall, annual average borehole electrical conductivity, annual average borehole water levels and annual sugarcane yield

This section covers the results of the annual cumulative rainfall, annual average borehole conductivity, annual average borehole water level, and annual yield analyses of the Makhathini Irrigation Scheme for five years (2016-2020).

4.3.1 Analysis of annual cumulative rainfall and annual average borehole electrical conductivity levels from 2016 to 2020

In 2016, the annual cumulative rainfall of 358.1 mm was recorded, while the annual average borehole electrical conductivity was recorded at 24.35 mS/m (Figure 8). As the year progressed into 2017, there was an increase in annual accumulative rainfall to 511.6 mm, while the annual average borehole electrical conductivity also increased to 69.68 mS/m. In 2018, 871.3 mm of annual accumulative rainfall was received, and the annual average borehole electrical conductivity was recorded at 34.65 mS/m. In 2019, annual cumulative rainfall of 513.4 mm was recorded, and an annual average borehole electrical conductivity of 76.19 mS/m was recorded. Lastly, in 2020, annual cumulative rainfall of 472.5 mm was recorded, while an annual average borehole electrical conductivity of 70.17 mS/m was recorded. The correlation coefficient analysis is depicted in Table 12. The results show that there is a low negative (R = -0.17335) correlation between annual accumulative rainfall and annual average borehole electrical conductivity. Furthermore, Table 13 illustrates a regression analysis of annual accumulative rainfall and average borehole electrical conductivity. The results indicate that the is no conclusive relationship between annual cumulative rainfall and annual average borehole electrical conductivity at a p-value of 0.165.

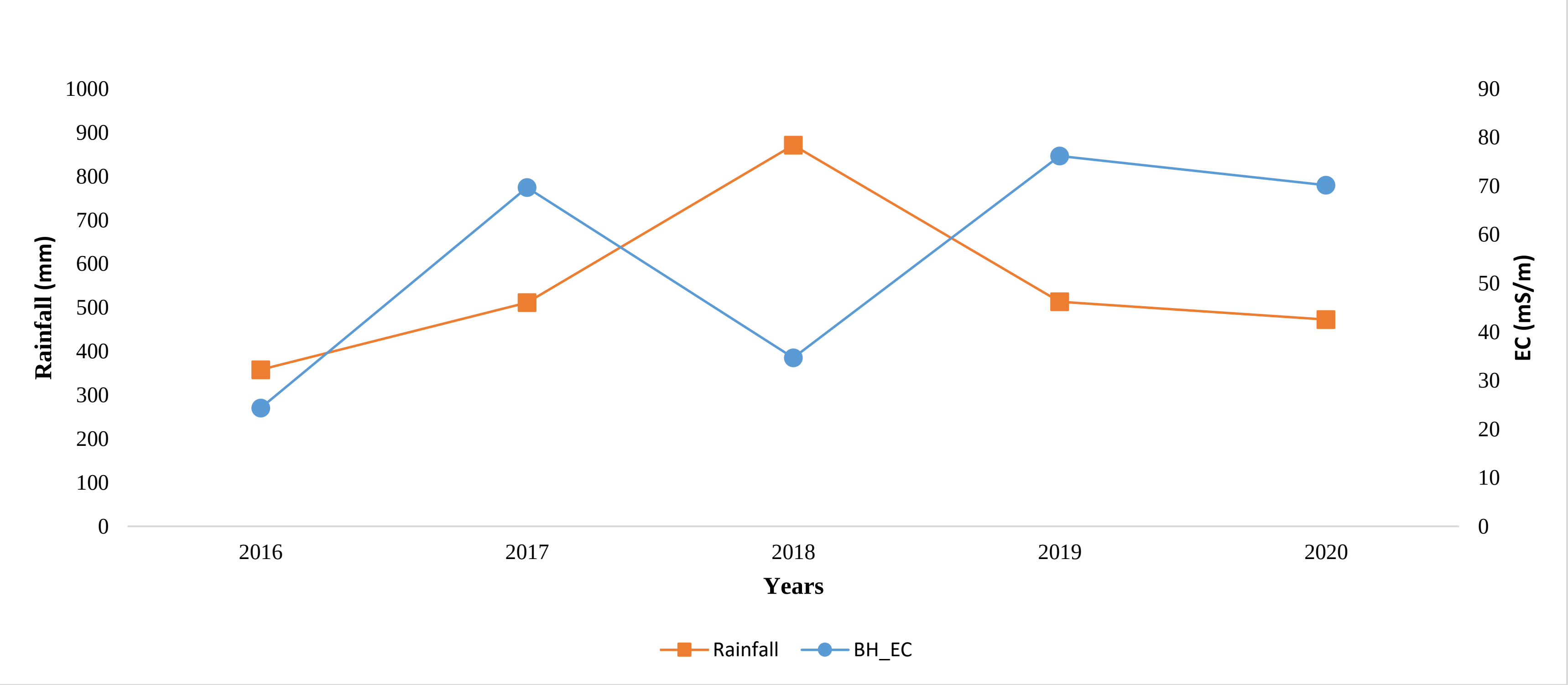

Figure 8: The annual cumulative rainfall (mm) and average borehole electrical conductivity (mS/m) from 2016 to 2020.

4.3.2 Annual accumulative rainfall and annual average water levels from 2016 to 2020

The relationship between annual accumulated rainfall and the annual average borehole water level is depicted in Figure 9. The annual accumulative rainfall in 2016 was 358.1 mm, and the annual average borehole water level was recorded at 5.57 m. In 2017, the annual accumulative rainfall received was 511.6 mm, while the annual average borehole water level was 5.29 m. The annual accumulated rainfall received in 2018 was 877.3 mm, and the average borehole water level was 4.73 m. In addition, in 2019, annual accumulative rainfall declined to 513.4 mm, while the annual average borehole water level was 4.09 m. In the last year of the five-year study period, the annual accumulative rainfall received was 472.5 mm, and the annual average borehole water level was 4.46 m. The correlation coefficient analysis is shown in Table 12. The results show that there is a low negative (R = -0.260) correlation between annual accumulative rainfall and annual average borehole water level. There is no significant difference between annual accumulative rainfall and annual average borehole water level at a p-value of 0.36 (Table 13).

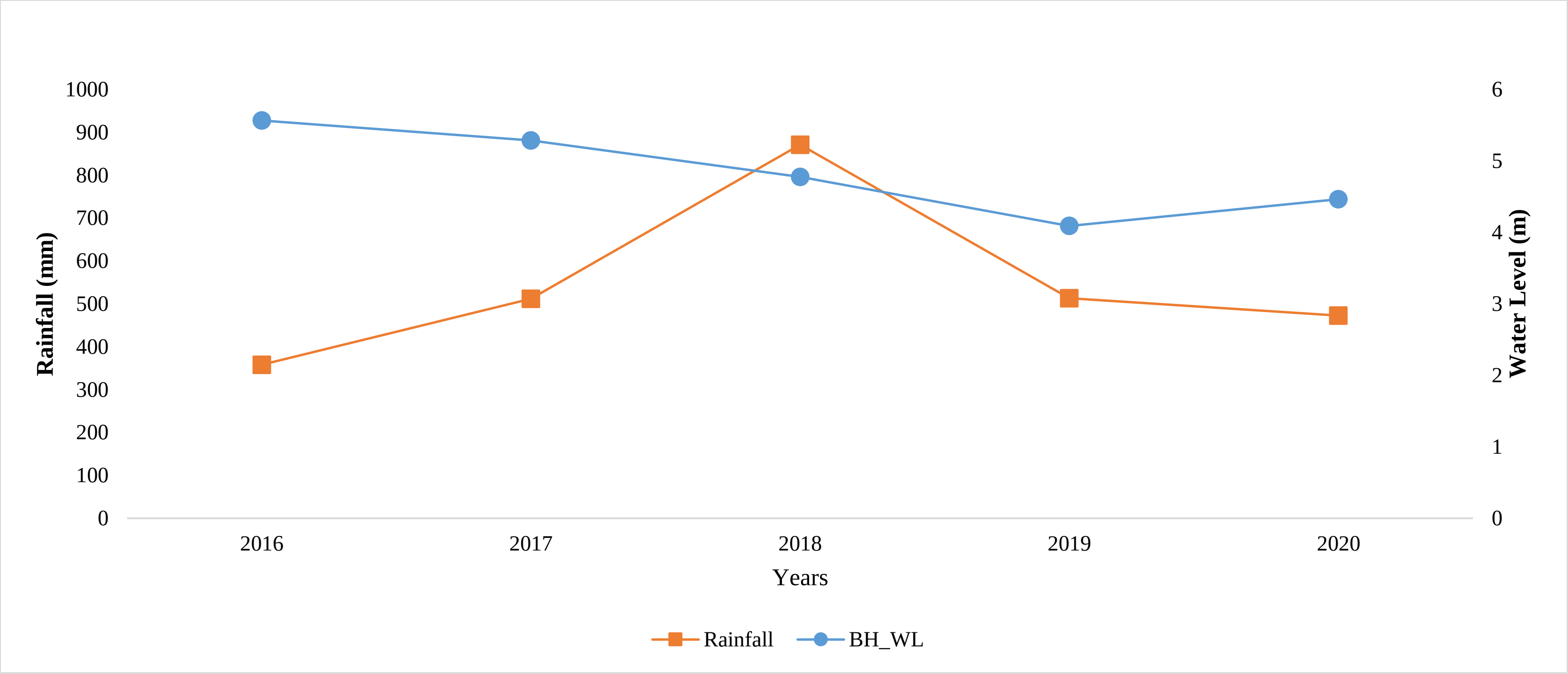

Figure 9: Annual accumulative rainfall (mm) and annual average borehole water level (m) from 2016 to 2020

4.3.3 The annual cumulative rainfall and sugarcane yields from 2016 to 2020

The relationship between the annual accumulated rainfall and annual yield is presented in Figure 10. In 2016, an annual accumulative rainfall of 358.1 mm was received, with an annual yield of 83 tons/ha recorded. The following year 2017, the annual accumulative rainfall was 511.6 mm, with a sugarcane yield harvest of 83 tons/ha. Additionally, in 2018, the harvested annual sugarcane yield was 83 tons/ha, while the rainfall received was 871.3 mm. Furthermore, in 2019, an annual accumulative rainfall of 513.4 mm was received, with an annual sugarcane yield of 50 tons/ha. Lastly, in 2020 the Makhathini irrigation scheme harvested an annual sugarcane yield of 50 tons/ha; the annual accumulative rainfall received was 472.5 mm. The correlation coefficient analysis is also illustrated in Table 12. The findings show a low positive ($R^2 = 0.248$) correlation between annual accumulative rainfall and annual sugarcane yield. The results indicate no significant difference between annual accumulative rainfall and annual sugarcane yield at a p-value of 0.461 (Table 13).

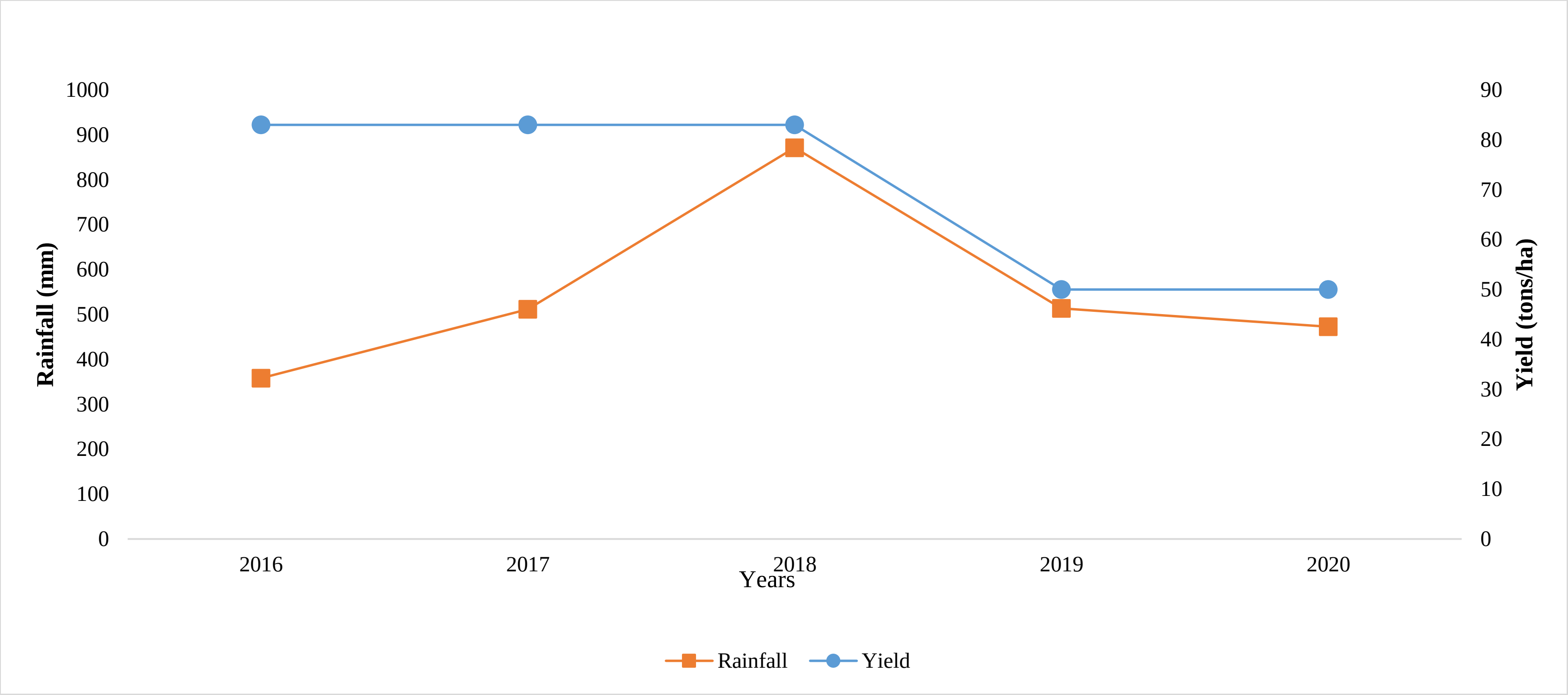

Figure 10: The annual accumulative rainfall (mm) and annual yields (tons/ha) from 2016 to 2020

Table 12: Correlation analysis between rainfall, borehole electrical conductivity, water level, and sugar cane yield

	BH_EC	BH_WL	Yield	Rainfall
BH_EC	1			
BH_WL	-0.634	1		
Yield	-0.700	0.854	1	
Rainfall	-0.173	-0.260	0.248	1

Table 13: Regression analysis of annual accumulative rainfall, electrical conductivity (EC), water level (WL), and Yield

Variables	R^2	p-value
Borehole electrical conductivity	0.030	0.106
Borehole water level	0.067	0.357
Yield	0.062	0.461

4.4 Analysis of annual soil salinity and annual sugarcane yield of the Makhathini Irrigation Scheme

This section demonstrates the analysis of annual average soil salinity expressed by soil electrical conductivity measured in mS/m and annual sugarcane yield measured in tons/ha of the Makhathini irrigation Scheme from 2016 to 2020.

The average soil electrical conductivity was measured at 32.77 mS/m in 2016. A value of 36.67 mS/m was measured in 2017 for the soil's electrical conductivity; in 2018, 43.01 mS/m was recorded. In 2019, the soil electrical conductivity was 48.21 mS/m, while it was measured at 60.38 mS/m in 2020, as shown in Figure 11. The single-factor ANOVA analysis for annual average soil salinity is illustrated in Table 14. The results show a significant variation with a p-value of less than 0.001.

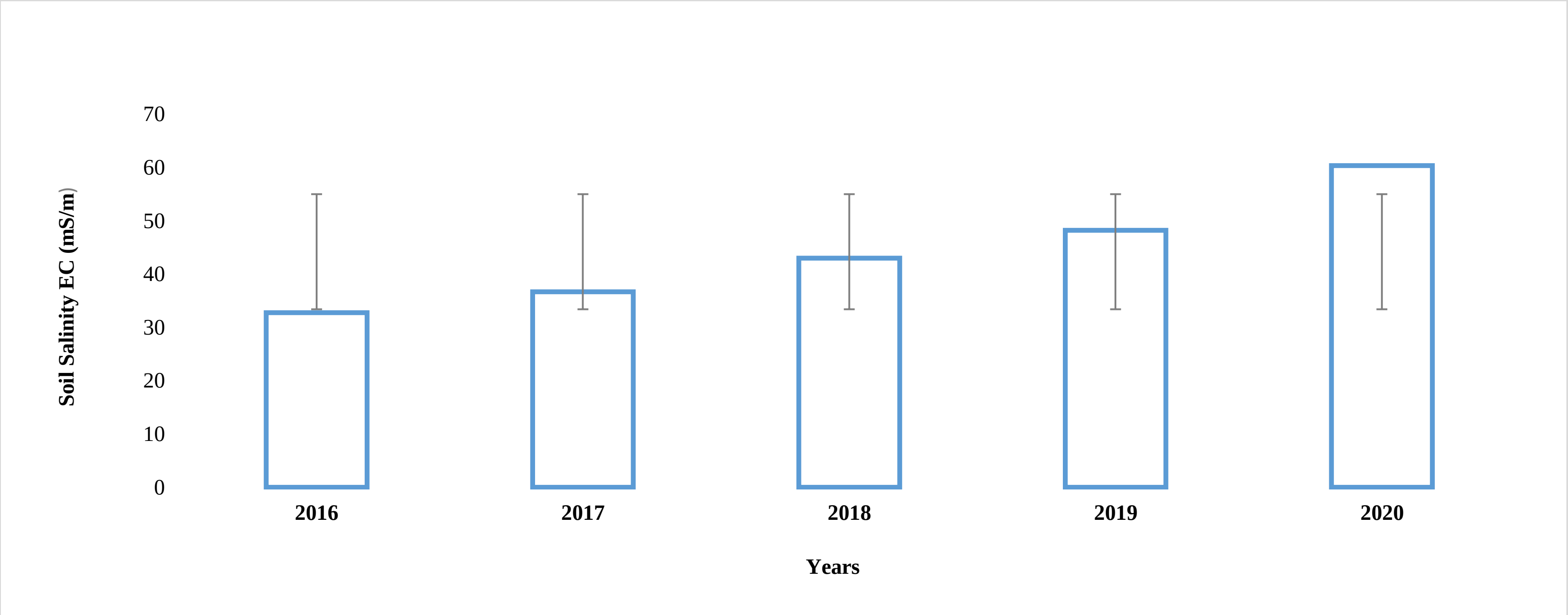

Figure 11: Annual Average Soil salinity of Makhathini Irrigation Scheme from 2016 to 2020. The bars indicate the standard error.

The regression analysis between the annual yield and average soil salinity is demonstrated in Figure 12. Figure 12 shows a negative linear relationship between annual yield and annual average soil salinity. The annual sugarcane yield and average soil salinity are statistically significant p = 0.005) (Figure 12).

Table 14: Anova: Single Factor Analysis of soil salinity

Source of Variation	SS	df	MS	F	p-value	F-critical
Between Groups	9739637	1	9739637	163473.6	<0.001	5.317655
Within Groups	476.6341	8	59.57926			
Total	9740114	9				

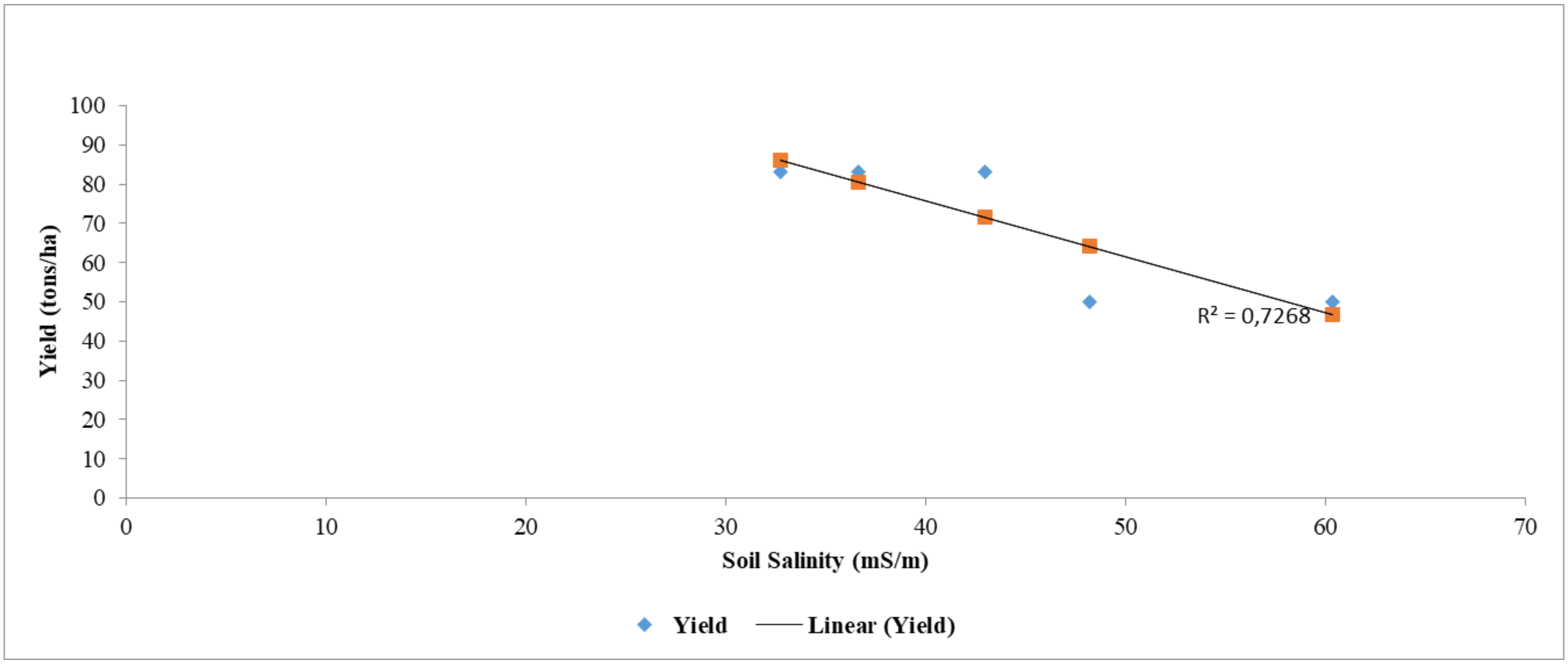

Figure 12: Regression analysis between annual yield (tons/ha) and annual average soil salinity (mS/m) ($p = 0.005$).

CHAPTER 5: DISCUSSION

This chapter discusses the interpretation of the borehole water properties analysis: electrical conductivities, water levels, and temperatures over different seasons between 2016 and 2020. It also provides an analysis of changes in irrigation water quality from Jozini/Pongola Dam over the seasons from 2016 to 2020. It further gives a comprehensive analysis of the influence of rainfall on borehole water properties and sugarcane yield. The chapter also shows the analysis of soil salinity in the Makhathini Irrigation Scheme and its impact on sugarcane yield from 2016 to 2020.

5.1 Borehole water properties, electrical conductivity, water level, and temperatures analyses

5.1.1 Borehole Electrical Conductivity

The electrical conductivity of boreholes shows that the overall mean and standard deviation changed between the dry and wet seasons. The dry season showed low levels of EC, while the wet season had high levels of EC across the five years (2016 – 2020). The findings are supported by a study conducted by Kumar (2016) on the influence of water level fluctuation on groundwater solute content in a tropical South Indian region, which revealed that EC increases post-monsoon (wet season). A similar finding was confirmed by Shabalala *et al*. (2013) in a study conducted on the Bonsma Dam located in the southern Drakensberg, KwaZulu-Natal, who found that EC levels are higher during the wet season as compared to the dry season. During the wet season in the Makhathini Irrigation Scheme, a high level of rainfall was received, contributing to the leaching of accumulated salts from the soil profile into the water table. The study by Ndlovu and Demlie (2020) indicated that KwaZulu-Natal receives 813 – 1382 mm of rainfall in the wet season.

Furthermore, Mmualefe and Torto (2011) noted that if there was a dilution of the accumulated salts during the wet seasons, then one would expect the EC levels to be low in the wet season. In the Makhathini Irrigation Scheme, salts accumulate in the soils during the dry seasons due to the overapplication of fertiliser. However, the accumulation is only evident in the wet season because the rain washes the accumulated salts into the water table, and it is therefore seen in the borehole EC levels. According to Reinders *et al*. (2016b), the inappropriate application of fertiliser causes excess nitrification, which accelerates soil salinisation.

In this study, the Tukey test shows that boreholes B9 and B17 had a significantly higher level of EC compared to the other 17 boreholes from 2016 to 2020; these boreholes are located in the North block of the Makhathini Irrigation Scheme, where the elevation is lowest. According to Lee *et al.* (2007), water electrical conductivity has an inverse relationship with topographic elevation. The compliance of EC levels according to South African Water Quality Guidelines shows that EC levels obtained in 2016 and 2018 were within the acceptable range, whereas in 2017, 2019, and 2020, EC levels were higher than the acceptable range and would be considered to be saline (DWAF, 1996). Furthermore, some abandoned agricultural lands under the Makhathini Irrigation Scheme have been noted to have salinisation problems (Reinders *et al*., 2016b). It is evident that there has been a build-up of salt in the Makhathini Irrigation Scheme from 2017 to 2020. In 2018, when high rainfall was recorded, there was a decline in EC levels due to rainfall leaching. Rainfall assists in the leaching of salt where poor irrigation water quality is being used (Minhas *et al*., 2019).

Similar to the results of SAR, the surface water electrical conductivity results show that PR1 was classified as "good," while PR2 surface water electrical conductivity was classified as "fair." The positive (cations) and negative (anions) ions produced when salts dissolve in water, such as bicarbonate ($HCO3^-$), Ca^{2+}, and Mg^{2+}, from the Makhathini Irrigation Scheme's return flow, could be attributed to the increase in surface water electrical conductivity (Fourie, 2017; DWAF, 1996). According to Shabalala *et al.* (2013), the increase in electrical conductivity levels in the river downstream of the Makhathini Irrigation Scheme may be due to the salt runoff during the wet season. The current study's mean electrical water conductivity ranged from 9.26 to 60.13 mS/m from 2016 to 2020. According to South African Water Quality (SAWQ) guidelines for agriculture: irrigation use of an EC threshold concentration level of 40 mS/m is accepted.

5.1.2 Borehole water levels

The borehole water levels for dry and wet seasons at the Makhathini Irrigation Scheme varied from 2016 to 2020. As expected, during the dry season, the borehole water levels were deep, while in the wet season, the borehole water levels were shallow. The results in Table 5 show that the borehole water levels for AMJ, JAS, OND, and JFM were deep across all sampling seasons. The deep borehole water levels across all seasons may be attributed to the drought that occurred in 2015/16, affecting South Africa and the whole Southern Region (Baudoin *et al*., 2017). In 2016, the Makhathini Irrigation Scheme recorded the lowest amount of accumulated rainfall. A study by Kahlown and Ashraf (2005) recommended that the ideal borehole water level for irrigated crops ranges from 1.5 m to 2.0 m. The average borehole water levels for the months of AJM, JAS, OND, and JFM were all below the recommended range, which is considered deep and less prone to waterlogging.

In 2017, borehole water levels for all sampling seasons were deep. However, OND and JFM borehole water levels rose during the wet season. The rise in borehole water levels may be attributed to the average rainfall received in 2017. Although there was an increase in water levels for the months OND and JFM, the overall average water levels remained below the optimum depth of 1.5 m to 2.0 m, which is ideal for irrigation or irrigated crops (Kahlown and Ashraf, 2005). During the months of AMJ and JAS in 2018, borehole water levels were deep; however, they were shallow for the months of OND and JFM. The shallow borehole water levels recorded during the wet season months were caused by heavy rainfall. The average water levels for the months of AMJ and JAS were within the recommended borehole water level for irrigation; however, in the months of OND and JFM, the borehole water levels were above the ideal level of 1.5 to 2.0 m, which is considered shallow and susceptible to waterlogging (Kahlown, and Ashraf, 2005).

The water level in boreholes was deep for months of AMJ, JAS, and JFM in 2019 and only shallow in OND. The shallow borehole water levels for the months of OND were due to rainfall received during the beginning of the wet season. Kahlown and Ashraf (2005) state that the water levels for the months of AMJ, JAS, and JFM were within the recommended borehole water level range. However, for the months of OND, the borehole water levels were above the recommended range. The borehole water levels for the year 2020, during the months of AMJ, JAS, and OND, were considered deep, whereas, for the months of JFM, the borehole water levels were shallow. The shallow borehole water levels for the months JFM were caused by wet season rainfall. According to Kahlown, and Ashraf (2005), the water levels for the months of AMJ, JAS, and OND were within the recommended borehole water level range. However, for the months of JFM, the borehole water levels were above the recommended range, which may be prone to waterlogged conditions.

The overall findings for the change in borehole water levels across the years and seasons indicate that rainfall is directly linked to borehole water level fluctuation. Sugarcane is a water-intensive crop and is grown in the Makhathini Irrigation Scheme. Most irrigated fields have reported difficulties with shallow water tables due to too frequent irrigation during the dry season and high rainfall during the wet season (Reinders *et al*., 2016b).

5.1.3 Borehole Temperature

According to Lee *et al.* (2007), groundwater temperature normally increases with borehole depth. Hence, the expectation is that the deep borehole water levels will have a high borehole temperature. Interestingly, in the Makhathini Irrigation Scheme, borehole temperature results for dry and wet seasons remained constant from 2016 to 2020. The constant borehole temperature for the Makhathini Irrigation Scheme may be attributed to all borehole monitoring points being at a depth of 18 m. A study by Kaur *et al*. (2011) on water-table behaviour for the Indian Punjab using GIS showed that the water table monitoring depth beyond 20 m is considered deep.

5.2 Irrigation water quality analysis

The results for irrigation water quality from Jozini/Pongola dam were sampled upstream (PR1) and downstream (PR2). The pH values for PR1 and PR2 show no statistically significant difference between the two sampling points. Both PR1 and PR2 are classified as "good" per the South African Water Quality Guidelines for Irrigation Water Classes, shown in Table 10. Makhathini Irrigation Scheme receives water with a good pH from Jozini/Pongola Dam from 2016 to 2020.

The findings of the sodium adsorption ratio indicate that PR1 had a "good" SAR, while PR2's SAR was "fair" across all seasons. The increase in SAR at PR2 could be attributed to an increase in Ca^{2+} and Mg^{2+} due to the return flow from Makhathini Irrigation Scheme, which occurs when bicarbonates, Ca^{2+}, and Mg^{2+} are present, and water pH is above 8.0 (Howell *et al.*, 2018; Van der Laan *et al*., 2012; Richards, 1954).

The results for nitrate and nitrite show an increase from PR1 to PR2 for the summer, autumn, and spring seasons. The nitrate and nitrite concentration at PR1 was classified as "good", while in PR2, nitrate and nitrite concentrations were only classified as "good" in the winter season. The increase in nitrate and nitrite concentrations at PR2 of the Makhathini Irrigation Scheme is attributed to runoff during the wet season when nutrients are discharged into the river (Shabalala *et al*., 2013).

The results for phosphate show a significant increase at PR2 compared to PR1. Contrary to the findings of Araújo *et al*. (2011), who in their study found that phosphate levels slightly increased during the wet season, the results of this study show that phosphate concentration does not vary with seasonal changes and is classified as unacceptable at the downstream (PR2) sampling point. This might be attributed to runoff from agricultural soils and domestic, farm, and industrial effluent during the rainy season (Trujillo-González *et al*., 2017).

The general findings for irrigation water quality parameters, namely pH, SAR, EC, NO_3^{-}, and NO_2 and PO_4^{-} show that the Makhathini Irrigation Scheme receives good quality irrigation water from the Jozini/Pongola dam at PR1 and discharges polluted water with agricultural effluents at PR2. With the exception of electrical conductivity (EC), sodium adsorption ratio (SAR), and phosphate, most of the evaluated chemical parameters were within acceptable ranges for water quality suitable for agricultural use. However, irrigators/farmers must manage the irrigation volumes carefully as it may lead to salt build-up, soil salinisation, and waterlogging in the long term. Plants may be stressed, and overall output might decrease if the environment has high EC and SAR levels (Hussain *et al*., 2019). Phosphate was found to be the major contributor to water quality degradation, which is discharged to the Pongola River at PR2. The presence of phosphorus in surface water can be attributed to multiple origins, such as agricultural soil run-off, as well as the discharge of domestic, farm, and industrial effluents (Shabalala *et al*., 2013). Water bodies that contain a high nutrient load, specifically nitrate and phosphate, tend to promote the proliferation of aquatic vegetation. However, this phenomenon has a detrimental impact on water quality, as it accelerates the growth of algal clusters, causes unpleasant odours, and leads to discoloration (Singh, 2013). The findings of the water quality study may indicate that the farmers in the Makhathini Irrigation Scheme manage fertiliser amounts and other agricultural inputs poorly, which may lead to the runoff of agricultural effluents into the Pongola River.

5.3 Correlation analyses

The results of the correlation analysis between annual accumulative rainfall and annual average borehole electrical conductivity showed a low negative correlation over the five years.

The correlation analysis between annual accumulative rainfall and annual average borehole water levels from 2016 to 2020 indicates a low negative correlation. The association between rainfall and borehole water levels show that an increase in rainfall results in shallow water levels. A study by Hussain *et al*. (2022) on water table response to rainfall and groundwater simulation using correlation analysis also found that the rise in the water table linearly depends on the rainfall amount per event. In 2016, the Makhathini Irrigation Scheme experienced drought, hence the deep borehole water levels. However, in 2018 high rainfall resulted in a shallow borehole water level.

The correlation analysis between annual accumulated rainfall and annual sugarcane yield from 2016 to 2020 indicates a low positive relationship. The results show that an increase in rainfall also increases yield. However, the low positive correlation coefficient shows a weak association between these two variables. According to Nell *et al.* (2015), the Makhathini Irrigation Scheme receives irrigation water from Jozini/Pongola dam and occasionally supplements irrigation with rainfall. The sugarcane is not rainfed-dependent, hence the minimal impact of rain on the yield received from 2016 to 2020.

The overall observation indicates that, although rainfall impacted borehole electrical conductivity, borehole water levels and sugarcane yield, its impact was minimal. Rainfall has a favourable impact on EC and negatively influences borehole water levels.

5.4 Annual soil salinity and annual sugarcane yield of the Makhathini Irrigation Scheme

The analysis results reveal a change in annual soil salinity from 2016 to 2020. The soil's electrical conductivity increased as the years progressed from 2016 to 2020. The accumulation of EC is attributed to various factors such as geology, agricultural land use and soils of the area (Shabalala *et al*., 2013). A study conducted in Uganda shows that the EC increases in dry seasons due to the evaporation of groundwater (Ngabirano *et al*., 2016). Therefore, the observed increase in EC at the Makhathini Irrigation Scheme from 2016 to 2020 may result from agricultural inputs, high evaporation, and excessive irrigation, which leads to the concentration of salts in the soil. The Makhathini Irrigation Scheme's geological characteristics may also contribute to the salts' accumulation. Marine deposits and localised salt-affected regions adversely impact the Makhathini Irrigation Scheme geology (Nell *et al.*, 2015). The Makhathini Irrigation Scheme soils consist of relatively high clay and silt content. As a result of salts that dissolve when discharged into water and are retained in clay soils with naturally poor hydraulic conductivity, the EC of clay soils is often high (Warrence *et al*., 2002). This may explain the high soil electrical conductivity of the Makhathini Irrigation Scheme.

The results shown in Figure 16 indicate a negative linear relationship between soil salinity and yield. The negative linear association indicates that an increase in soil salinity results in a decrease in yield. A study by Morway and Gates (2012) shows that high soil salt concentrations may limit water mobility and negatively impact plant production. In addition, high EC may prevent plants from competing for ions in water and soil, resulting in the toxicity of ions such as chloride and sodium (De La Mora-Orozco *et al*., 2018).

The overall analysis of soil salinity in the Makhathini Irrigation Scheme reveals a gradual increase in the soil's electrical conductivity over the five years. The build-up of salts causes a reduction in the amount of sugarcane that can be harvested.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

Several significant findings could be established in light of the established study objectives and research questions. The findings of this study confirm that the conditions of salinisation and waterlogging coexist. The water logging problem was evident in the Northern block of the scheme, where boreholes B9 and B17 are located, which warrants the need to implement necessary mitigation measures. This study also established a link between rainfall, borehole water properties, soil properties and sugarcane yield in the Makhathini Irrigation Scheme, which are key to determining the water table patterns and making informed decisions in managing irrigation volumes, waterlogging and salinity. Based on the findings of this research, it is clear that interactions of water levels and borehole electrical conductivity indicate that borehole water should be managed to minimise salt leaching and accumulations in the soil profile. Other mitigation options should be considered, such as reusing drained water for irrigation. This will supplement the water supply and aid in improved fertiliser applications, which may reduce non-point source water pollution.

One of the practical approaches to address the waterlogging problem would be the installation of a drainage system. This will be helpful when an intermittent ponding technique is used to help remove the accumulated salt in the soil profile; thus, it is important to consider this. The crop choice from perennial crops to seasonally appropriate crops also need to be considered. The waterlogging in the Makhathini Irrigation Scheme will be lessened, and the quantity of water applied will be reduced.

Proper management must also be given to the interaction between EC, water level, rainfall, and irrigation volumes applied. There is a possibility that salts may accumulate in the soil profile during dry periods. Continuous monitoring of EC and water levels may be necessary, as well as using irrigation to flush salts from the soil profile while adjusting the fertiliser applications accordingly. In contrast, heavy rainfall may result in nutrient leaching and should be considered when scheduling fertiliser applications. The study's findings show a high concentration of PO_4^- in the return flow from the Makhathini Irrigation Scheme. Fertiliser-rich drained water should be handled according to guidelines to help farmers reduce non-point pollution and the decline of the water quality of nearby rivers and dams.

Except for SAR, EC, and PO_4^-, which may be attributable to human inputs, seasonality, and geological weathering, respectively, most water quality metrics were within acceptable levels of fitness for agricultural use. The majority of the water quality parameters were within acceptable limits of fitness for agricultural use. It was determined that these elements contributed to the decline of water quality. The EC and SAR of the water fell somewhere in the middle of the good and fair irrigation classes, which indicates that it is only moderately suitable for irrigation. Although they exceeded the recommended limits, the water is still moderately suitable for irrigation. SAR and EC may cause salinity and sodicity problems over the long run; however, these problems will need to be monitored. The contaminated drained water could end up in nearby waterbodies such as rivers, thus threatening aquatic life.

Lastly, the findings from this research will assist in informing the government department (Department of Agriculture) in prioritising the North Block for the installation of subsurface drainage systems in the Makhathini Irrigation Scheme in order to address salt and waterlogging issues that may occur in the future. Unless the situation is addressed, the salt and waterlogging issues will result in the loss of the field for sugarcane production, which would be catastrophic for the farmers of Makhathini, who depend on agriculture for their livelihood.

6.1 Limitations

This study aimed to characterise borehole water and soil properties across seasons for 2016–2020 and establish links to rainfall and sugarcane yield in the Makhathini Irrigation Scheme, KwaZulu-Natal, in order to identify areas prone to waterlogging and salinization. The constraints encountered were as follows:

- The available data were inadequate to proceed with any further investigations.
- Poor irrigation scheme maintenance prevents access to borehole monitoring points and hinders data collection.
- Inadequate maintenance of irrigation schemes poses a hindrance to the accessibility of borehole monitoring points and impedes the collection of data.
- A number of the borehole monitoring locations have incurred damage as a result of agricultural activities related to soil preparation.

6.2 Future studies

The findings of this study provide recommendations for guiding future research in the study areas and throughout South Africa:

- Influence of fertiliser and agrochemicals to soil salinity in the Makhathini Irrigation Scheme.
- Irrigation and rainfall effects on Makhathini Irrigation Scheme's shallow water table patterns.
- A study to explore the potential that dilapidated underground infrastructure has on waterlogging in the Makhathini Irrigation Scheme.
- Impact of drained/saline water on the receiving environment.
- Investigate farmers' perception of adopting on-farm best management practices and use of water efficiency technology.

REFERENCES

Ali, H., 2011. Practices of Irrigation & On-farm Water Management: Volume 2 (Vol. 2). Springer Science & Business Media.

Araújo, F.G., Costa de Azevedo, M.C. and Lima Ferreira, M.D.N., 2011. Seasonal changes and spatial variation in the water quality of a eutrophic tropical reservoir determined by the inflowing river. *Lake and Reservoir Management*, *27*(4), pp.343-354.

Ayars, J.E., Christen, E.W., Soppe, R.W. and Meyer, W.S., 2006. The resource potential of in-situ shallow ground water use in irrigated agriculture: a review. *Irrigation Science*, *24*, pp.147-160.

Backeberg, G.R., Bembridge, T.J., Bennie, A.T.P., Groenewald, J.A., Hammes, P.S., Pullen, R.A. and Thompson, H., 1996. Policy Proposal for Irrigated Agriculture in South Africa. WRC Report No. KV96/96. *Water Research Commission*, *Pretoria*, *South Africa*.

Barnes, A.C., 1974. Agriculture of the Sugar Cane. Second Edit.

Bastiaanssen, W.G., Allen, R.G., Droogers, P., D'Urso, G. and Steduto, P., 2007. Twenty-five years modelling irrigated and drained soils: State of the art. *Agricultural Water Management*, 92(3), pp.111-125.

Basu, N., and Van Meter, K., 2014. Sustainability of Groundwater Resources. *Comprehensive Water Quality and Purification*, pp.57-75. https://doi.org/10.1016/B978-0-12-382182-9.00062-1

Baudoin, M.A., Vogel, C., Nortje, K. and Naik, M., 2017. Living with drought in South Africa: lessons learnt from the recent El Niño drought period. *International Journal of Disaster Risk Reduction*, 23, pp.128-137.

Bernstein, L., Francois, L.E. and Clark, R.A., 1966. Salt Tolerance of N. Co. Varieties of Sugar Cane. I. Sprouting, Growth, and Yield 1. *Agronomy Journal*, 58(5), pp.489-493.

Bui, E.N., 2017. Causes of soil salinization, sodification, and alkalinization. In *Oxford Research Encyclopedia of Environmental Science*.

Chaieb, G., Abdelly, C. and Michalet, R., 2019. Interactive effects of climate and topography on soil salinity and vegetation zonation in North-African continental saline depressions. *Journal of Vegetation Science*, 30(2), pp.312-321.

Cherchian, S.C., 2019. Effect of water application methods on salinity leaching efficiency in soils of different textures. University of California, Riverside.

Chhabra, R. and Chhabra, R., 2021. Irrigation and salinity control. *Salt-affected Soils and Marginal Waters: Global Perspectives and Sustainable Management*, pp.487-544.

Choudhary, O.P. and Kharche, V.K., 2018. Soil salinity and sodicity. *Soil Science: An Introduction*, 12, pp.353-384.

Connor, J.D., Schwabe, K., King, D. and Knapp, K., 2012. Irrigated agriculture and climate change: the influence of water supply variability and salinity on adaptation. *Ecological economics*, 77, pp.149-157.

Cucci, G., Lacolla, G., Boari, F., Mastro, M.A. and Cantore, V., 2019. Effect of water salinity and irrigation regime on maize cultivated on clay loam soil and irrigated by furrow in Southern Italy. *Agricultural Water Management*, 222, pp.118-124.

Dandekar, C.B. and Chougule, B.A., 2010. Drainage of irrigated lands. In *9th International Drainage Symposium held jointly with CIGR and CSBE/SCGAB Proceedings, 13-16 June 2010, QuÃŠbec City Convention Centre, Quebec City, Canada* (p. 1). American Society of Agricultural and Biological Engineers.

Darzi-Naftchali, A., Mirlatifi, S.M., Shahnazari, A., Ejlali, F. and Mahdian, M.H., 2013. Effect of subsurface drainage on water balance and water table in poorly drained paddy fields. *Agricultural Water Management*, 130, pp.61-68.

De La Mora-Orozco, C., González-Acuña, I.J., Saucedo-Terán, R.A., Flores-López, H.E., Rubio-Arias, H.O. and Ochoa-Rivero, J.M., 2018. Removing organic matter and nutrients from pig farm wastewater with a constructed wetland system. *International Journal of Environmental Research and Public Health*, 15(5), p.1031.

Deng, C. and Bailey, R.T., 2020. Assessing causes and identifying solutions for high groundwater levels in a highly managed irrigated region. *Agricultural Water Management*, 240, p.106329.

Department of Agriculture, Forestry and Fisheries (DAFF), 2014. Sugarcane Production Guidelines. Directorate Knowledge and Information Management. Pretoria.

Department of Water Affairs and Forestry (DWAF), 1996. South African Water Quality Guidelines (second edition). Volume 4: Agricultural Use: Irrigation. Pretoria.

Dev, G. and Bajwa, M.S., 1972. Studies on salt tolerance of sugarcane. *Indian Sugar Calcutta.*

Devkota, K.P., Devkota, M., Rezaei, M. and Oosterbaan, R., 2022. Managing salinity for sustainable agricultural production in salt-affected soils of irrigated drylands. *Agricultural Systems*, 198, p.103390.

Dikeogu, T.C., Okeke, O.C., Nwachukwu, H.G.O. and Agbo, C.C., 2021. Salinization and Waterlogging in Agricultural Lands: Causes, Effects and Mitigation.

Dominy, C., Haynes, R. and Van Antwerpen, R., 2002. Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. *Biology and Fertility of Soils*, 36(5), pp.350-356.

Dubb, A., 2016. The Rise and Decline of Small-Scale Sugarcane Production in South Africa: A Historical Perspective. *Journal of Agrarian Change*, 16(4), pp.518-542.

Dubois, O., 2011. The state of the world's land and water resources for food and agriculture: managing systems at risk. Earthscan.

Ehlers, L., Barnard, J.H., Dikgwatlhe, S.B., Van Rensburg, L.D., Ceronia, G.M., Du Preez, C.C. and Bennie, A.T.P., 2007. Effect of Irrigation and Water Table Salinity on the Growth and Water Use of Selected Crops. WRC Report No. 1359/1/06. *Water Research Commission*, Pretoria, South Africa. p.150.

Ehlers, L., Bennie, A.T.P. and Du Preez, C.C., 2003. The contribution of root accessible water tables towards the irrigation requirements of crops. *Water Research Commission, Pretoria, South Africa*.

Fair Labour Association, 2012. Improving Workers' Lives Worldwide – Task and Risk Mapping of Sugarcane Production in India. Available online: http://www.fairlabour.org/sites/default/files/documents/reports/task_and_risk_mapping_of_sugarcane_production_in_india.pdf (accessed 29 May 2022).

Ferro, N.D., Berti, A., Matthews, P., Giardini, L. and Morari, F., 2010. Study of the effects of structure on soil aggregate stability using a 3D network model. In *Proceedings of the 19th World Congress of Soil Science: Soil solutions for a changing world, Brisbane, Australia, 1-6 August 2010. Symposium 2.1. 2 the physics of soil pore structure dynamics* (pp. 87-89). International Union of Soil Sciences (IUSS), c/o Institut für Bodenforschung, Universität für Bodenkultur.

Fourie, K.L., 2017. Evaluation of salinity and irrigation guidelines for lucerne (Doctoral dissertation, University of the Free State).

Freisem, C. and Scheumann, W., 2001. Institutional arrangements for land drainage in developing countries (Vol. 28). IWMI.

Gany, A.H.A., Sharma, P. and Singh, S., 2019. Global review of institutional reforms in the irrigation sector for sustainable agricultural water management, including water users' associations. *Irrigation and drainage*, 68(1), pp.84-97.

Garside, A.L. and Bell, M.J., 2007. The value of legume breaks to the sugarcane cropping system-cumulative yields for the next cycle, potential cash returns from the legume, and duration of the break effect. In *Proceedings of the 2007 Conference of the Australian Society of Sugar Cane Technologists held at Cairns, Queensland, Australia, 8-11 May 2007* (pp. 299-308). Australian Society of Sugar Cane Technologists.

George, E., Horst, W. J., and Neumann, E., 2012. Adaptation of Plants to Adverse Chemical Soil Conditions. *Marschner's Mineral Nutrition of Higher Plants (Third Edition)*, pp.409-472. https://doi.org/10.1016/B978-0-12-384905-2.00017-0

Ghamarnia, H., Gowing, J. and Rose, D., 2004. Water use from shallow saline water tables in wheat lysimeter experiment. In *Proceedings of ICID Interregional Conference on food production and water: social and economic issues of irrigation and drainage, Moscow, Russia, 5-11 September 2004* (pp. 2-9). International Commission on Irrigation and Drainage (ICID).

Gowing, J.W., Rose, D.A. and Ghamarnia, H., 2009. The effect of salinity on water productivity of wheat under deficit irrigation above shallow groundwater. *Agricultural Water Management*, 96(3), pp.517-524.

Gupta, R.K. and Abrol, I.P., 1990. Salt-affected soils: their reclamation and management for crop production. *Advances in Soil Science*, pp.223-288.

Gustafson, E. J., Miranda, B. R., Shvidenko, A. Z. and Sturtevant, B. R., 2020. Simulating Growth and Competition on Wet and Waterlogged Soils in a Forest Landscape Model. *Frontiers in Ecology and Evolution*, 8, p.443.

Hailu, B. and Mehari, H., 2021. Impacts of Soil Salinity/Sodicity on Soil-Water Relations and Plant Growth in Dry Land Areas: A Review. *Journal of Natural Science Research*, 12(3), pp.1-10.

Hopmans, J.W., Qureshi, A.S., Kisekka, I., Munns, R., Grattan, S.R., Rengasamy, P., Ben-Gal, A., Assouline, S., Javaux, M., Minhas, P.S. and Raats, P.A.C., 2021. Critical knowledge gaps and research priorities in global soil salinity. *Advances in Agronomy*, 169, pp.1-191.

Hornbuckle, J.W., Christen, E.W., Ayars, J.E. and Faulkner, R.D., 2005. Controlled water table management as a strategy for reducing salt loads from subsurface drainage under perennial agriculture in semi-arid Australia. *Irrigation and Drainage Systems*, 19(2), pp.145-159.

Houk, E., Frasier, M. and Schuck, E., 2006. The agricultural impacts of irrigation induced waterlogging and soil salinity in the Arkansas Basin. *Agricultural Water Management*, 85(1-2), pp.175-183.

Howell, C.L., Myburgh, P.A., Lategan, E.L. and Hoffman, J.E., 2018. Effect of irrigation using diluted winery wastewater on the chemical status of a sandy alluvial soil, with particular reference to potassium and sodium. *South African Journal of Enology and Viticulture*, 39(2), pp.1-13.

Hussain, F., Wu, R.S. and Shih, D.S., 2022. Water table response to rainfall and groundwater simulation using physics-based numerical model: WASH123D. *Journal of Hydrology: Regional Studies*, 39, p.100988.

Hussain, S., Shaukat, M., Ashraf, M., Zhu, C., Jin, Q. and Zhang, J. (2019). 'Salinity Stress in Arid and Semi-Arid Climates: Effects and Management in Field Crops', in Hussain, S. Climate Change and Agriculture. IntechOpen. DOI: 10.5772/intechopen.87982.

Kahlown, M.A. and Ashraf, M., 2005. Effect of shallow groundwater table on crop water requirements and crop yields. *Agricultural Water Management*, 76(1), pp.24-35.

Kaur, S., Aggarwal, R. and Soni, A., 2011. Study of water-table behaviour for the Indian Punjab using GIS. *Water Science and Technology*, 63(8), pp.1574-1581.

Khwidzhili, R.H. and Worth, S.H., 2016. The sustainable agriculture imperative: implications for South African agricultural extension. *South African Journal of Agricultural Extension*, 44(2), pp.19-29.

Kumar, S.P.J., 2016. Influence of water level fluctuation on groundwater solute content in a tropical south Indian region: a geochemical modelling approach. *Modeling Earth Systems and Environment*, 2(4), pp.1-9.

KwaZulu Natal Department of Agriculture Rural Development (KZNDARD), 2016. Makhathini Research Station. Research Directorate.

Lee, J.Y., Lee, G.S. and Song, S.H., 2007. An Interpretation of Changes in Groundwater Level and Electrical Conductivity in Monitoring Wells in Jeiu Island. *Journal of the Korean Earth Science Society*, 28(7), pp.925-935.

Leogrande, R. and Vitti, C., 2019. Use of organic amendments to reclaim saline and sodic soils: a review. *Arid Land Research and Management*, 33(1), pp.1-21.

Li, X., Chang, S.X. and Salifu, K.F., 2014. Soil texture and layering effects on water and salt dynamics in the presence of a water table: a review. *Environmental Reviews*, 22(1), pp.41-50.

Maas, E.V. and Hoffman, G.J., 1977. Crop salt tolerance—current assessment. *Journal of the Irrigation and Drainage Division*, 103(2), pp.115-134.

Machado, R.M.A. and Serralheiro, R.P., 2017. Soil salinity: effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. *Horticulture*, 3(2), p.30.

Mackay, A.D., Saggar, S., Trolove, S.N. and Lambert, M.G., 1995. Use of an unsorted pasture sample in herbage testing for sulphur, phosphorus, and nitrogen. *New Zealand Journal of Agricultural Research*, 38(4), pp.483-493.

Madramootoo, C.A., Johnston, W.R. and Willardson, L.S. eds., 1997. *Management of agricultural drainage water quality* (Vol. 13). Food & Agriculture Organisation.

Malota M, Senzanje A., 2016. A diagnosis of sub-surface water table dynamics in low hydraulic conductivity soils in the sugar cane fields of Pongola, South Africa. *Physics and Chemistry of the Earth*, 92, pp.61-69.

Marthews, T.R., Quesada, C.A., Galbraith, D.R., Malhi, Y., Mullins, C.E., Hodnett, M.G. and Dharssi, I., 2014. High-resolution hydraulic parameter maps for surface soils in tropical South America. *Geoscientific Model Development*, 7(3), pp.711-723

Materechera, S.A., 2011. Soil salinity in irrigated fields used for urban agriculture under a semi-arid environment of South Africa. *African Journal of Agricultural Research*, 6(16), pp.3747-3754.

Meyer, J.H. and Van Antwerpen, R., 2001. September. Soil degradation as a factor in yield decline in the South African sugar industry. In *Proceeding of the International Society of Sugar Cane Technologies*, 24, pp. 8-15.

Meyer, W.S., White, B. and Smith, D., 1998. Water use of Lucerne over shallow water tables. *International Water & Irrigation Review*, 18(3), p.4.

Minhas, P.S., Qadir, M. and Yadav, R.K., 2019. Groundwater irrigation induced soil sodification and response options. *Agricultural Water Management*, 215, pp.74-85.

Mjindi Farming. 2016. Annual report 2015/16. Jozini: Mjindi Farming (Pty) Ltd.

Mjindi Farming. 2017. Annual report 2016/17. Jozini: Mjindi Farming (Pty) Ltd.

Mjindi Farming. 2018. Annual report 2017/18. Jozini: Mjindi Farming (Pty) Ltd.

Mjindi Farming. 2019. Annual report 2018/19. Jozini: Mjindi Farming (Pty) Ltd.

Mjindi Farming. 2020. Annual report 2019/20. Jozini: Mjindi Farming (Pty) Ltd.

Mmualefe, L.C. and Torto, N., 2011. Water quality in the Okavango Delta. *Water Sa*, 37(3).

Moore, P.H. and Botha, F.C. eds., 2013. Sugarcane: physiology, biochemistry and functional biology. John Wiley & Sons.

Morway, E.D. and Gates, T.K., 2012. Regional assessment of soil water salinity across an intensively irrigated river valley. *Journal of Irrigation and Drainage Engineering*, 138(5), pp.393-405.

Muir, B.M., Rhodes, R., Naidoo, P. and Eweg, M.J., 2010. The South African and Southern African Regions–Part I: Sugarcane Production. In Sustainability of the Sugar and Sugar− Ethanol Industries. *American Chemical Society*, pp. 83-97.

Mvelase, L.M., 2021. The economic impact of a sugar-sweetened beverages tax in South Africa (Doctoral dissertation, University of Kwa-Zulu Natal).

Ndlovu, M.S. and Demlie, M., 2020. Assessment of meteorological drought and wet conditions using two drought indices across KwaZulu-Natal Province, South Africa. *Atmosphere*, 11(6), p.623.

Nell, J.P., Niekerk, A.V., Muller, S.J., Vermeulen, D., Pauw, T., Stephenson, G.R. and Kemp, J.N., 2015. Methodology for monitoring waterlogging and salt accumulation on selected irrigation schemes in South Africa. WRC Report, (TT 648/15). *Water Research Commission, Pretoria, South Africa.*

Nelson, P. and Ham, G., 1998. BSES Burdekin, and the Cooperative Research Centre for Sustainable Sugar Production. In *Proceedings of the Australian Society of Sugar Cane Technologies*, 20, pp. 245-250.

Nelson, P.N. and Ham, G.J., 2000. Exploring the response of sugarcane to sodic and saline conditions through natural variation in the field. *Field Crops Research*, 66(3), pp.245-255.

Ngabirano, H., Byamugisha, D. and Ntambi, E., 2016. Effects of seasonal variations in physical parameters on quality of gravity flow water in Kyanamira Sub-County, Kabale District, Uganda.

Nishiuchi, S., Yamauchi, T., Takahashi, H., Kotula, L. and Nakazono, M., 2012. Mechanisms for coping with submergence and waterlogging in rice. *Rice*, *5*, pp.1-14.

Northey, J.E, Christen, E.W, Ayars, J.E. and Jankowski J. 2006. Occurrence and measurement of salinity stratification in shallow groundwater in Murrumbidgee Irrigation Area, south-east Australia. *Agricultural Water Management*, 81, pp.23-40.

Nour, A.H., El-Wakeel, A.F. and Allam, A.L., 1989. Effect of soil salinity on sugarcane yield. In *Proceeding of the International Society of Sugar Cane Technology*, 20th Congress (pp. 532-535).

Okur, B. and Örçen, N., 2020. Soil salinisation and climate change. In *Climate change and soil interactions* (pp. 331-350). Elsevier.

Oosterbaan, R.J. and Nijland, H.J., 1994. Determining the saturated hydraulic conductivity, chapter 12. *Drainage Principles and Applications, International Institute for Land Reclamation and Improvement (ILRI), Wageningen*, *1125*.

Osman, K.T., 2018. Saline and sodic soils. In *Management of soil problems* (pp. 255-298). Springer, Cham.

Qadir, M., Noble, A.D. and Chartres, C., 2013. Adapting to climate change by improving water productivity of soils in dry areas. *Land Degradation & Development*, 24(1), pp.12-21.

Rahman, M.M., Shahrivar, A.A., Hagare, D. and Maheshwari, B., 2022. Impact of Recycled Water Irrigation on Soil Salinity and Its Remediation. *Soil Systems*. 6(1), p.13.

Reinders, F.B., Oosthuizen, H., Senzanje, A., Smithers, J.C., Van der Merwe, R.J., Stoep, I. and Rensburg, L.V., 2016a. Development of technical and financial norms and standards for drainage of irrigated lands: Volume 3: Guidance for the implementation of surface and sub-surface drainage projects in South Africa. *WRC Report*, (TT 655/15). *Water Research Commission, Pretoria, South Africa.*

Reinders, F.B., Oosthuizen, H., Senzanje, A., Smithers, J.C., Van der Merwe, R.J., Stoep, I. and Rensburg, L.V., 2016b. Development of technical and financial norms and standards for drainage of irrigated lands Volume 2: Supporting information relating to the updating of technical standards and economic feasibility of drainage projects in South Africa. *WRC Report. Water Research Commission, Pretoria, South Africa.*

Reinders, F.B., Oosthuizen, H., Senzanje, A., Smithers, J.C., Van der Merwe, R.J., Stoep, I. and Rensburg, L.V., 2016c. Development of technical and financial norms and standards for drainage of irrigated lands: Volume 3: Guidance for the implementation of surface and sub-surface drainage projects in South Africa. WRC Report, (TT 655/15). *Water Research Commission, Pretoria, South Africa.*

Rhoades, J.D., 1974. Drainage for salinity control. *Drainage for Agriculture*, 17, pp.433-461.

Richards, L.A., 1954. Diagnosis and improvement of saline and alkali soils. Handbook No. 60. US Department of Agriculture, Washington, DC, p.160.

Rietz D, Haynes R. 2003. Effects of irrigation-induced salinity and sodicity on soil microbial activity. *Soil Biology & Biochemistry* 35:845–854.

Rietz, D.N. and Haynes, R.J., 2002. Effect of irrigation-induced salinity and sodicity on sugarcane yield. In *Proceeding of the South African Sugar Technology Association*, 76, pp.173-185.

Rietz, D.N., Haynes, R.J. and Chidoma, S., 2001. Effects of soil salinity induced under irrigated sugarcane in the Zimbabwean lowveld on soil microbial activity. In *Proceeding of the South African Sugar Technology Association*, 75, pp.68-75.

Rozeff, N., 1995. Sugarcane and salinity-a review paper. Sugar Cane (United Kingdom).

Rozema, J., 1994. Agricultural problems of saline arable land in Pakistan. In *Ecological responses to environmental stresses* (pp. 278-289). Springer, Dordrecht.

Shabalala, A.N., Combrinck, L. and McCrindle, R., 2013. Effect of farming activities on seasonal variation of water quality of Bonsma Dam, KwaZulu-Natal. *South African Journal of Science*, 109(7), pp.1-7.

Shahid, S.A., Zaman, M. and Heng, L., 2018a. Introduction to soil salinity, sodicity and diagnostics techniques. In *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques* (pp.1-42). Springer, Cham.

Shahid, S.A., Zaman, M. and Heng, L., 2018b. Salinity and sodicity adaptation and mitigation options. In *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques* (pp.55-89). Springer, Cham.

Shankar, V. and Evelin, H., 2019. Strategies for reclamation of saline soils. In *Microorganisms in saline environments: Strategies and functions* (pp. 439-449). Springer, Cham.

Sheldon, A.R., Dalal, R.C., Kirchhof, G., Kopittke, P.M. and Menzies, N.W., 2017. The effect of salinity on plant-available water. *Plant and Soil*, 418(1), pp.477-491.

Sibiya, T.G. and Hurly, K.M., 2011. Sustaining small-scale sugarcane cooperatives in South Africa through clustering, collaboration, goal alignment and record-keeping. Mt Edgecombe: KZN South Africa.

Singels, A, Sithole P, Mcfarlane S.A, Basdew I, Nicholson R.J, and Jones, M.R. 2020. Review of South African Sugarcane Production in the 2019/20 Season. South African Sugarcane Research Institute, Private Bag X02, Mount Edgecombe, 4300, South Africa

Singh, A., 2019. Environmental problems of salinisation and poor drainage in irrigated areas: Management through the mathematical models. *Journal of Cleaner Production*, 206, pp.572-579.

Singh, A.L., 2013. Nitrate and phosphate contamination in water and possible remedial measures. book: Environmental Problems and Plant Edition: Ist Chapter: Chapter Publisher: Springer Verlag GmbH Heidelberg, Germany Editors: Dwivedi, N, pp.44-56.

Singh, R., and Sengar, R., 2020. Effect of salinity stress on morphological and yield attributes of sugarcane (*Saccharum of ficinarum L.*) genotypes. *International Journal of Chemical Studies*. 8. 2312-2316. 10.22271/chemi.2020.v8.i5af.10648.

South African Sugar Association (SASA). 2012. South African Sugar Industry Directory 2012/13; South African Sugar Association (SASA): Durban, South Africa.

South African Sugar Association (SASA). 2020. South African Sugarcane Value Chain Master Plan to 2030 Report. p.4.

Stavi, I., Thevs, N. and Priori, S., 2021. Soil salinity and sodicity in drylands: A review of causes, effects, monitoring, and restoration measures. *Frontiers in Environmental Science*, p.330.

Stirzaker, R.J., 2009. Strategy, tactics, and heuristics for managing solutes in horticultural crops. In *VI International Symposium on Irrigation of Horticultural Crops,* 889, pp.59-65.

Stirzaker, R.J., 2011. Strategy, tactics and heuristics for managing solutes in horticultural crops. *Acta Horticulturae*. 889. pp.59-65. 10.17660/ActaHortic.2011.889.4.

Streutker, A., Molenaar, H.W., Hamman, H., Nel, C.C. and Mulder, J.H., 1981. Irrigation, crop yield and drainage on the Vaalharts irrigation scheme: 2. The occurrence of broken soil and the influence of drainage on it. *Water S.A.* 7(3), pp.175-184.

Suarez, D.L., Wood, J.D. and Lesch, S.M., 2006. Effect of SAR on water infiltration under a sequential rain–irrigation management system. *Agricultural Water Management*, 86(1-2), pp.150-164.

Trujillo-González, J.M., Mahecha-Pulido, J.D., Torres-Mora, M.A., Brevik, E.C., Keesstra, S.D. and Jiménez-Ballesta, R., 2017. Impact of potentially contaminated river water on agricultural irrigated soils in an equatorial climate. *Agriculture*, 7(7), p.52.

Van der Laan, M., Van Antwerpen, R., and Bristow, K.L., 2012. River water quality in the northern sugarcane-producing regions of South Africa and implications for irrigation: A scoping study. *Water SA*, 38(1), pp.87-96.

Van der Molen, W.H., Beltrán, J.M. and Ochs, W.J., 2007. *Guidelines and computer programs for the planning and design of land drainage systems* (No. 62). Food & Agriculture Organisation.

Vengosh, A., 2003. Salinization and Saline Environments. *Treatise on Geochemistry*, pp.1-35. https://doi.org/10.1016/B0-08-043751-6/09051-4

Von der Meden, E.A., 1966. Note on salinity limits for sugarcane in Natal. In *Proceedings of the South African Sugar Technology Association Congress*, 40, pp. 273-275.

Wallender, W.W., Grimes, D.W., Henderson, D.W. and Stromberg, L.K., 1979. Estimating the Contribution of a Perched Water Table to the Seasonal Evapotranspiration of Cotton 1. *Agronomy Journal*, 71(6), pp.1056-1060.

Walmsley RD, 2000. Perspectives on eutrophication of surface of waters: policy/research needs in South Africa. *Water Research Commission, Pretoria, South Africa.*

Wannakomol, A., 2005. Soil and groundwater salinization problems in the Khorat Plateau, NE Thailand: integrated study of remote sensing, geophysical and field data (Doctoral dissertation).

Warrence, N.J., Bauder, J.W. and Pearson, K.E., 2002. Basics of salinity and sodicity effects on soil physical properties. *Department of Land Resources and Environmental Sciences, Montana State University-Bozeman, MT*, *129*, pp.1-29.

Yannopoulos, S.I., Grismer, M.E., Bali, K.M. and Angelakis, A.N., 2020. Evolution of the materials and methods used for subsurface drainage of agricultural lands from antiquity to the present. *Water*, 12(6), p.1767.

Young, W.F., Horth, H., Crane, R., Ogden, T. and Arnott, M., 1996. Taste and odour threshold concentrations of potential potable water contaminants. *Water Research*, 30(2), pp.331-340.

Zalidis, G., Stamatiadis, S., Takavakoglou, V., Eskridge, K. and Misopolinos, N., 2002. Impacts of agricultural practices on soil and water quality in the Mediterranean region and proposed assessment methodology. *Agriculture, Ecosystems & Environment*, 88(2), pp.137-146.

Zhao, X., Xia, J., Chen, W., Chen, Y., Fang, Y., and Qu, F., 2019. Transport characteristics of salt ions in soil columns planted with Tamarix chinensis under different groundwater levels. *PLoS ONE*, *14*(4). https://doi.org/10.1371/journal.pone.0215138

Zulu, N.S., Sibanda, M. and Tlali, B.S., 2019. Factors affecting sugarcane production by small-scale growers in Ndwedwe Local Municipality, South Africa. *Agriculture*, 9(8), p.170.