

The long-term impact of Northern Wastewater Treatment Works effluent on macroinvertebrates and water quality in the Jukskei River.

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DEDICATION

This dissertation is dedicated to my wife and children, who have always been there for me, even when I had to spend time away from them and work on weekends to complete this program on time.

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ABSTRACT

In South Africa, poor wastewater treatment plant operation and maintenance and neglect of sewage treatment infrastructure have become a source of concern. This problem also manifests itself in the increasing incidence of untreated wastewater, which is non-compliant with national water resources legislation, policies, norms, and standards to protect water resources.

The Northern Wastewater Treatment Works is situated in the densely populated Gauteng Province. The study aim was to look at the long-term impacts of Northern Wastewater Treatment Works effluent on macroinvertebrates and water quality in the Jukskei River over ten years (2010-2020). The study primarily focused on historical data collected and analysed by Johannesburg Water SOC Ltd over ten years (2010–2020). Furthermore, some primary data was gathered and analysed using standard laboratory analysis methods.

The study investigated how wastewater effluent affected macroinvertebrates and the water quality of the Jukskei River concerning the issued water use licence, DWS general wastewater, and resource quality objectives (RQOs) limits. Standard aquatic sampling methods were used to collect primary data for the low and high flow surveys, which took place between July and October 2020. This period was representative of the dry and the wet season. The water quality was measured in situ with a handheld calibrated HACH meter for primary data. pH, conductivity (S/cm), temperature (°C), and dissolved oxygen (DO) in mg/L were among the constituents measured. Chemical water quality was also examined using standard sampling protocols. The water quality analysis was completed at a SANS accredited laboratory.

Macroinvertebrate sampling was conducted using a standard SASS net and dislodging macroinvertebrates from their habitat and MIRAI. The SASS5 survey was completed during primary data collection at different biotopes, i.e. stone biotopes, vegetation biotopes, and gravel, sand, and mud biotopes. The SASS5 data interpretation guideline was used to interpret the SASS5 information during the survey.

Secondary data included Johannesburg Water SOC Ltd.'s monthly water quality and biomonitoring data. The data from three selected monitoring points were collected over ten years, from January 2010 to October 2020, and analysed to establish historical trends and seasonal variation in contaminants loads for each parameter. The long term impact of wastewater was assessed using the following parameters; electrical conductivity, pH, nitrate, chemical oxygen demand, ammonia, *e coli*, phosphate (as orthophosphate) and suspended solids.

The collected data were arranged into dry and wet seasons. The data was analysed in Microsoft Excel to assess the differences in water quality of selected monitoring points and create time-series graphs to examine the changes in water quality variables over time. Furthermore, biomonitoring data were analysed to determine the available macroinvertebrate community at the three selected monitoring points. The overall results indicated that the critical parameters in the Jukskei River for all three selected monitoring points exceeded both general, licence wastewater discharge and RQO limits. The results also showed partial effectiveness of the Northern Works in treating wastewater. The water quality of the Jukskei River was found to have exceeded some of the essential parameters (Ammonia, suspended solids and *E. coli*). These could be due to equipment malfunctioning or high inflow, which is above the capacity of the works and non-point source pollution within the Jukskei River catchment.

The three sampling points were initially analysed separately, and then the data were merged to compare parameters from the three sampling sites. An ANOVA was used to determine any statistically significant difference between the three selected sampling sites. A p-value of 0.05 or less was considered statistically significant.

The results showed that out of eight parameters, only five parameters were compliant with WUL limits (EC, nitrate, COD, Orthophosphate and pH), and the other three (ammonia, suspended solids, *E. coli*) were not compliant with WUL's wastewater discharge limit. The final results showed that most results came from the upstream and discharge points of Northern Works.

The biomonitoring reports analysis of primary and secondary data collection has also shown a decrease in intolerant macroinvertebrates within the study area. The present ecological status has also deteriorated from category C to E/F, indicating that the Jukskei River has been significantly modified, probably due to different anthropogenic sources upstream and partially treatment of wastewater at the WwTW. The primary data also indicated that poor water quality has contributed to a poor community of macroinvertebrates. It was the dominant driver contributing to the modified state of the Jukskei River. The absence of intolerant taxa indicated changed Physico-chemical conditions within the Jukskei River.

Keywords: Water Quality; Management; Wastewater Treatment Works, Trends; History; Macroinvertebrates; Parameters and Jukskei River.

LIST OF ABBREVIATIONS

BOD:	Biological Oxygen Demand
CoJ:	City of Johannesburg
Cl:	Chlorine
DO	Dissolved Oxygen
DWS:	Department of Water and Sanitation
DWJ27:	Upstream sampling point
EC:	Ecological Category
<i>E. coli:</i>	<i>Escherichia coli</i>
EWR:	Ecological Water Requirements
IDP:	Integrated Development Plan
J5:	Downstream sampling point
JW:	Johannesburg Water
ML:	Megaliter
NH ₃ :	Ammonia
NO ₃ :	Nitrate
NFE:	Northern Final Effluent
NIWS:	National Integrated Water System
NWA:	National Water Act
NWRS:	National Water Resource Strategy
O ₂ :	Oxygen
PO ₄ ³⁻ :	Orthophosphate
PES:	Present Ecological State
pH:	Power of hydrogen
REC:	Recommended Ecological Category
RHP:	River Health Programme
RQO:	Resource Quality Objectives
SANS:	South African National Standard

SASS5:	South African Scoring System version 5
TDS:	Total Dissolved Solids
TS:	Total Solids
TSS:	Total Suspended Solids
TPC:	Threshold of Probable Concern
TWQR:	Target Water Quality Range
WAS:	Waste Activated Sludge
WSA	Water Services Authority
WRC:	Water Resource Classification
WwTW:	Wastewater Treatment Works
WRAP:	Wastewater Risk Abatement Plan
WUL:	Water Use Licence

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CHAPTER 1 INTRODUCTION

1.1 Background

Since 1956, South Africa made it mandatory that wastewater be treated to appropriate standards through the South African Water Act (Act 54 of 1956). It returned to the water stream from which it was obtained. Wastewater and sewage treatment plants became increasingly stressed as the water demand grew because of economic development and population increase (Mema, 2010).

According to Edokpayi *et al.* (2017), improperly treated wastewater can also have a significant impact mostly on receiving rivers, with hazardous consequences that can be immediate or continuous. High levels of ammonia and chlorine, high loads of oxygen-demanding compounds, or dangerous quantities of metals and organic pollutants cause acute consequences from wastewater effluents (Edokpayi *et al.*, 2017). Each of these factors led to a substantial decline in the quality of the aquatic ecosystem, resulting in changes in their abiotic characteristics and biotic communities (Dodds, 2006; Nothington and Hershey, 2005; Quinn and Hickey, 1990; Young *et al.*, 2008; Zhang *et al.*, 2014).

Gauteng is South Africa's most populous province; It has the smallest geographical area, which poses a challenge because of its high population density, putting strain on its water resources by producing a large volume of wastewater effluent (Landau and Gindrey, 2008). The Northern WwTW is located in the City of Johannesburg's quaternary catchment A21C and discharges its effluents into the Jukskei River. The first unit was commissioned in 1962 (Johannesburg Water, 2018).

Northern WwTW has been authorised to discharge 195 275 000 m³/a of wastewater into the Jukskei River. Johannesburg Water's Northern Wastewater Treatment Works is the largest domestic wastewater treatment plant in South Africa. It treats 400 Mega litres per day (ML/d) of domestic wastewater from the north of the Hillbrow ridge. It includes Alexandra, Randburg, Sandton and some regions in Midrand and Roodeplaat (Kamika *et al.*, 2014). According to Rampedi (2016), the Jukskei River has been plagued by various water quality issues, particularly bacterial ones and other causes such as rising pH levels and fluctuating concentrations of sulphates, potassium, and phosphates nitrates.

Macroinvertebrates can be long-term indicators of influences caused by WwTW effluents, as shown by Kosmala *et al.* (1999) in field and laboratory surveys (Davies *et al.*, 2012). Discharges of these effluents usually cause an increase in the amount of organic matter and nutrients in the water, which promotes an increase in microbial activity (Gulis and Suberkropp, 2003) and the

consequent reduction of dissolved oxygen concentration in water (Dodds, 2006). Poor water quality may compromise the population's health in direct contact with rivers (Haseena *et al.*, 2017).

1.2 Problem Statement and Rationale

Insufficient servicing and functioning of the WwTW structure is a cause of concern in South Africa (Mema, 2010). This poor operation of WwTW has led to many cases of non-compliance with national water act standards and guidelines meant to safeguard the country's water resources (Ntombela, 2013).

Water scarcity and the degradation of quality water have become major issues. The Department of Water and Sanitation (DWS) has been using different strategies, such as measures centred on command and control. Administrative and criminal justice tools use these targets and acceptable norms, implemented, reviewed, and enforced (Ntombela, 2013).

Due to poor performance and insufficient operation of wastewater treatment works, DWS also introduced the Green Drop Programme in 2008. A program is a tool based on incentives, instead of methods of command and control, to encourage compliance with the national water act objectives and principles rather than direct regulation, incentive, and reward. The incentive-based mechanism is established on DWS rewarding high-performing wastewater works, encouraging positive behaviour rather than punishing bad behaviour (Ntombela, 2016).

The Green Drop Programme aims to gradually improve wastewater management in South Africa by identifying and evolving the required core competencies. It further aims to draw together the current goodwill demonstrated by the Water Services Authority (WSA) and government support programs to achieve the focus, commitment, planning, and resources required for quality in wastewater treatment (Ntombela, 2016).

Gauteng is a densely populated province, which strains water resources because wastewater and sewage treatment plants are becoming increasingly stressed as the economy and population grow (Mitchell *et al.*, 2014).

A growing population puts pressure on the WwTW, pushing the WwTW plants to be capable of treating far more than the original purpose for which they were designed (Mitchell *et al.*, 2014). Due to equipment failures and the treatment works' inability to handle the increased loads, this could result in an untreated wastewater overflow into a river (Presiner, 2020). The discharge of untreated wastewater effluent poses a severe burden on water resources by changing water quality. The pollution of the river system has a negative impact on the health of aquatic organisms

as well. The Jukskei River passes through the Alexandra Township, which is a severely overpopulated area and creates pressure on the infrastructure and blocked sewers, triggering frequent overflows of waste into the river (Rampedi, 2016).

1.3 Research question

Is the Northern WwTW effluent having a long-term impact on macroinvertebrates and the water quality of the Jukskei River?

1.4 Research Aims

This study aimed to investigate the long-term impact of effluent from Northern Wastewater Works on macroinvertebrates and water quality in the Jukskei River. This will be assessed against Northern WwTW water use licence discharge limits, national general wastewater discharge limits, and resource quality objectives to determine any long-term impact on macroinvertebrates and water quality Jukskei River coming from Northern WwTW discharged effluent.

1.5 Research Objectives

To accomplish the aim, the following research objectives will be created:

- Examine the trends in concentration loads of selected chemical parameters and the physical and microbiological water quality values of primary data for two seasons (dry and wet seasons) of the selected monitoring points.
- To compare water quality trends with Water Use Licence discharge parameters, DWS Wastewater Quality Guideline and Resource Quality Objectives limits for the period of 10 years (2010 -2020) of selected monitoring points.
- To use the SASS5 macroinvertebrate bioassessment procedure in conjunction with Physico-chemical measurements to ascertain the availability of tolerant and intolerant macroinvertebrate communities and the present ecological state of Jukskei River.
- To examine the biomonitoring reports of secondary data to assess the present ecological state and availability of tolerant and intolerant macroinvertebrate communities at the selected monitoring points.

1.6 Limitation of the study

Due to time constraints for the collection and laboratory analyses of the water samples, the primary data were collected for only two seasons (wet and dry seasons). The study mainly focused on the secondary data available from Johannesburg Water (Pty) Ltd. However, the primary data sampled and analysed were used to validate the secondary data to see if the WwTW

was within the same range in the same seasons. These historical and primary data were used to assess contamination trends and loads within the Jukskei River. The parameters analysed were selected based on the availability of secondary data to allow comparison.

1.7 Layout of the Study

Chapter 1: Introduction

The chapter summarises the research's background information, research question, research aim and study objectives.

Chapter 2: Literature review

A review of similar studies was completed previously, both national and international, regarding the impact of wastewater treatment works effluent on water quality and macroinvertebrate communities.

Chapter 3: Methodology

This chapter describes the methods and materials utilised to collect data during the study period, and their limitations are discussed in detail in this chapter. It goes on to describe the study area's environmental setting.

Chapter 4: Data Analysis and Discussion of the Results

This chapter discusses the findings and results of the research study.

Chapter 5: Conclusion and Recommendations

The chapter reviews and finishes the study's research findings and makes various recommendations based on the study findings.

CHAPTER 2 LITERATURE REVIEW

2.1 Infrastructure of Wastewater Treatment Plants in South Africa

According to the Institute for Security Studies (2018), half of South Africa's water infrastructure is in disrepair, and restoring it will require significant financial investment as well as political will. According to the study, what is needed is an investment in basic infrastructure, such as repairing leaky pipes and wastewater treatment facilities. South Africa built this infrastructure once, and now it must maintain it (Donnenfeld *et al.*, 2018).

The 'Green Drop' report of 2014 (Donnenfeld *et al.*, 2018), the most recent in the series, by the Department of Water and Sanitation (DWS), also indicated that approximately 25% of South Africa's are in a 'grave state,' requiring immediate intervention, and the remaining 25% are classified as 'high risk,' because of poor maintenance.

According to Crookes *et al.* (2018), SA treats only about half of its wastewater, whereas arid Israel treats about 90%. Increasing the amount of wastewater treated would significantly increase the country's water supply, he adds. According to Crookes *et al.* (2018), Inaction on SA's current wastewater-treatment infrastructure could have disastrous consequences for population, the environment, and the economy. Municipalities in South Africa blame the deterioration of water infrastructure on a lack of government funding, but studies show that they used just over 30% of their allocated budget in 2009 (Mitchell *et al.*, 2014).

Most operational expenditure for the municipal wastewater sector was directed towards other expenditure items, including wastewater treatment chemicals and other raw materials. However, despite the poor state of most wastewater treatment works, only 17.4% of total expenditure was for repairs and maintenance of these treatment works (Water World, 2010). Municipal water and wastewater capital expenditure involve constructing new treatment plants and network expansion and rehabilitation. In 2009, South African municipalities were allocated R8.8816 billion for their water and wastewater capital budgets. These municipalities used 2814.4 million of their total allocated budget in 2009 (31.7%) (Water World, 2010).

Several municipalities, particularly district and local municipalities, do not keep up-to-date information about their wastewater treatment works. Such information is critical in understanding the funding requirements of wastewater treatment plants. This has resulted in poor maintenance of infrastructure. Municipalities need to effectively take advantage of their allocated budgets to justify their claim of limited funding from the national government. This under usage of capital

budgets has placed pressure on current infrastructure to meet increased demand for acceptable levels of service delivery in the water and sanitation sector (Haigh *et al.*, 2010).

Many wastewater treatment plants in South Africa discharge their waste directly into adjacent rivers or streams, which are utilised for various water needs by the surrounding villages. Goole *et al.* (2017) stated in their report of WwTW that Limpopo Province is rarely purified to a suitable standard, as confirmed by Edokpayi *et al.* (2017).

Emfuleni Leeuwkuil WwTW gets an average daily waste flow (ADWF) of 42,000 m³/d, 116% more than the plant's design capacity. Due to ageing infrastructure and insufficient maintenance, numerous bio-filters were no longer operational by 2016 (Eunice *et al.*, 2020). An activated sludge plant with a constructed capacity of 20000 m³/d, for example, handled a surplus hydraulic capacity of 40000 m³/d. In contrast, a bio-filter plant with a total of 16,000 m³/d received approximately 20000 m³/d of influent flow on average (Eunice *et al.*, 2020).

2.2 The State of Wastewater Treatment Plant in South Africa

Wastewater includes all used water in residential homes and businesses and stormwater and land runoff. It must be treated before being released into the environment to avoid destruction or threat to the environment or human health (Edokpayi *et al.*, 2017).

The fundamental purpose of wastewater treatment should be to safeguard public health and the environment by efficiently disposing of residential and industrial wastewater produced during water consumption (Edokpayi *et al.*, 2017). One purpose of wastewater treatment would be recycling wastewater for irrigation, thereby conserving finite water resources in arid and semiarid locations around the world. There was no treatment for wastewater (Edokpayi *et al.*, 2017). Instead, the effluent was channelled through gutters and canals from houses into waterways, eventually ending up in rivers, streams, lakes, and oceans that people used (Edokpayi *et al.*, 2017). Due to a smaller population and low population density and human activities, this natural treatment method based on reduction appeared sufficient, leading to a lower pollution burden than in current times (Edokpayi *et al.*, 2017).

Their investigation of wastewater treatment facilities in the Limpopo Province of South Africa found that wastewater is rarely treated to suitable standards, corroborated by Edokpayi *et al.* (2017). The findings showed that poor performance of wastewater treatment facilities in that region could be due to a lack of a budget dedicated for WwTW infrastructure, a scarcity of competent people, lousy design, or corruption (Edokpayi *et al.*, 2017).

A wastewater treatment plant contains grit, debris, suspended solids, nutrients, organic chemicals, and metals (Henze *et al.*, 2008). The municipal wastewater structure varies significantly from one location to the next (Henze *et al.*, 2008).

2.3 The Effects of Population Growth and Urbanization on Wastewater Treatment Works

Gauteng Province is South Africa's smallest province, accounting for 22.4 per cent of the country's population (Stats SA, 2010). Because of massive human activities such as agriculture, industry, and mining, which generate waste that has significant negative effects on the receiving environment, particularly on water quality, the province's water resources are stressed to a large extent. According to Naidoo and Olairan (2014), population growth and other human activities have significantly impacted water quality in the area, resulting in a decline in public health (Mothetha, 2016). Cities are rapidly growing, with recent estimates placing the global population at 7.2 billion populations. Despite this, metropolitan areas account for only 3-4 per cent of international land area but house half of the world's population.

Johannesburg is South Africa's largest metropolitan municipality in terms of population, size and economy. The city contributed around 16% to the national Gross Domestic Product (GDP) in 2020 (City of Johannesburg, 2020). The population of most urban settlements is growing as people migrate to these areas searching for employment or better living conditions from nearby sources of opportunity. Water and sewer pipes have become overburdened as the population has grown, resulting in frequent bursts and sewage effluent pollution of affected water bodies (Dube *et al.*, 2017).

According to Edokpayi *et al.* (2017), increased population and industrial growth resulted in many untreated wastes being channelled into water bodies as raw water. Eutrophication, fish kills, and cholera outbreaks have commonly been reported in communities that use contaminated water for domestic and other purposes (Edokpayi *et al.*, 2017).

2.4 State of Water Resources in South Africa

Water is a strategic natural resource that is transient in nature due to its fundamental physics and chemistry. This signifies it is a flux rather than a stock, unlike any natural resource (gold, coal, oil, and iron ore). Water's double essential characteristics: a change and fugitive in nature make it "special," and If correctly, it has the potential to become a renewable resource (Turton, 2018).

Freshwater supply is one of the world's most pressing issues, with surface sources providing around one-third of the world's drinking water (Edokpayi *et al.*, 2017). Its clean water and abundant biodiversity frequently distinguish Africa. There is no doubt that the quantity and quality

of water are critical to the ecosystem. Water scarcity in Africa is exacerbated by inadequate water and wastewater treatment, especially considering rising population increase and urban development (Wang *et al.*, 2014). Freshwater resources in South Africa are under severe pressure from existing anthropogenic impacts, and global climate change is likely to exacerbate this stress (Dallas *et al.*, 2014).

2.5 River Health

Poor water quality may compromise populations' health that directly contacts rivers (Haseena *et al.*, 2017). Several studies have found that wastewater treatment plants (WWTP's) discharge impact benthic macroinvertebrates ecosystems, even in rivers already under stress from other factors (Ortiz and Puig, 2007; Spanhoff *et al.*, 2007; Grantham *et al.*, 2012). Mostly, aquatic macroinvertebrates are common in most aquatic ecosystems and are typically sedentary with restricted mobility or sessile hence they are employed as markers to measure river health (Farrell *et al.*, 2015).

2.6 Mechanism for Wastewater Service Regulation and Control

According to Section 24 of South Africa's constitution (1996), everyone has the right to an environment that is not harmful to their health or well-being, as well as the right to have the environment protected for the benefit of current and future generations through reasonable legislative and other measures that prevent pollution and ecological degradation. The constitution considers the importance of protecting the environment and environmental degradation through the framework legislation and secondary legislation.

The regulation of wastewater services, on the other hand, is the responsibility of the national government and, more specifically, the Department of Water and Sanitation (DWS) (RSA, 1998). This includes, among other things, ensuring compliance with the country's water legislation, particularly water quality requirements, and punishing non-compliance (DWAf, 2003; Ntombela, 2013). The National Environmental Management Act (Act 107 of 1998) (NEMA), the National Water Act (Act 36 of 1998) (NWA), and the Water Services Act are all applicable laws in this regard. These pieces of legislation contain most of the legal provisions for regulating the pollution caused by the wastewater sector.

2.6.1 National Environmental Management Act of 1998 (Act 107 of 1998)

According to the National Environmental Management Act (Act 107 of 1998) (NEMA), the emphasis is on preventing ecosystem disruption and loss of biological diversity. As a result, it is concerned with wastewater dumping into rivers systems that can cause changes in the quality of

water and the disappearance of aquatic life due to contaminant concentrations. The Act also emphasises the importance of monthly monitoring of the quality of domestic wastewater discharges and ensuring that it meets effluent standards before release.

Anyone who commits an offence involving threatening species or protected species, or an alien species or commencing the commercialisation phase of bioprospecting without a permit issued in terms of Chapter 7, a fine may be determined, either in terms of subsection (1) or equal to three times the commercial value of the specimen or activity in respect of which the offence was committed, whichever is the greater (National Environmental Biodiversity Act (Act 10 of 2004)).

2.6.2 National Water Act of 1998 (Act 36 of 1998)

The act establishes a broad legal framework for the organisation of water resources, with Chapter 3 stating that water resource protection is required for their use, expansion, protection, administration, and management. Part 3 of the Act deals with the Reserve, consisting of the primary human needs reserve and the ecological reserve. The basic human needs reserve provides the essential needs of individuals served by the water resource in question and includes water for drinking, food preparation, and personal hygiene. The ecological reserve relates to the water required to protect the aquatic ecosystems of the water resource.

According to the act under Part 1: General Principles, requirements must be implemented, and only the licenced water users are permitted to undertake the following water use activities:

- Dumping waste or waste-contaminated water into a water resource through a pipe, canal, sewer vent, or other drains.
- Disposing of garbage in a way that could endanger a supply of water.
- Discharging of water that contains wastewater from or has been heated in any way during any industrial or power generation operation.

The National Water Act (Act 36 of 1998) (NWA) also develops and implements Resource Quality Objectives (RQO) to ensure that the country's water resources are protected and used in a sustainable manner in the future. The RQO's mission is to establish clear objectives for the quality of water resources (Table 1). The act also emphasises the need to strike a balance between the need for protection and the use of water resources (DWA, 2014). All key water resources within the Upper Crocodile Water Management Area (now known as Limpopo Water Management), of which the Jukskei River Catchment is a component, have been classified, and RQOs have been established (Mothetha, 2016). Resource Quality Objectives (RQOs) remain controlling goals that consider the reserve's and other users' quality requirements. Meeting the established RQOs will thus ensure that the resource is fit for use by its other users (Mothetha, 2016).

The overall ecological condition of the Jukskei River is in a D category, implying it is highly modified, with a significant loss of habitat, biota and ecosystem functioning (Singh *et al.*, 2015). Instream nutrient concentrations must be improved to maintain aquatic ecosystem health and water users' prescribed ecological category and water quality requirements. The pH range must be kept within defined ranges to support the aquatic ecology and water user requirements. The macroinvertebrate assemblage must be maintained or improved within the D ecological category (DWS, 2019).

According to the National Water Act, wastewater effluent discharged into South African river systems must be kept within permitted limits to avoid ecological concerns. A violation of Section 151 (2) of the National Water Act No. 36 of 1998 can result in a fine, up to five years in prison, and the cost of remediation (Table 1).

Table 1: DWS Wastewater Limits Values Applicable to Discharge of Wastewater into Water Resources (DWAF, 2013)

Substance/Parameter	General Limit	Special Limit
Faecal Coliforms (per 100 mL)	1000	0
Chemical Oxygen Demand	75 (i)	30 (i)
pH	5. 5-9.5	5.5-7.5
Ammonia (ionised and un-ionised) as Nitrogen (mg/l)	6	2
Nitrate/Nitrate as Nitrogen (mg/L)	15	1.5
Chlorine as free Chlorine (mg/L)	0.25	0
Suspended Solids (mg/L)	25	10
Electrical conductivity (mS/m)	70 mS/m above intake to a maximum of 150 mS/m	50 mS/m above background receiving water, to a maximum of 100 mS/m.

Ortho-Phosphate as phosphorous (mg/L)	10	1 (median) and 2.5 (maximum)
Fluoride (mg/L)	1	1
Soap, oil or grease (mg/L)	2,5	0
Dissolved arsenic (mg/L)	0,02	0,01
Dissolved Cadmium (VI) (mg/L)	0,005	0,001
Dissolved Copper (mg/L)	0,01	0,002
Dissolved Cyanide (mg/L)	0,02	0,01
Dissolved Iron (mg/L)	0,3	0,3
Dissolved Lead (mg/L)	0,01	0,006
Dissolved Manganese (mg/L)	0,1	0,1
Dissolved selenium (mg/L)	0,02	0,04
Dissolved Zn (mg/L)	0,1	0,04
Boron (mg/L)	1	0,5

Table 2: Resource Quality Objectives for Rivers and Dams for Upper Crocodile/ Hennops/ Hartebeespoort (DWS, 2019)

Indicator	Numerical RQO Limit
pH	6.5 (5 th percentile) and 9.0 (95 th percentile)
Electrical Conductivity	≤ 65 milliSiemens/metre (mS/m) (95 th percentile)
DO	≥ 6 milligrams/litre (mg/L)
Ammonia	≤ 0.1 milligrams/litre (mg/L) (95 th percentile)
Nitrate/Nitrite	≤ 4.0 milligrams/litre (50 th percentile)

Orthophosphate as Phosphorus	0.5 milligrams/litre (mg/L)
<i>E. coli</i>	130 counts/100 millilitres (95 th percentile)
Chloride	≤ 60 milligrams/litre (mg/L) (95 th percentile)

2.7 Command-and-Control Based Mechanism

South Africa regulates the wastewater treatment plant in terms of treatment and effluent discharge using a different command and control-based mechanism. The country does not operate in isolation; it is also a signatory to international standards and treaties. For a long time, DWS relied on command-and-control measures to implement the pieces above of legislation pertaining to water resource regulation. Such measures are based on directive-based regulation, in which objectives and acceptable standards are established and then applied, monitored, and enforced using administrative and criminal justice tools (Ntombela, 2013).

However, the effective use of these measures in the context of wastewater service regulation is limited due to the constitutional imperative of a cooperative government, which requires state organs to avoid criminal proceedings against one another (RSA, 1996). The Enforcement Protocol for Organs of State (Enforcement Protocol) is a command-and-control instrument, though it also considers the principle of cooperative government (Ntombela, 2013).

2.8 Mechanisms Based on Incentives

In light of the challenges facing the implementation of the Enforcement Protocol, DWS launched the Green Drop Programme in 2008. This programme is an incentive-based mechanism, which, in contrast to command-and-control type mechanisms, aims to facilitate compliance with regulatory objectives and standards through motivation and reward rather than direct regulation. The programme is based on DWS's realisation that rewarding positive behaviour may be more efficient and effective than sanctioning negative behaviour (Ntombela, 2013).

The Green Drop Programme aims to sustainably improve the quality of wastewater management in South Africa by identifying and developing the core competencies required to achieve this. Furthermore, it aims to draw together the current goodwill demonstrated by WSAs and existing

government support programmes to realise the focus, commitment, planning, and resources necessary to achieve excellence in wastewater treatment (DWA, 2013).

2.9 The Significance of a Wastewater Treatment Plant

To avoid harm or risk to the environment or human health, wastewater includes all used water in homes and industries, as well as stormwater and land runoff. It must be treated before being released into the environment (Edokpayi *et al.*, 2017). The primary goal of wastewater treatment is to protect human health and the environment by safely disposing of home and industrial wastewater produced during water consumption (Edokpayi *et al.*, 2017). One goal of wastewater treatment is to recycle wastewater for irrigation purposes, thereby conserving water resources limited in arid and semiarid regions of the world (Edokpayi *et al.*, 2017).

Wastewater treatment works are designed to remove organic debris, sediments, nutrients, bacteria-causing creatures, and other contaminants from wastewater influent before releasing it into the water resource (Mothetha, 2016). According to Manungufala *et al.* (2011), wastewater treatment works that are not operational significantly impact the river's water quality.

The generic mainstream wastewater treatment processes employed on the Northern WwTW works (Figure 1) shows a generic wastewater treatment process flow diagram that includes the following key components:

- Preliminary treatment includes wastewater screening, grit/detritus removal from waste, and influent wastewater flow metering.
- Primary sedimentation in circular sedimentation tanks with in-tank primary sludge thickening and primary scum removal.
- The PST overflow flow and load balancing are typically conducted in balancing/equalisation tanks, receiving the Primary Sludge fermentation products stream.
- Biological Nutrient Removal (BNR) treatment in a Johannesburg, 4-Stage activated sludge process incorporates pre-anoxic, anaerobic, anoxic, and aerated zones with appropriate internal recycling.
- Secondary clarification in circular clarifiers with effective separation of the activated sludge solids and the clear treated effluent. The Secondary Settling Tank underflow (return activated sludge) is recycled to the upstream BNR reactor.
- Disinfection uses an industrial product containing calcium hypochlorite dosed at a contact tank with sufficient retention time to achieve the target microbiological quality of the treated effluent.

In addition, Johannesburg Water developed and implemented primary sludge fermentation on all of their BNR treatment processes. The primary sludge is fermented to convert particulate COD compounds into readily biodegradable compounds (such as volatile fatty acids). The fermented Primary Sludge is then recycled back to the mainstream treatment process to enhance the Phosphorus and Nitrogen removal processes (Johannesburg Water Guidelines for the design of Wastewater treatment unit processes (Johannesburg Water Bulk Wastewater Design, 2019).

The mainstream wastewater treatment processes produce fermented primary sludge and waste activated sludge as by-products. Johannesburg Water is upgrading the sludge and bio-solids treatment portion of its operations to include the following key unit treatment processes:

- Waste activated sludge is typically screened and pre-thickened in traditional gravity thickeners. Gravity Belt Thickeners are increasingly applied to achieve a thickened WAS consistency of 5 to 6% total solids.
- Thickened Waste Activated Sludge (WAS) can then be further pre-conditioned using several microbiological cell lysis technologies upstream of the anaerobic digestion process. The cell lysis preconditioning is aimed at increasing the digestibility of the WAS.
- Thickened WAS that has been thickened (and possibly pre-conditioned) is fed to the anaerobic digesters. Waste fermented Primary Sludge is pumped separately to the anaerobic digesters but distributed via the same feed sludge distribution system.
- Combined sludge stabilisation is performed using anaerobic digesters, incorporating digester heating and mixing to maintain stable mesophilic digestion conditions.
- Biogas is captured from the anaerobic digestion process and has in the past been preferentially used as a fuel to heat the upstream anaerobic digestion process. JW is implementing several Biogas to Energy projects based on the Combined Heat Power (CHP) approach.
- Digested sludge is stored in a storage tank before further dewatering, typically using Belt Filter Press (BFP) technology. The dewatered sludge cake may be further processed on sludge drying/composting beds before final disposal for beneficial use in horticulture or agriculture.

The sludge treatment and stabilisation processes generate several sludge liquor recycle streams that contain high nitrogen and phosphorus levels. These sludge liquor recycling streams are collected and lime treated to precipitate excess phosphorus compounds. The pre-treated sludge liquor recycles streams are then returned to the mainstream treatment process, typically to preliminary treatment or upstream flow balancing tanks (Figure 1).

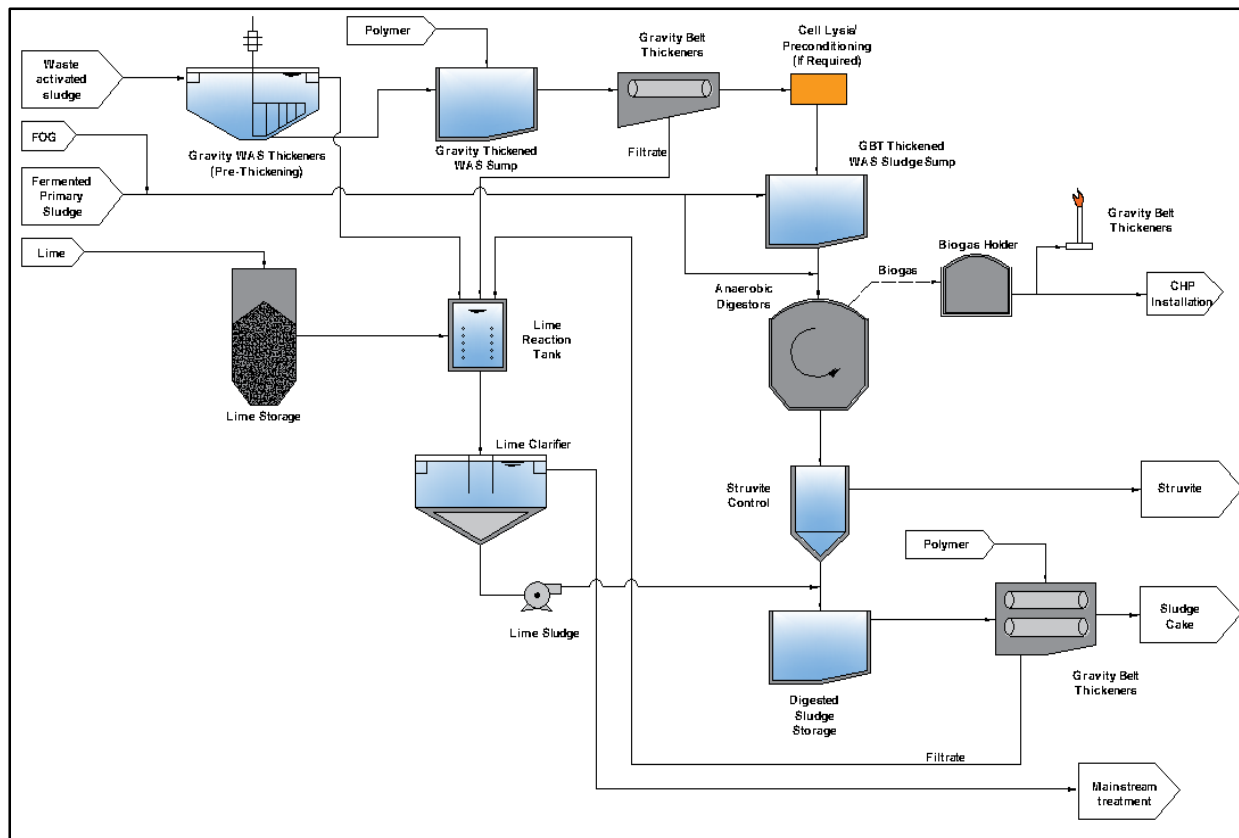


Figure 1: Northern WwTW Flow Schematic (Johannesburg Water, 2019).

2.10 Potential Impact of Wastewater Effluent on Water Quality and Macroinvertebrates

According to Akpor *et al.* (2011) and Englert *et al.* (2013), wastewater from treatment plants contains a high concentration of contaminants in the form of bacteria's, resulting in a decrease in the water quality of the water resource.

The quality of South Africa's municipal wastewater and sewer treatment infrastructure, according to Mema (2010), contributes to a range of water pollution issues waterborne diseases. Monitoring the effluent quality discharged into water sources is vital to preserving the ecosystem.

2.11 Microbial Pollution Caused by Wastewater Effluents

The most severe threat to human health is thought to be pathogenic microorganisms, according to Toze (2006) and Akpor *et al.* (2011). These contaminants enter the river through the release of partially treated wastewater or sewage leaks, the leakage of poorly maintained septic tanks, and runoff (Isobe *et al.*, 2004). Consumption of water polluted with these microbial contaminants results in infectious diseases including cholera, typhoid, hepatitis and cryptosporidiosis (WHO, 1993).

The study by Mema (2010) highlighted that the state of municipal wastewater and sewer treatment infrastructure in South Africa contributes to numerous water pollution problems such as diarrhoea and cholera outbreaks experienced in Delmas town, Mpumalanga Province in 2007.

2.12 Physical and Chemical Pollution Caused by Wastewater Effluent

In developing countries, pollution from physical and chemical substances in wastewater has become a big issue (Lokhande *et al.*, 2011). Untreated wastewater elevated the concentration levels of chemical variables up to 20 times the acceptable values for the water resource, according to a study conducted in Mumbai, India, by Lokhande *et al.* (2011).

According to Arpor and Muchie (2011) and Osonde (2007), the standard physical and chemical quality variables of concern in municipal wastewater include aluminium, ammonia, chemical oxygen demand (COD), chlorine, conductivity, dissolved oxygen (DO), faecal coliforms, fluoride, iron, magnesium, manganese, nutrients (nitrate and phosphate), pH, sodium, sulphate and suspended solids.

2.12.1 Non-metals

According to Gheorghe *et al.* (2017), metals are regularly discharged in aquatic systems through natural and anthropogenic sources such as industrial and domestic sewage discharges, mining, farming, electronic waste, anthropogenic accidents, navigation traffic, and climate change events like floods. Furthermore, metals dissolve quickly and absorb by fish and invertebrates, resulting in various negative impacts ranging from beneficial to fatal. Although some metals, such as micronutrients (Cu, Zn, Fe, Mn, Co, Mo, Cr, and Se) and (ii) macronutrients (Ca, Mg, Na, P, and S), are necessary for living organisms at low concentrations, at higher concentrations, they can cause toxic effects that disrupt organisms' growth, metabolism, or reproduction, with consequences for the entire trophic chain (Gheorghe *et al.*, 2017).

Non-essential metals including Pb, Cd, Ni, As, and Hg augment the overall harmful effect on organisms even at shallow doses. High quantities of metals in the environment may represent a concern to natural resources and human health due to their serious effects, long persistence, bio-accumulative qualities, and bio-magnification in the food chain (Gheorghe *et al.*, 2017).

2.12.2 Sulphates

Sulphates occur naturally in numerous minerals like barite, epsomite and gypsum m, and these minerals contribute to the mineral content when dissolved in water (WHO, 2004). Sulphates are commonly found in many natural glasses of water and wastewaters and are sometimes present in high concentrations due to their natural occurrence.

2.12.3 pH

pH indicates hydrogen presence and a measure of H⁺ ion activity (DWAF, 1996). The number of acids and bases in the water determines its acidity and alkalinity. The pH is neutral when both are present in equal levels or acidic when there are more acids than bases in the water (pH below 7). Freshwater with a high pH is toxic and corrosive due to the artificial addition of alkaline wastes. This can sometimes be attributed to the formation of ammonia from nutrient ions and reducing conditions (Dube, 2020).

Low and high pH levels impact both plant and animal life. For example, some fish will not survive at low pH levels, whereas acidic pH levels increase gill permeability in fish (Wright and Welbourn, 2002).

An increase in the pH (over 10.7) of the final effluent, according to Hodgson and Larmee (1998), could result in a reduction in coliforms. Phosphates precipitate metal ions, including calcium, magnesium, and iron, in wastewater when the pH rises, resulting in lower phosphorus contents (Powell *et al.*, 2008). The high pH of freshwater is also toxic and corrosive due to the artificial addition of alkaline wastes. Sometimes, this may be due to the formation of ammonia from nutrient ions and reducing conditions (Dube, 2020).

2.12.4 Total suspended solids

Suspended solids are particles that can enter surface water bodies from land-use practices, human-induced activities, erosion, disturbance of riparian vegetation and from industrial and domestic discharges carrying suspended sediment loads (DEAT, 2006). Suspended solids can be found in sanitary and industrial wastewaters (CCME, 2008). A high concentration of TSS impacts the aquatic environment by clouding (turbid) and increasing the temperature of the water body (Wilson, 2010). Wilson (2010) reiterated that as TSS levels increase, the water body begins to lose its ability to support the diversity of aquatic life (Mothetha, 2016).

2.12.5 Nutrients

Nutrients are the chemicals required by plants for growth and reproduction (Davies *et al.*, 1998). Some nutrients occur naturally and are essential for the normal development of living species. However, the same nutrients can be harmful if found at unacceptable levels, posing a risk to humans and animals. Nitrogen is primarily derived from raw faeces and untreated sewage. It has been discovered that nutrient loads result in lower dissolved oxygen concentrations in the receiving environment, negatively affecting the ecosystem (Morrison *et al.*, 2001).

Nutrients such as ammonia and nitrates are known to be fatally toxic to aquatic species at high concentrations, resulting in too much plant production and problematic algal blooms (Chapman, 1996). Nutrient ions in wastewater are derived from both inorganic fertiliser and domestic sewerage effluent. Failure to altogether remove these nutrients increases the risk of algal blooms in the water bodies receiving the waste (Odjadjare and Okoh, 2009).

2.12.5.1 Nitrates

Nitrates are naturally present in soil and water; however, an excess of nitrates (greater than 45 mg/L) can be considered a contaminant of surface and groundwater (Elias, 2004). According to Elias (2004), human activities are the principal cause of nitrate overload in water. Agriculture, human waste, and industrial pollutants contribute to these emissions (Nyenje *et al.*, 2010).

According to Odjadjare and Okoh (2010), the final wastewater effluents contribute nitrate to the receiving environment. As a result of algal blooms, excessive plant growth, oxygen depletion, and limited sunlight penetration, excessive nutrient enrichment in the water resource results in a loss of aquatic life and overall ecosystem damage (Odjadjare and Okoh, 2010).

2.12.5.2 Phosphates

Phosphorus is required for plant and animal growth. Phosphorus exists in freshwater and aquatic systems as a particulate and dissolved phase. Particulate matter includes living and dead plankton, phosphorus precipitates, phosphorus adsorbed to particulates, and amorphous phosphorus (Mosley *et al.*, 2004). Orthophosphate is derived from organic sewage waste and inorganic fertilisers, and the known significant sources of pollution include industrial effluent, household detergents, and human wastewater (Dube *et al.*, 2020).

Inorganic phosphorus (usually in the soluble orthophosphate form), organic phosphorus excreted by organisms, and macromolecular colloidal phosphorus make up the dissolved phase. Phosphate has no harmful impact on the body. However, if its content in water resources surpasses 1.0 mg/L, it can interfere with thickening in wastewater treatment facilities, causing organic particles harbouring bacteria that aren't removed before being distributed (Edokpayi *et al.*, 2017).

When wastewater effluent is discharged into bodies of water, phosphorus accumulates in the bodies of water where the effluent is discharged. In freshwater systems, phosphorus is often the limiting nutrient, but not all the time and any increase cause increased aquatic vegetation, resulting in eutrophication (Nyenje *et al.*, 2010).

2.12.5.3 Ammonia

Ammonia is a good indicator of water quality, particularly in land use where agricultural activities predominate because nitrogen is fixed in soil and water by plants and soil microbes and thus can end up in aquatic systems (Dube, 2020). Ammonia can be found in laundry detergents as well as industrial chemicals. Because high levels of ammonia and nitrates are commonly encountered, ammonia and nitrates are positively correlated to wastewater treatment works. Ammonia is reduced, then nitrite is formed, further oxidised to form nitrate. On the other hand, in areas with high COD levels, nitrates are reduced to form nitrites, which are then oxidised to form ammonia (Sanchez *et al.*, 2007). Ammonia, pH, and COD are closely related and influenced by the seasons (Dube, 2020).

According to Durga *et al.* (2011), ammonia in the surface water is usually due to domestic and agricultural wastes. Ammonium cation and hydroxyl ions are formed when ammonia dissolves in water. In soil and water, the ammonium cation is less mobile than ammonia and engages in biological processes such as nitrogen fixation, mineralisation, and nitrification (WHO, 2003a). Fish and other aquatic organisms are killed by ammonia gas. Nitrifying bacteria can break down ammonia to produce nitrites and nitrates in the presence of dissolved oxygen (WHO, 2003a).

2.12.6 Faecal Coliforms

According to Bartram and Balance (1996), waste discharge from municipal sewers is one of the world's most serious water quality issues. Human faeces are present in municipal sewage. Water contaminated by these effluents may contain pathogenic (disease-causing) organisms posing a risk to human health if used as drinking water or food preparation. Microbiological analysis is used routinely to detect faecal contamination in water. A higher sodium chloride concentration and an alkaline pH provide an ideal environment for faecal coliforms, particularly *Enterococcus* sp (WHO, 2011).

2.12.7 Temperature

The thermal conditions of a river catchment area are influenced by its climate, structural features, and anthropogenic activities (Palmer *et al.*, 2004). Water temperature increases typically cause decreased oxygen solubility and increased toxicity of certain chemicals, both of which can cause stress in many aquatic organisms (Palmer *et al.*, 2004). For spawning and the development of eggs and young, some aquatic creatures, such as fish, require a specified temperature (Petts, 1984).

2.12.8 Electrical Conductivity

Electrical conductivity measures water's ability to conduct an electric current (Dallas and Day 2004; (DWAF, 1996a). The EC measures the total amount of material dissolved in a water sample; it is frequently used to characterise water quality (Dallas and Day 2004). The EC value is proportional to the total dissolved solutes (TDS) in the water. TDS concentration changes can be toxic because the density of the water determines the flow of water into and out of the organism's cells (Mitchell and Stapp, 1992; Du Preez *et al.*, 2000). EC levels may increase naturally in the natural environment and due to anthropogenic activities such as domestic and industrial wastewater discharges and surface run-off (Du Preez *et al.*, 2000).

2.13 Relevant Case Studies

2.13.1 Study on the Impact of Wastewater on Macroinvertebrates and Water Quality

Mothetha (2016) researched municipal wastewater treatment and its impact on the receiving environment: a case study of the Olifantsvlei wastewater treatment facility in Gauteng Province, South Africa. The goal of the study's plan was to determine the impact of wastewater effluent on the environment of the Klip River system, the plant's performance, and regional and temporal fluctuations in water quality along with the Klip River system.

According to the water quality analysis, only sulphates were less significant in distinguishing across sampling places among the ten water quality indicators evaluated. For the temporal variations, eight water quality parameters (ammonium, Chlorine, Conductivity, sodium, nitrates, pH, sulphates and suspended solids) are the most significant parameters to discriminate between the four seasons.

The study results revealed similarities in water quality loading between the summer and winter seasons and between the winter and autumn seasons. COD, ammonium, suspended solids, and *E. coli* levels were high in the summer and winter seasons, while sodium, chlorine, and pH levels were high in the autumn and spring seasons.

According to the study, the Olifantsvlei Wastewater Treatment Works (WwTW) properly treats wastewater to the required criteria before it is discharged into the Klip River system, according to study according to the survey, the Olifantsvlei Wastewater Treatment Works study's conclusions wastewater to the required criteria before it is discharged into the Klip River system. According to the study's conclusions, the Olifantsvlei WwTW was found not contributing to high levels of pollutants to the Klip River system.

The study was done by Jesus *et al.* (2020), which looked at the effect of two Wastewater Treatment Plants (WwTW) discharges on the structure of the River Tinto's benthic macroinvertebrates communities (Portugal). The study discovered that embankments, channelling, and riverbank settlements had significantly altered the natural hydro-morphological characteristics of the Tinto River. Based on water quality, environmental parameters, and benthic macroinvertebrate communities, the Tinto River's ecological status ranges from insufficient to poor macroinvertebrate communities are generally taxonomically deficient and have low levels of diversity. Other faunal groups present, such as Ephemeroptera and Mollusca, are subordinate to *Annelida* and *Diptera*.

The study concluded that the water quality and the benthic macroinvertebrates community were significantly and negatively affected by the WwTWs, despite improving the hydro-morphological conditions downstream of the WwTWs.

2.13.2 State of Wastewater Treatment Works in South Africa

Mitchell SA *et al.* (2014) researched wastewater treatment works and the financing mechanisms to obtain a green drop rating. According to the study, the first Green Drop assessment was carried out in 2009. 449 WwTWs were evaluated in this first round out of 853 municipal WwTWs. Thirty-two of the WwTWs estimated were given Green Drop Status, but many received very low scores.

The current precarious state of South Africa's wastewater treatment works is extremely concerning. It hurts the health of people and ecosystems and social issues. This is a matter that requires immediate and urgent attention. The study identified skills and the cost of improving WWTWs through refurbishment and improvements as the drivers for change and improvement, regardless of plant size (Mitchell *et al.*, 2014).

The CSIR published The State of Municipal Infrastructure in South Africa and its Operation and Maintenance: An Overview in 2006. According to a CSIR survey of a significant number of municipal wastewater treatment works in Gauteng, several of them were regenerating effluent that did not meet DWAF criteria. Some plants emitted effluent that was barely indistinguishable from the raw sewage. One or more of the following were usually cited as reasons:

- The municipal government's gross under-budgeting for wastewater maintenance,
- There is inadequate understanding of WwTW technology, and
- Officials do not appear motivated to carry out their responsibilities with attention and energy.

2.13.3 Assessment of Water Quality and Associated Impacts of the Sewage Discharges into the Mooi River Catchment

Dube (2020) study found that most physical, biochemical and microbiological quality indicators for natural surface water were higher than expected between July 2015 and January 2018. According to the findings, the discharged treated wastewater from WwTWs deteriorated the water quality of the Mooi River and its tributaries.

The statistical analysis findings using the t-test revealed a substantial variation in water quality upstream and downstream. Even if the discharge is regularised and planned, according to the study, there may be a long-term impact on the self-sustainability of aquatic ecosystems along the three rivers (Loop Spruit, Wonderfontein Spruit and the Mooi River), as well as a health risk to users, cattle, and animals. Most wastewater discharge metrics monitored in the receiving river system violated national and international quality standards and the WwTW discharge water use license.

2.13.4 Alexandra Township's Impact on the Jukskei River's Water Quality

A study done by Matowanyika (2010) found that a housing shortage in Alexandra Township, South Africa, has resulted in informal settlements on any open land, including the banks of the Jukskei River. The proximity of the dwellings, among other things, has made refuse removal difficult and sanitation facilities inadequate. As a result, waste, including human excreta, is dumped on open land or disposed of in the Jukskei. This waste affects the water quality of the Jukskei River as a result; the study determined how the water quality changed as the Jukskei River flowed through Alexandra.

Between May and December 2009, eleven physical, chemical, and microbiological parameters were monitored using standard methods at four sites in the Jukskei catchment. Water entering Alexandra had only a significant increase in turbidity (27.1 ± 4.5 NTU), whereas water exiting Alexandra had a substantial increase in pH ($7.7 \pm 0.$). Nitrate (0.36 ± 0.07 mgN/l) and orthophosphate (0.41 ± 0.17 mgP/l) *E. coli* levels in the water upstream and downstream of Alexandra did not differ statistically.

The high nitrate, orthophosphate, and *E. coli* levels downstream of Alexandra were almost certainly caused by raw sewage, domestic, and animal waste. Most of the parameters measured in the water exiting Alexandra fell within the acceptable ranges of aquatic ecosystem guidelines. However, the aquatic and domestic guidelines rated ammonium-N and electrical conductivity as poor. *E. coli* levels were greater above the limits for drinking water (0 CFU/mL) and recreational water (1.3 CFU/mL). The wet season had significantly higher turbidity and total suspended solids

than the dry season. Still, the dry season had higher orthophosphate, suspended particle organic matter, pH, and electrical conductivity at all sites. The changing seasons did not affect temperature, nitrate N, or dissolved oxygen at all locations. The findings imply that some activities, such as inadequate garbage disposal in Alexandra, might seriously impact the Jukskei River's water quality.

The wet season had significantly higher turbidity and total suspended solids than winter. In contrast, the winter season had higher orthophosphate, suspended particulate organic matter, pH, and EC at all sites. The changing seasons did not affect temperature, nitrate-N, or dissolved oxygen at any site.

2.13.5 Historical Water Quality Trends in the Gauteng Province of South Africa's Jukskei River

According to Jardine da Silva (2016), due to its geographical location in the built-up and densely populated landscape, the Jukskei River has historically been subject to many water quality problems, particularly of a bacterial nature as pollution from other sources. According to the study, the river was subjected to increasing pH levels as well as and variable concentrations of sulphates, potassium, phosphates, and nitrates between 1995 and 2005. According to the study, potential flooding and changes in water quality are expected to be directly related to changes in the surface coverage of the built environment surrounding the Jukskei River.

As the severity and frequency of flooding have increased, major stormwater management issues in urban areas have emerged, with negative societal and environmental consequences. According to the study, there is an urgent need to continuously monitor water quality because pollution loads accumulated in the Jukskei channel eventually reach Hartebeespoort Dam, which is already severely enriched with minerals and nutrients—understanding the relationship between land use change, rainfall trends, and water availability (Da Silva, 2016).

Total pollutant concentrations at three sites along the Jukskei River were measured using the Department of Water Affairs data spanning 28 years, from 1986 to 2014 (Da Silva, 2016). Pollutant concentrations at the sites may have decreased over time due to increased water flow and urban land use coverage (Da Silva, 2016).

The study raised impermeable surfaces to increase flow into the Jukskei River, allowing for pollutant dilution. Depending on the other water quality inputs, this effect could be boosted by increased impermeable surfaces within Johannesburg (Da Silva, 2016).

2.13.6 Case Study on Assessment of the Impacts of Municipal Wastewater from Lydenburg Wastewater Treatment Works, Mpumalanga, South Africa.

Munyai (2019) found that urban population growth, urbanisation, and economic growth put a strain on the performance of wastewater treatment works, causing them to operate above capacity, resulting in blockages and spillages of raw sewage released in the water resource, thereby water quality decline in the receiving environment. The quality of water outcomes showed that the physio-chemical analysis of both primary and secondary data at the Lydenburg wastewater treatment works discharge point was above the recommended limits, and the pH ranged between 5 and 10 upstream, downstream, and at the discharge point, which is within the recommended limit. PO_4 concentrations range from 0 to 10 mg/L.

Water quality parameters exceeded general a particular al recommended limits, resulting in non-compliance. The study also assessed the performance of Lydenburg WwTW using existing 5-year water quality data obtained from the DWS by comparing physicochemical parameters to wastewater DWS discharge limits. According to the study's findings, the Dorps River flows through areas associated with industries, residential, informal settlements, and agriculture, all of which are linked to the Lydenburg WwTW. The results clearly showed that the final wastewater released by Lydenburg WwTW impacted the water quality of the Dorps River system.

2.13.7 Case Studies on Statistical Analysis

The parametric one-way analysis of variance (ANOVA) was used in Matowanyika (2010) study to detect differences in water quality among four sites because samples were collected per parameter at each location throughout the sampling period. Time-series graphs were created using Microsoft Office Excel software (2007).

Da Silva (2016) conducted a case study on the historical water quality trends of the Jukskei River. Over 28 years, the Department of Water Affairs (DWA) collected water quality data and compiled it into large datasets of monthly monitoring data. The data was initially available from 1972 to 2014; however, the study revealed significant gaps between 1972 and 1986. As a result, to maximise accuracy when calculating an average, DWA data was only used from 1986 to 2014.

CHAPTER 3 METHODOLOGY

3.1 Introduction

This section provides the environmental setting of the study area and the methodology used to collect and analyse the data for this research. It then compared the results to the Resource Quality Objective, water use license limits, and wastewater guidelines.

3.2 Description of the Study Area

Northern wastewater treatment works (Figure 2) is located in Johannesburg North near Diepsloot in the City of Johannesburg within quaternary drainage area A21C in the Upper Crocodile (west) water management area. The wastewater treatment works final treated effluent is discharged into the Jukskei River, a Crocodile (West) River tributary.

The Jukskei River is one of the largest of three rivers draining the northern suburbs of the Witwatersrand. It arises from an underground spring in the Bezuidenhout Valley, east of Johannesburg (da Silva, 2016). The catchment area of the Jukskei River is approximately 77,650 hectares (Figure 4) (da Silva). It traverses a range of urban settlements such as Alexandra Township, Buccleugh and Midrand. The Northern WwTW consists of five units:

- Unit 1, with a nominal capacity of 45 ML/d, was commissioned in 1962. The unit treats stormwater and sewage overflows, and the effluent it produces is used to irrigate the Northern Farm.
- Unit 2: was commissioned in 1963 but later decommissioned except for six of the digesters, four of which have been completely refurbished. The bio-filters were demolished in 2007 to construct a new 50 ML/d activated sludge treatment plant.
- Unit 3 includes screening, de-gritting, primary sedimentation, raw sludge acid fermentation, flow balancing, bioreactors, final clarification, and chlorination.
- Unit 4 includes screening, de-gritting, primary sedimentation, raw sludge acid fermentation, flow balancing, final clarification, chlorination, sludge thickening, dewatering, solar drying, and composting.
- Unit 5: Gravity thickened waste activated sludge is anaerobically digested, dewatered on filter belt presses, and solar dried and composted. The plant's design treatment capacity is 435 ML/d, and it includes a drying/composting area with a capacity of 100 dry tons per day. The final effluent from the works is discharged into the Jukskei River.

The Northern WwTW (Figure 2) collects and treats sewage (99% domestic and 1% industrial) from the eastern portion of the city centre, Bedfordview, Modderfontein, Western Klein Jukskei, Delta, Cydna, and Bruma catchments, as well as the Vorna Valley and Diepsloot areas. The current flow measurement indicates that the combined capacity of the Northern basin will exceed the Northern WwTW capacity in the near future. Furthermore, Northern WwTW is approaching its maximum design capacity (Johannesburg Water WRAP, 2018).

The Northern WwTW has 4985 km of sewer mains that form part of the pipe network. The number of sewer connections is estimated to be over 100 thousand. There are 16 sewer pump stations. The available treatment capacity of the Works is recorded as 405ML/d against a designed capacity of 450ML/d. The Northern WwTW has been classified as a Class A treatment facility by DWS. The Northern WwTW makes use of a surface aeration system (Johannesburg Water WRAP, 2018).

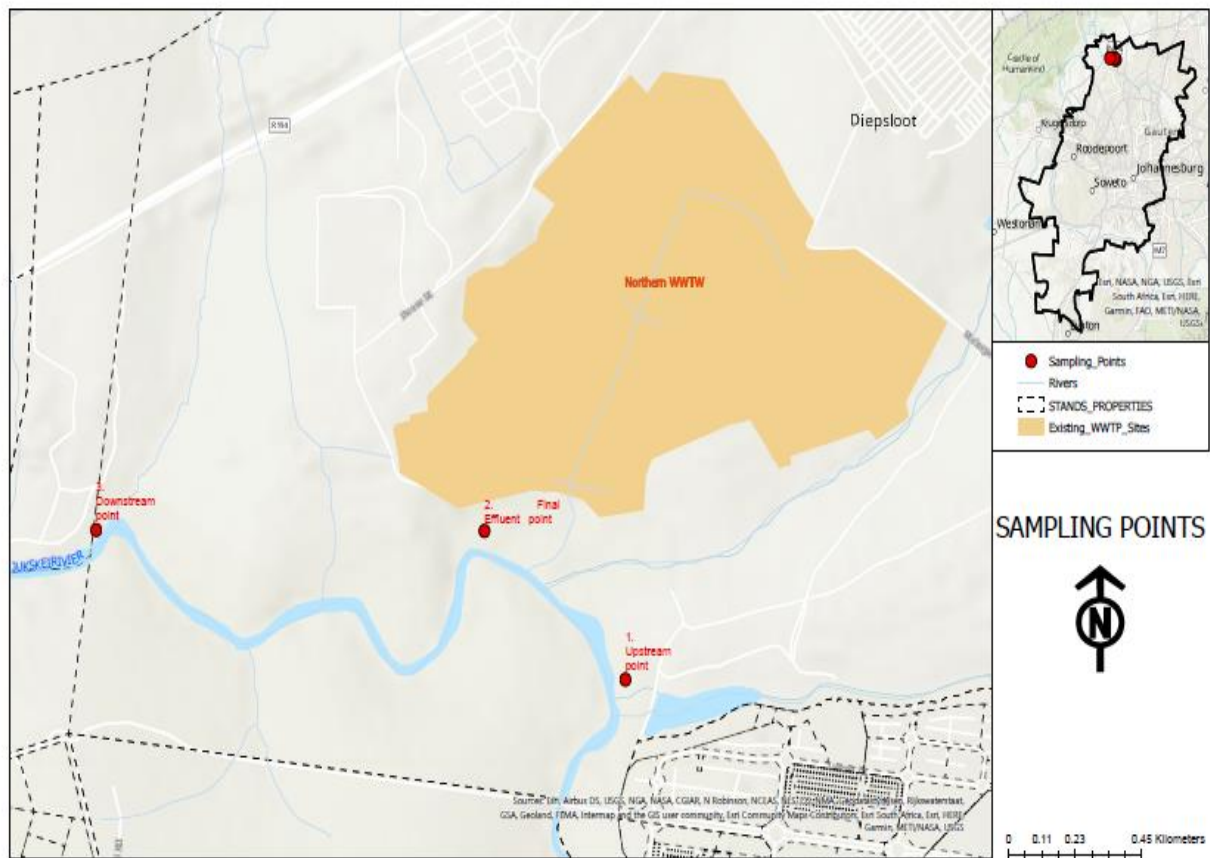


Figure 2: Northern Wastewater Treatment Works with selected monitoring points (Johannesburg Water, 2021) (ArcGIS pro 10.5)

3.2.1 Jukskei River Catchment

the Jukskei River is one of the main rivers that confluence into the western Crocodile River basin. It is one of the three largest rivers draining the northern suburbs of the Witwatersrand and arises from an underground spring in the Bezuidenhout Valley, east of Johannesburg (Gauteng Province). It passes through a range of urban settlements such as Alexandra Township, Buccleuch, and Midrand before its confluence with the Crocodile River and flows into the Hartbeespoort dam (Hoorzook *et al.*, 2021).

The Jukskei River is contaminated with mine water amongst other contaminants such as untreated effluent, industrial waste, agricultural chemicals and hydrocarbon and chemical discharges (Burke and Bokako, 2004; Cambell, 1996; Huizenga, 2004; Matowanyika, 2010; Mawela, 2008; Neswiswi, 2014; Roux and Oelofse, 2010).

The morphology of the Jukskei River (Figure 3) is a classic example of a trellis drainage system. The highest point of the Jukskei is 1695 mamsl, with a height of 45 m across a length of 66 km, giving it an average slope of 7.3 m/km. Therefore, the river is steep and fast-flowing (van Veelen, 2002). Due to relatively steep slopes, none of the streams in the catchment meander and the streams run pretty straight. There are also no significant obstacles or changes in geology to influence the river's course (van Veelen, 2002).

According to Singh *et al.* (2015), the overall ecological condition of the Jukskei River is in a D category, implying it is highly modified, with a significant loss of habitat, biota and ecosystem functioning. The overall ecological condition of the Jukskei River is in a D category, implying it is highly modified, with a significant loss of habitat, biota and ecosystem functioning. The site monitored, A21C01167, showed a slight improvement in health between 2013 and 2014/15.

The lowest reach of the river showed that the river is in an upper D ecological category. There seems to be an improvement in the ecological health of the reach since 2013, although the condition remains in a D category. The macro-invertebrates are very poor, bordering on a D/E category (Singh *et al.*, 2015).

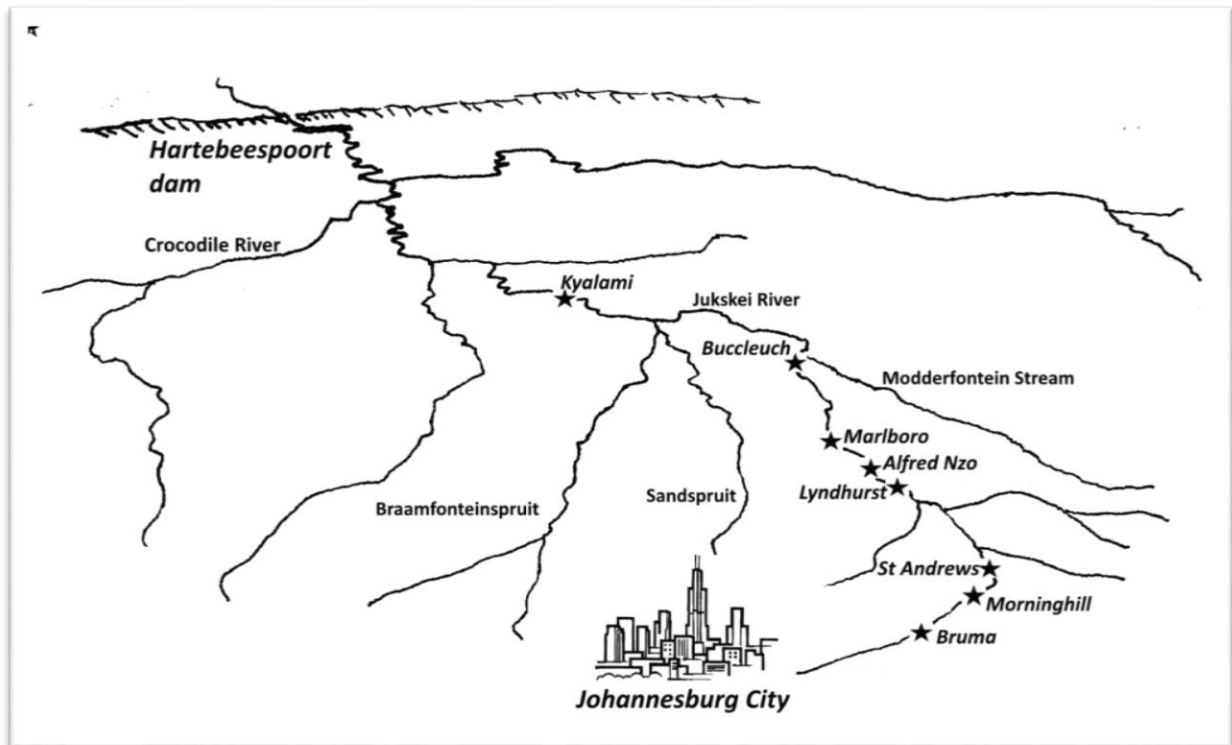


Figure 3: Jukskei River catchment (Edenvale River Watch, 2017)

3.2.2 Geology, Soil and Topography

The geology of the Jukskei River catchment comprises granite and gneiss (Huizenga and Harmse, 2005). The granite outcrops in the Jukskei riverbed are a medium-to-coarse-textured pink or grey rock. The geology of the catchment does not play an essential role in the drainage patterns as the catchment is geologically relatively uniform (van Veelen, 2002).

3.2.3 Natural vegetation

According to Mucina and Rutherford (2006), the natural vegetation types within the Jukskei catchment include the Egoli Granite Grassland covering the majority of the catchment, which is endemic to the province, poorly conserved and therefore highly threatened with an area to the south made up of Soweto Highveld Grassland and a small area to the east of Alexandra made up of Carletonville Dolomite Grassland.

The Egoli Granite Grassland comprises undulating plains supporting tall, usually. Usually, *Hyperhenia hirta* dominated grassland with some rocky outcrops supporting woody species. Only 3% of this veld type is conserved in statutory reserves, even though the veld type is considered endangered. Over two-thirds of this vegetation type are transformed by cultivation, urbanisation, mining, and dam building, as well as roads and infrastructure (da Silva, 2016).

3.2.4 Climatic conditions

South Africa has an arid to semi-arid climate with high rainfall variability (Vogel, 2000). The study site is in a negative runoff zone, which means that the annual evaporation exceeds the annual rainfall (Miller, 2002). Only 8.6% of yearly rainfall accounts for surface water in SA (Weaver *et al.*, 1999).

The Gauteng Province is located on South Africa's interior plateau and receives most of its rainfall throughout the summer. Annual rainfall in Gauteng ranges from just over 700 mm on the Witwatersrand (about 1700 m a.m.s.l.) to just over 600 mm north of the Magaliesberg (about 1100 m a.m.s.l.) (SAWS, 1998). The majority of Gauteng is in the Moist Highveld Grassland climatic zone, which is cool with average annual maximum temperatures in the south of 22°C and 25°C in the north. There are approximately 100 days of rain in Johannesburg, whereas there are approximately 85 days in Pretoria (Kruger, 2004).

The Central Bushveld climate region encompasses the extreme northern parts of Gauteng. According to Kruger (2004), December and January see the most rainfall in Gauteng. The climate in the Jukskei River catchment is warm and moderate.

The annual average temperature for 2020 for South Africa was in the region of 0,5°C, higher than the 1981—2010 average (South African Weather Services, 2020). The long-term trend is estimated to be around 1,6°C per decade, higher than the average global trend. The annual rainfall average is 713 mm. January is the wettest month, with an average monthly rainfall of 125 mm. The driest month is July, with an average monthly rainfall of 4 mm (South African Weather Services, 2020).

3.2.5 Socio-economic factors

Gauteng is the country's fastest-growing province, according to the City of Johannesburg (2018), with Johannesburg accounting for an estimated 5.05 million of the province's total population. At the moment, at least 3000 people move into the city each month. Migration has contributed to an average city population growth rate of 3% over the last ten years. This is more than double the national average, and the population of Johannesburg has more than doubled since 1996. The people of Johannesburg is expected to reach 5.3 million by 2021. This necessitates adequate city plans to deal with a growing population (City of Johannesburg, 2018).

In Johannesburg, 95.5 per cent of all households have access to improved sanitation services. The sanitation backlog (the number of households without sanitary toilets) has steadily decreased since 2006, and it now stands at 4.5%. However, less than half of informal settlement households

have access to proper sanitation is a significant concern (City of Johannesburg IDP 2018/19 Review, 2018). Johannesburg's baseline economic growth rate is expected to increase to 2.6 % in 2021, up from 1.2% in 2018. The City of Johannesburg, due to its financial-economic position, continues to attract migrants from other provinces and within the Southern African Development Community (SADC) region. All these require a proper plan to deal with the influx of skilled and unskilled labour from other parts of the country and continent (City of Johannesburg, 2018).

3.3 Data Collection

Throughout the study, a quantitative research method was used to collect both primary and secondary data. The secondary data for the selected monitoring points were requested from Johannesburg Water SOC Ltd. The data on water quality for Northern WwTW for ten years (2010 to 2020) was obtained. The primary data was collected at the same selected monitoring points as for Northern WwTW to examine and determine the potential impact on water quality and macroinvertebrate availability in the Jukskei River due to Northern WwTW's wastewater effluent. The data received included sampling records, quality indicators that are routinely monitored, the Physico-chemical and microbiological methods of analysis used, and the measured data.

During the study period, records on the concentration of each element (received as monthly MS Excel reports) were analysed and organised into data tables for each element. The data was used to create graphs that showed the trends and variation in the concentrations of each measured parameter in water at each sampling site over time. The figures also show the set control limits (Water use licence, national wastewater standards limits, and RQOs) to prevent pollution of the Jukskei River due to wastewater effluent. Thus, each measured parameter could be easily identified as out-of-limit (non-compliant) data for each measured parameter.

The figures serve as a check of each measured parameter against the water use licence for the selected monitoring points of Northern WwTW, DWS general wastewater guidelines and RQOs. Therefore, the aim was to investigate and determine the long-term impact on macroinvertebrates and the water quality of the Jukskei River due to wastewater effluent within its catchment area.

3. 3.1 Primary Data

The primary data was collected upstream of the Northern WwTW, Northern final effluent point (Discharge point) and downstream point of the Northern WwTW where Johannesburg Water contains daily samples (Table 3). The standard sampling methods were used during low and high flow seasons between July and October 2020 (DWAF, 1996a). This period represents both the dry and wet seasons. The sampling locations were chosen based on safety, accessibility, and

representativeness of the study area. Samples for microbiological and chemical specimens were kept in separate cooler boxes before being delivered to Ex-Lab Earth for analysis.

Table 3: Primary and secondary selected monitoring points

Location	Description	GPS Coordinates
1. Upstream point (DWJ 27)	Reference point 573m before wastewater effluent enters the Jukskei River.	- 25.956300 27.989610
2. Northern Works Final Effluent point (NFE)	Northern Works Final Effluent. The final effluent point is the discharge point into the Jukskei River.	- 25.952200 27.985569
3. Downstream point (J5)	Reference point 1.15 km after Northern Works discharge point.	-25.952804 27.973886

3. 3.1.1 Water Quality

During the low flow and high flow assessment, the *in situ* and *ex situ* water quality analysis was done at all selected sites. Because of the direct influence of water quality on aquatic ecosystems, the results are essential for interpreting biological results. The results were compared with Target Water Quality Range (TWQR) for aquatic ecosystems (DWAF, 1996) and Northern WwTW Water Use Licence (WUL) limits. Ex-Lab Earth analysed the *ex situ*-*situ* water quality. The TWQR was used to compare the low flow and high flow surveys (DWA, 2013).

Water quality was measured *in situ* using a handheld HACH meter (Figure 4). Among the constituents measured were pH, conductivity (S/cm), temperature (°C), and dissolved oxygen (DO) in mg/L. Chemical water quality was also assessed using ISO 5667-2:2017:1991 standard sampling protocols. The relevant water quality guidelines indicated in DWAF (1996a) were used to evaluate the trophic status of the watercourse as presented in table 4 and table 5, whilst standard conversions using pH and temperature were used to derive un-ionised ammonia concentrations (Table 5) (DWAF, 1996b).

Table 4: Total nitrogen concentration interpretation (DWAF, 1996a)

Average summer inorganic nitrogen concentration (mg/L)	Effects
<0.5	Oligotrophic conditions; usually moderate levels of species diversity; usually low productivity systems with rapid nutrient cycling; no nuisance growth of aquatic plants or blue-green algae.
>0.5-2.5	Mesotrophic conditions; usually high levels of species diversity; usually productive systems; nuisance growth of aquatic plants and blooms of blue-green algae; algal blooms seldom toxic.
2.5-10	Eutrophic conditions; usually low levels of species diversity; usually highly productive systems, with nuisance growth of aquatic plants and blooms of blue green algae; algal blooms may include species which are toxic to man, livestock and wildlife.
>10	Hypertrophic conditions; usually very low levels of species diversity; usually very highly productive systems; nuisance growth of aquatic plants and blooms of blue-green algae, often including species which are toxic to man, livestock and wildlife.

Table 5: Inorganic phosphorous (PO₄-P) concentration categories (DWAF, 1996a)

Average summer inorganic phosphorus Concentration (mg/L)	Effects
<0.005	Oligotrophic conditions; usually moderate levels of species diversity; usually low productivity systems with rapid nutrient cycling; no nuisance growth of aquatic plants or blue-green algae.
<0.005-0.25	Mesotrophic conditions; usually high levels of species diversity; usually productive systems; nuisance growth of

	aquatic plants and blooms of blue-green algae; algal blooms seldom toxic.
>0.25	Hypertrophic conditions; usually very low levels of species diversity; usually very highly productive systems; nuisance growth of aquatic plants and blooms of blue-green algae, often including species which are toxic to man, livestock and wildlife.

Table 6: Un-ionized ammonia concentration criteria (DWAF, 1996a)

Target water quality range and criteria	Un-ionized ammonia concentration ($\mu\text{g N/L}$)
Target Water Quality Range	7
Chronic Effect Value (CEV)	15
Acute Effect Value (AEV)	100



Figure 4: Water quality meter used for *in situ* measurements

3.3.2. Aquatic macroinvertebrates

The South African Scoring System Version 5 (SASS 5) (Dickens and Graham, 2002) is a rapid bio-assessment method to assess the integrity of macro-invertebrates in flowing aquatic ecosystems. Sampling was conducted using standard size SASS net dislodging macroinvertebrates from their habitat. The SAS5S survey was completed at different biotopes, i.e. Stone biotopes, vegetation biotopes and gravel sand and mud biotopes. SASS Data Interpretation Guidelines (Dallas, 2007) were used to interpret the SASS 5 information collected during the survey.

The monitoring of aquatic macroinvertebrates forms an integral part of monitoring the health of an aquatic ecosystem as they are relatively sedentary and enable the detection of localised disturbances. Their relatively long life histories (± 1 year) allow for the integration of pollution effects over time. Field sampling is easy, and since the communities are heterogeneous and several phyla are usually represented, response to environmental impacts is ordinarily detectable in terms of the community as a whole (Roux *et al.*, 2010).

Aquatic macroinvertebrates were sampled using the qualitative kick sampling method called SASS5 (South African Scoring System, version 5) (Dickens and Graham, 2002). The SASS5 protocol is a biotic index of the condition of a river or stream, based on the resident macroinvertebrate community, whereby each taxon is allocated a score according to its level of tolerance to river health degradation (Dallas, 1997). This method relies on churning up the substrate with your feet and sweeping a finely meshed SASS5 net (mesh size of 1000 micron) over the churned-up area.

The SASS5 index was explicitly designed to assess perennial streams and rivers and is unsuitable for evaluating impoundments, isolated pools, wetlands or pans (Dickens and Graham, 2002).

The net is rested on the Stones-In-Current (SIC) biotope substrate. The upstream area trap is disturbed by kicking the stones over and against each other to dislodge macroinvertebrates. The catch is also swept under the edge of marginal and aquatic vegetation. Kick samples are collected from gravel, sand and mud (GSM) substrates. Identification of the organisms is made to the family level (Thirion *et al.*, 1995; Davies and Day, 1998; Dickens and Graham, 2002; Gerber and Gabriel, 2002).

The endpoint of any biological or ecosystem assessment is a value expressed either in the form of measurements (data collected) or in a more meaningful format by summarising these measurements into one or several index values (Cyrus *et al.*, 2000). The indices used for this study were the SASS5 Score and Average Score per Taxon (ASPT). The ASPT score is calculated as follows: SASS5 Score/ No. of Taxa.

3.3.2.1 Macroinvertebrate Response Assessment Index (MIRAI)

Aquatic macroinvertebrate assemblages and communities provide an excellent understanding of a river's flow regime and water quality. Furthermore, they are an essential part of the riverine ecosystem. Macroinvertebrates are important organic matter processors in aquatic systems. They play an important role in water purification and serve as a food source for aquatic and terrestrial biota (Thirion, 2007).

The physical-chemical tolerance of individuals guides aquatic macroinvertebrate assemblages in a population to various environmental influences (Thirion, 2007). The habitat selection of a given aquatic macroinvertebrate species results in a distribution pattern reflecting the optimal overlap between habit (mode of existence) and physical environmental conditions such as habitat and flows. As a result, the often discontinuous distribution of aquatic macroinvertebrate populations is a result of results from the interaction of habitat, habit, and food resource availability. The following are the primary variables of a stream system that influence aquatic organism productivity:

- The flow regime.
- Physical habitat structure (such as channel shape and substrate distribution), as well as
- Water quality (e.g. temperature, dissolved oxygen).

According to Thirion (2007), the aquatic invertebrate ecological category is determined by incorporating the ecological needs of the taxa in a community, as well as their responses to changing environmental conditions. These are based on an interpretation of the natural assemblage's invertebrate taxa's environmental requirements, preferences, and intolerance, particularly river delineation, and their responses to changes in habitat conditions caused by changes in driver components (King *et al.*, 2000).

3.3.3 Secondary Data

Secondary data included monthly water quality measurements and biannual biomonitoring data collected and analysed by Johannesburg Water SOC Ltd. The ten (10) years data of the selected monitoring points were obtained from January 2010 to October 2020 and were processed to determine the trends, seasonal variation, and contaminants loads for each water quality variable. The water quality results from the accredited JW Lab were compared to the existing water use licence (WUL) dated May 2018 (Table 7), DWS general wastewater limit figures applicable to wastewater discharge into water resources, and RQOs of the Upper Crocodile (west) water management area (DWS, 2017).

Table 7: Northern WwTW (DWS, 2018) Water Use Licence limits

Variables	Limits
pH	6.5 – 8.5
Electrical Conductivity (mS/m)	100
COD (mg/L)	55
Suspended Solids (mg/L)	15
Ammonia (mg/l)	2
Nitrate/Nitrite (mg/L)	10
Orthophosphate (mg/L)	<1
<i>E. coli</i> (per 100mL)	<150
Residual Chlorine (mg/l)	2

The data was divided into two seasons (wet and dry). The dry season included March to July, and the wet season included September to February. The data were analysed using Microsoft Office Excel (2010) software to compare the secondary water quality data with issued water use licence discharge limits, general wastewater discharge limits and RQOs limits of selected monitoring points (Table 3), and to create time-series graphs to examine the changes in water quality variables over time. The biomonitoring data were reviewed to assess the availability of tolerant and intolerant macroinvertebrate communities at selected monitoring points and present ecological states



a) Upstream point



b) Discharge point



c: Downstream point

Figure 5: Photos (a – c) showing three selected sampling points along Northern WwTW.

3.2.4 Data analysis

The data collected from Johannesburg Water (JW) was analysed quantitatively. Microsoft Excel was used to compare water quality trends with Water Use Licence discharge parameters, DWS Wastewater Quality Guideline and RQS limits for ten years (2010 -2020) of selected monitoring points (Upstream, discharge and downstream point). Time series graphs were created to examine the changes in water quality variables over time for selected eight parameters from the secondary data obtained from JW (2010 - 2020). These graphs show the variation of each parameter as well as against the DWS general wastewater limits, WUL and RQOs guidelines in the study area.

The primary data was compared with Target Water Quality Range (TWQR) for aquatic ecosystems (DWAF, 1996) and Northern WwTW WUL limits. The analysed primary data was used to validate the secondary data to see if the WwTW was within the same range in the same seasons. From this comparative analysis, statements on the long-term impact on the Jukskei River were made.

3.3.5 Statistical Analysis

Secondary data of water quality was obtained from Johannesburg Water for the selected parameters. The selected monitoring points were determined based on ten (10) years of data. The data was set according to the monitoring points and period of monitoring.

3.5.1 Data Preparation and Cleaning

Johannesburg Water provided secondary data for three upstream, discharge, and downstream sampling points. The three sampling points were appointed separately. There were many gaps in the time series data, as there were days when there was missing data. The data also had duplicates, which were corrected during the analysis.

The three sampling points were initially analysed separately, and then the data were merged to check the difference in the sample means of the different variables from the three sampling sites. The central limit theorem was used to assume normality, as the sample size was large enough ($n > 30$) (Wegner, 2010).

Each parameter's mean observations were calculated on an annual basis. Using the limits from the Northern WWTW, WUL variables were classified as compliant or non-compliant. Each element had its cut-off value for compliance (Table 7).

One-way analysis of variance (ANOVA) was used to determine statistically significant differences between the parameters at the three selected monitoring points. The Bonferroni post-hoc test checked which variables had statistically significant difference means.

3.3.6 Ethical consideration

The information used for this study was obtained from Johannesburg Water SOC Ltd, an entity of the City of Johannesburg Metro municipality. Permission was granted to use the data on the condition that the results are part of the Johannesburg Water property and the City of Johannesburg Municipality. The entity may use the results for a solution. The results of this study may be presented at JW forums conducted by the Johannesburg Water Innovation Committee.

The university Scientific Committee of Sub-programme 4 determined that the proposed project follows the scientific method and meets the requirements outlined in North-West University's academic rules for Master's and Doctoral Students (NWU). The proposed methodology does not pose any ethical risk/poses a risk to human participants, and the following is an ethics code: NWU-1285-20-A9 (See appendix A and B).

CHAPTER 4 DATA ANALYSIS OF RESULTS AND DISCUSSION

4.1 Introduction

This chapter assesses WUL compliance and compares the results to the DWS general wastewater discharge limits and RQOs of the Upper Crocodile (west) water management area, employing the method described in the previous chapter to examine the long-term impacts of wastewater effluent on macroinvertebrates and water quality in the Jukskei River.

4.2 Presentation of Primary data collection

In situ and *ex-situ*, water quality analyses were conducted at all three selected monitoring points in the Northern WwTW during the primary data collection. Because of the direct influence water quality has on aquatic ecosystems, the results are essential for interpreting biological results. Table 8 displays the in-situ results. Results have been compared to the Target Water Quality Range (TWQR) for aquatic ecosystems (DWAF, 1996a) and Northern WwTW Water Use Licence limits. The *ex-situ* water quality was analysed by Ex Lab Earth the data. The *ex-situ* results of this are presented in Table 9.

Table 8: Northern WwTW 2020 *In situ* water quality results

Sampling Point	pH	EC (µS/cm)	DO (mg/L)	Temperature (°C)
TWQR	6.5-9.0	15	>5.00	5-30
WUL	6.5-8.5	1000	-	-
01 July 2020				
Upstream point	8.02	556	7.07	15.0
Discharge point	8.33	725	9.90	13.0
Downstream	7.95	590	7.43	15.3
26 October 2020				
Upstream point	6.65	529	4.76	23.2
Discharge point	6.64	750	6.21	24.5
Downstream point	6.53	536	6.17	25.3

The *in situ* results of the Jukskei River selected monitoring points show that most water quality parameters for the July and October surveys fell within the RQOs, TWQR, and WUL limits and would not limit aquatic biota. Despite low dissolved oxygen levels at the upstream point during the October survey falling below the TWQR, the depressed levels would not limit local biotic

integrity. The laboratory water chemistry analysis indicated that pH and EC were in line with the in situ water quality. The COD measures the amount of oxygen likely to break down organic waste (DWAF, 1996a). The COD increased from site to downstream during both surveys.

Table 9: *Ex-situ* water quality results for Northern WwTW 2020

Variable	N. WwTW WUL Limits	01 July 2020			26 October 2020		
		Upstream	Discharge point	Downstream	Upstream	Discharge point	Downstream
pH	6.5 – 8.5	7.9	8	7.7	7.0	7.5	7.0
Electrical Conductivity (mS/m)	100	59	77	64	55	78	56
Chemical Oxygen Demand (mg/L)	55	44.24	22.15	45.27	40.87	45.76	41.18
Suspended Solids (mg/L)	15	<21	22	<21	<21	<21	32
Ammonia (mg/L)	2	2.7	0.09	<0.06	14	2.3	10
Nitrate/Nitrate (mg/L)	10	16	22	18	2.1	32	4.5
Orthophosphate (mg/L)	<1	0.85	3.6	1.1	2	9.3	1.7
<i>E. coli</i> (CFU/100ml)	<150	>2420	12	980	>2420	613	>2420

Suspended solids results showed the hypereutrophic conditions at all the sites, which often result in increased turbidity associated with treated effluent discharges. Increased turbidity lowers light penetration, decreasing the photosynthesis potential of the system, leading to a reduction in primary production and food availability for aquatic biota (Dallas and Day, 2004). Suspended solids are known to settle, smothering instream habitat, altering substrates and causing shifts in biotic communities (DWAF, 1996a). The high suspended solid levels were expected to lower the biotic integrity of the Jukskei River. Sources of SS pollution includes discharges from WWTWs and industrial processes, and agricultural runoff (Dube, 2020).

Orthophosphate as phosphorus and nitrate enrichment increased from upstream to downstream of the WwTW, indicating eutrophic conditions during the July survey, which typically increase algae levels and limit aquatic biota diversity at all sampled sites (Mothetha, 2016). Hypertrophic conditions were noted in the Jukskei River during the October survey. They would result in low levels of species diversity as it causes excessive growth of nuisance plants and blooms of algae, Influencing primary productivity within a system. Both systems deteriorated from eutrophic in July to hypertrophic in October due to the increased phosphorus and nitrate within the river system.

The total ammonia concentrations within the Jukskei River increased upstream to downstream and indicated chronic toxic conditions for aquatic biota. The results showed that ammonia was within the limit at the discharge point and downstream around July. This could be the anthropogenic activities upstream of Northern Works.

The pH in the natural water environment is mainly influenced by various factors such as discharge effluents, leachate of acidic metal ions, acidic precipitation (rainfall), other microbial activity (Naidoo, 2013b). The dissolved oxygen is expected to decrease as the toxicity increases (DWAF, 1996a). The source of the hypertrophic and eutrophic conditions can be attributed to a combination of sewage input and land use activities upstream within the Jukskei River and tributary catchments (Dube *et al.*, 2017).

There are no guideline values for *E. coli* in aquatic ecosystems in SA (Osuolale *et al.*, 2015). The livestock drinking water standards for South Africa permit <200 counts or Colony Forming Units (CFU) per 100 mL to avoid health risks (DWAF, 1996b). The Jukskei River sites had elevated *E. coli* of more than 2420 counts per 100 ml during both surveys. The discharge point increased from 12 counts per 100 ml in the July survey to 613 counts per 100 ml in October.

4.2.1 Macroinvertebrate Results of Primary data collection

The sampling was conducted using a standard-size SASS net, dislodging macroinvertebrates from their habitat. The SAS5S survey was carried out in various biotopes, including stone biotopes, vegetation biotopes, and gravel, sand, and mud biotopes. The SASS5 data interpretation guidelines (Dallas, 2007) were used to interpret the SASS5 information collected during the surveys. Below is the summary of aquatic macroinvertebrate results and associated ecological categories presented in Table 10 - 12.

Tolerant taxa sampled in all sites for the primary data collection included *Oligochaeta* (Earthworms), *Hirudinea* (Leeches) and *Chironomidae* (Midges) with a sensitivity score ranging from 1 to 3. Only four (4) moderately tolerant taxa were sampled and mainly collected at discharge point with a sensitivity score of six (6), namely *Baetidae* 2 species (Mayflies), *Gomphidae*

(Clubtails), *Hydropsychidae* 2 species and *Ancylidae* (Limpets). According to the assessment, tolerant taxa made up most of the aquatic macroinvertebrate communities (Intolerance Rating >5), with a low diversity of moderately tolerant taxa sampled at the downstream point.

Table 10: Macroinvertebrate Assessment Results

Taxon	Sensitivity Score	01 July 2020			26 October 2020		
		upstream	downstream	discharge	upstream	downstream	discharge
Turbellaria (Flatworm)	3		1				
Annelida							
Oligochaeta (Earthworms)	1	A	A	A	A	A	B
Hirudinea (Leeches)	3	B	B	A	A	A	A
Crustacea							
Potamonautidae* (Crabs)	3		1				1
Ephemeroptera (Mayflies)							
Baetidae 1 sp (Mayflies)	4		A	A	B		
Baetidae 2 sp (Mayflies)	6			B		A	A
Odonata (Dragonflies and Damselflies)							
Coenagrionidae (Sprites and Blues)	4	A		B	A	A	A
Gomphidae (Clubtails)	6						1
Libellulidae (Skimmers)	4			A			
Hemiptera (Bugs)							
Belostomatidae* (Giant water bug)	3						A
Corixidae* (Water boatmen)		3	A			A	
Veliidae* (Ripple bugs)	5						A
Trichoptera (Caddisflies)							
Hydropsychidae 2 sp	6			A			B
Coleoptera (Beetles)							
Dytiscidae/Noteridae*	5				A		

(Diving beetles)							
Hydrophilidae* (Water scavenger beetles)	5				1		
Diptera (Flies)							
Ceratopogonidae (Biting midges)	5				1		
Chironomidae (Midges)	2	C	C	A	C	C	B
Culicidae* (Mosquitos)	1				A		
Muscidae (House flies/ Stable flies)	1		A			A	A
Simuliidae (Black flies)	5	A		B	A	A	B
Tabanidae (Horse flies)	5						1
Gastropoda (Snails)							
Ancylidae (Limpets)	6			B			1
Bulininae*	3				A	A	
Physidae* (Pouch snails)	3	B	B				A
Total Taxa		7	7	11	8	9	18
		01 July 2020			26 October 2020		
Taxon	Sensitivity Score	upstream	downstream	discharge	upstream	downstream	discharge
Sensitivity scores: 1 – 5: Highly tolerant to pollution 6 – 10: Moderately tolerant to pollution 11 – 15: Very low tolerance to pollution *Airbreathing taxa		Abundance estimates: 1: A single individual 2 – 10 individuals B: 11 – 100 individuals C: 100 – 1000 individuals					

Based on the 2020 study ASPT, the aquatic macroinvertebrate communities comprised primarily of tolerant taxa (Intolerance Rating < 5, while a low diversity of moderately tolerant taxa

(Intolerance Rating 6 - 10) were sampled in low abundances at the discharge point. Despite discharge indicating modified water quality compared to the water quality on the Jukskei River. It was noted that it presented a higher ASPT, SASS scores and number of Taxa (10). This might be attributed to moderate biotope diversity with stones in and out of current, marginal vegetation out of current and sand compared to the poor biotope diversity on the Jukskei River. Therefore, habitat availability was the limiting factor for the local biota at the Jukskei River.

Table 11: Macroinvertebrate Assessment Result (Ecological category)

Selected monitoring Sites	July 2020			October 2020		
	Upstream point	Discharge point	Downstream point	Upstream point	Discharge point	Downstream point
SASS5 Score	22	43	22	27	72	27
No. of Taxa	7	11	7	8	18	9
ASPT*	3.1	3.9	2.4	3.4	4.0	2.9
Ecological Category	E/F	E/F	E/F	E/F	D	E/F

In July 2020, the results of the MIRAI derived an ecological category of class E/F or seriously modified state for Jukskei River. In October 2020, the discharge point was D. This could be due to the effective treatment of wastewater from wastewater in the Northern WwTW. However, this require further investigation. The poor water quality has contributed to the impoverished community and was the dominant driver for the modified state of the Jukskei River. The absence of intolerant taxa (> 5 sensitivity score) indicated changed Physico-chemical conditions within reach. The results of the MIRAI assessment (Thirion, 2007) are provided in Table 11 for the July and October surveys.

Table 12: MIRAI Assessment Results

Metric Group	Jukskei River
Flow modification	29.7
Habitat	27.6
Water Quality	27.1
Ecological Score	28
Invertebrate Category	E

The results of the MIRAI derived an ecological category of class E or seriously modified state for both the Jukskei River (Table 11). All three factors (Flow, Habitat and Water quality) contributed to the poor community. Still, water quality and habitat were the dominant drivers for the modified state of the Jukskei River. The absence of intolerant taxa (>5 sensitivity score) indicated modified Physico-chemical conditions and poor physical conditions within reach.

The ecological categories recorded during the July survey were essentially modified (class E/F) at all sites. The ecological categories recorded during the October survey didn't change and remained seriously modified (Class E/F) at downstream.

4.3 Presentation of the secondary data

As part of the study to investigate the long-term impact of wastewater on macroinvertebrates and water quality, secondary data was obtained from Johannesburg Water. To assess its effects, the electrical conductivity, pH, nitrate, chemical demand oxygen, ammonia, *E. coli*, phosphates (as orthophosphate), and suspended solids of wastewater were measured. The data was analysed in Microsoft Excel to determine the impact of Northern WwTW on the Jukskei River's water quality and macroinvertebrates. An ANOVA was used to determine whether there were statistically significant differences between the parameters at the three selected sampling sites. A p-value of 0.05 or less was considered statistically significant.

The secondary data was obtained from JW for ten (10) years. JW already analysed the data. The data were grouped into dry and wet seasons, where a monthly average figure was used. Before analysis, the collected data was divided into two seasons (wet and dry). The dry season lasted from March to July and lasted from September to February. Each chart of secondary data analysis contains horizontal solid lines that indicate the WUL limit, general DWS wastewater discharge limit, and RQOs limits. The figures consist of three lines representing upstream, downstream, and

the Northern WwTW final effluent. All average and data cleaning calculations were completed using Microsoft Excel (2010).

Table 13: Mean readings for the selected three sampling points

Sampling point	No.	Mean	P-value
Ammonia (mg/L)			
Upstream	2925	1.33	<0.0001
downstream	631	5.32	
Discharge	3445	7.66	
Nitrates (mg/L)			
Upstream	487	4.1	<0.0001
downstream	499	8.1	
Discharge	117	5.8	
pH			
Upstream	486	7.8	<0.0001
downstream	498	7.7	
Discharge	670	7.5	
COD (mg/L)			
Upstream	397	25.3	<0.0001
downstream	00.0	0	
Discharge	3418	50.8	
EC (mg/L)			
Upstream	2953	48.3	<0.0001
downstream	656	59.8	
Discharge	3451	63.7	
Orthophosphate (mg/L)			
Upstream	2925	0.4	<0.0001
downstream	628	0.7	
Discharge	6900	0.9	
Suspended Solids (mg/L)			
Upstream	486	43.4	<0.0001
downstream	498	50.6	
Discharge	670	12.9	
E coli (cfu/100ml)			

Upstream	1798	- 47560.97	<0.0001
downstream	640	- 53535.7	
Discharge	2097	374.6	

4. 3.1 Seasonal Performance of Northern WwTW using the secondary data

4. 3.1.1 Ammonia

The concentrations of ammonia ranged from 0.1 to 9.9 mg/L at the upstream sampling point, 0.2 to 30 mg/L at the discharge point, and two mg/L to 14 mg/L at the downstream point (Figure 6). There were gaps in the data obtained from Johannesburg Water as there was no data for 2010-2011 for the upstream site and the 2010 downstream site. The ammonia concentrations fluctuated with seasons (dry and wet) and were increased from 2014 to 2020.

The upstream monitoring is situated within the Steyn City Estate. The ammonia concentration between 2010 and 2016 during the dry and wet seasons complied with WUL limits and DWS general wastewater discharge limits for both seasons, wet and dry. However, from the 2016 dry season, the ammonia concentration fluctuated in both seasons. This could be due to point sources from the WwTW, industries and non-point sources from urban runoff and agricultural activities. Ammonia in the surface water is typically caused by domestic and agricultural wastes, according to Durgapersad (2005).

The ammonia concentration at the discharge point fluctuated between 2012 and 2014, but it was within the WUL limits and the DWS wastewater discharge limits. However, it was above the RQOs limit. The ammonia concentration was found to be low during the wet season, and that could be because of summer rainfall that might have helped dilute the ammonia concentration (Figure 6). However, between 2015 and 2019, the ammonia concentration was variable in each season, exceeding the WUL limit of 2 mg/L, the DWS wastewater limit, and RQOs.

The high concentration of ammonia could be attributed to the failure of the WwTW to treat ammonia efficiently or to non-point sources of ammonia. To ensure that ammonia is effectively treated and stays within the limit, the ammonia concentration in wastewater should be continuously monitored.

The majority of results came from upstream and discharge points. Mean ammonia readings varied significantly between the three sampling sites. The Bonferroni posthoc test showed that samples from downstream were on average 3.99 mg/L less than those from upstream ($p < 0.0001$). Readings at downstream were higher on average (difference = 6.33 mg/L, $p < 0.0001$). The

difference in mean values between discharge point and downstream was statistically significant (Table 13 and 14).

14: Post-hoc Analysis of ANOVA

Sampling Point	Sampling point	Mean difference	p-value
Ammonia (mg/L)			
Downstream	Upstream	3.98	< 0.001
Discharge	Upstream	6.32	<0.001
Discharge	Downstream	2.34	<0.001
COD (mg/L)			
Discharge	Upstream	25.5	<0.001
Electrical Conductivity (mg/L)			
Downstream	Upstream	11.6	<0.001
Discharge	Upstream	15.5	<0.001
Discharge	Downstream	3.9	<0.001
E coli (cfu/100ml)			
Downstream	Upstream	5974.7	0.072
Discharge	Upstream	-47186.3	<0.001
Discharge	Downstream	-53161	<0.001
Nitrate (mg/L)			
Downstream	Upstream	4.0	<0.001
Discharge	Upstream	1.8	0.015
Discharge	downstream	-2.2	0.002
Orthophosphate (mg/L)			
Downstream	Upstream	0.4	<0.001
Discharge	Upstream	0.5	<0.001
Discharge	Downstream	0.1	0.003
Suspended Solids (mg/L)			

Downstream	Upstream	7.3	0.662
Discharge	Upstream	-30.4	<0.001
Discharge	Downstream	-37.7	<0.001
pH			
Downstream	Upstream	-0.2	<0.001
Discharge	Upstream	-0.3	<0.001
Discharge	Downstream	-0.1	<0.001

During both seasons, the ammonia concentration at the downstream point between 2011 and 2015 was within the WUL and DWS wastewater limits. However, between 2016 and 2019, the ammonia concentration was above the limits, caused by partially treated wastewater coming from the works. Furthermore, high ammonia concentration downstream also is attributed to effluent input. This effluent could be that WwTW treatment is not effectively removing ammonia concentrations in compliance with the DWS wastewater discharge limit, or the system could be overloaded because the volume of received influent is always more significant than the capacity of the WwTW (Edokpayi *et al.*, 2017).

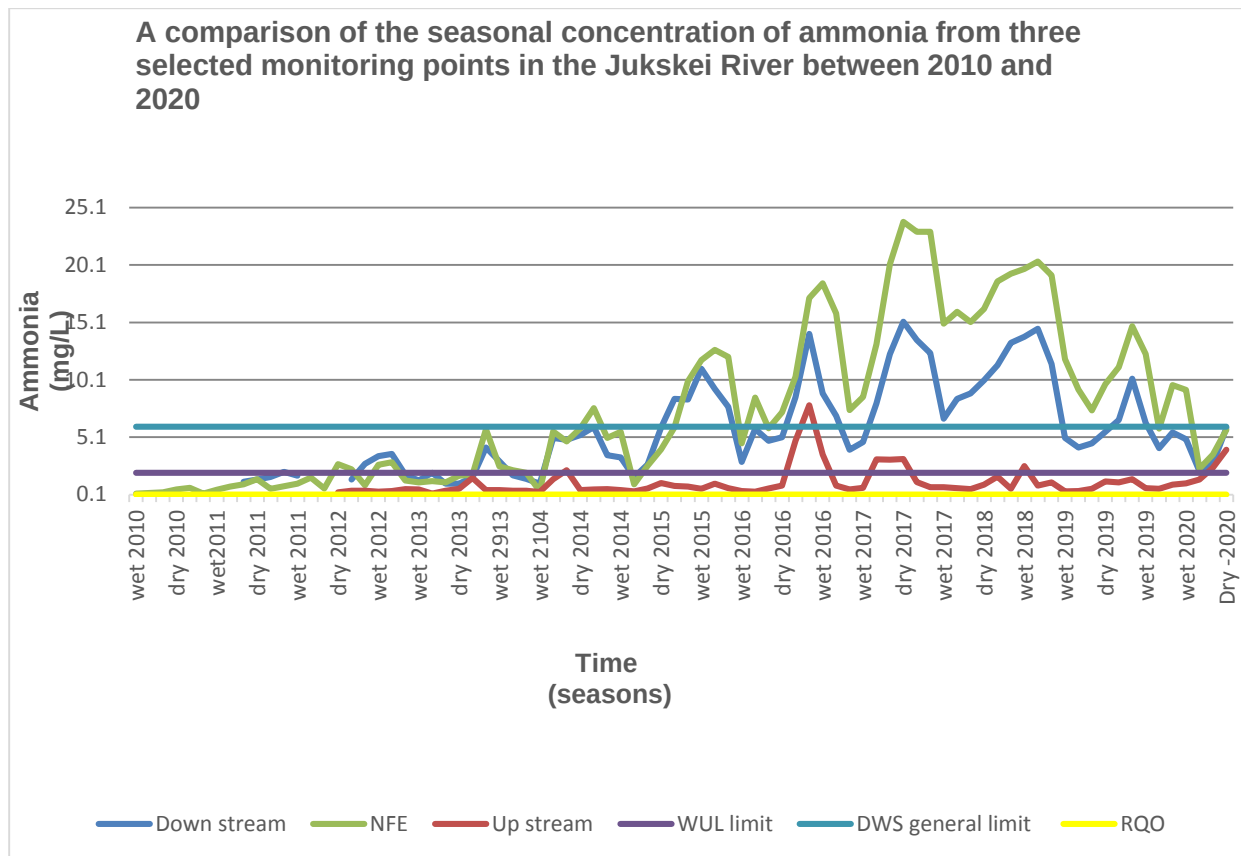


Figure 6: A comparison of the seasonal concentration of ammonia from three selected monitoring points in the Jukskei River for the period between 2010 and 2020.

4.3.1.2 Nitrate

Nitrate (NO_3) concentration started from 0.5 to 20 mg/L at the upstream sampling point, 0.25 to 12 mg/L at the discharge point, and 0.5 to 20 mg/L downstream. There was no data for upstream or downstream in 2010. According to the findings, high concentrations were also observed at the upstream and downstream points. This could be explained by upstream urbanisation or industrial activity (Nyenje *et al.*, 2010) (Figure 7).

There was a significant difference between the affluent and the downstream point regarding nitrate concentration. This could be due to the poor quality of effluent discharged into the river (Odjadjare and Okoh, 2010).

The nitrate concentration was discovered to be higher than the DWS wastewater discharge limit, the RQO limits, and the WUL limits (Figure 7). At the upstream point, the nitrate concentration was less than the DWS general limit and less than the WUL limit. The effluent quality discharged into the river could account for a less significant change in nitrate concentration at the downstream point (Odjadjare and Okoh, 2010).

The results showed that the difference in mean nitrate readings varied significantly between the three sampling sites. Samples from downstream were four mg/L higher than the upstream point ($p < 0.0001$). Nitrate readings at downstream were less on average (difference = 1.7 mg/L, $p < 0.0001$). The difference in mean values between the discharge point and the downstream point was statistically significant (difference = 2.3mg/L, $p < 0.0001$) (Table 13).

According to Abbaspour (2011), Egun (2010), Elias (2004), Odjadjare and Okoh (2010), high levels of nitrates can result in excessive nutrient enrichment in the water body, which can lead to a loss of diversity in the aquatic biota and overall ecosystem degradation. Agricultural run-off containing inorganic fertiliser residues and untreated animal and human waste are two of the most significant sources of nitrate pollution in surface water (Dube, 2020). The eutrophication of the Hartebeespoort Dam has been blamed on high nutrient concentrations in the Jukskei River, a tributary of the dam. The Jukskei River's water quality issues, particularly the high bacterial load, are linked to urbanisation (Matowanyika, 2010).

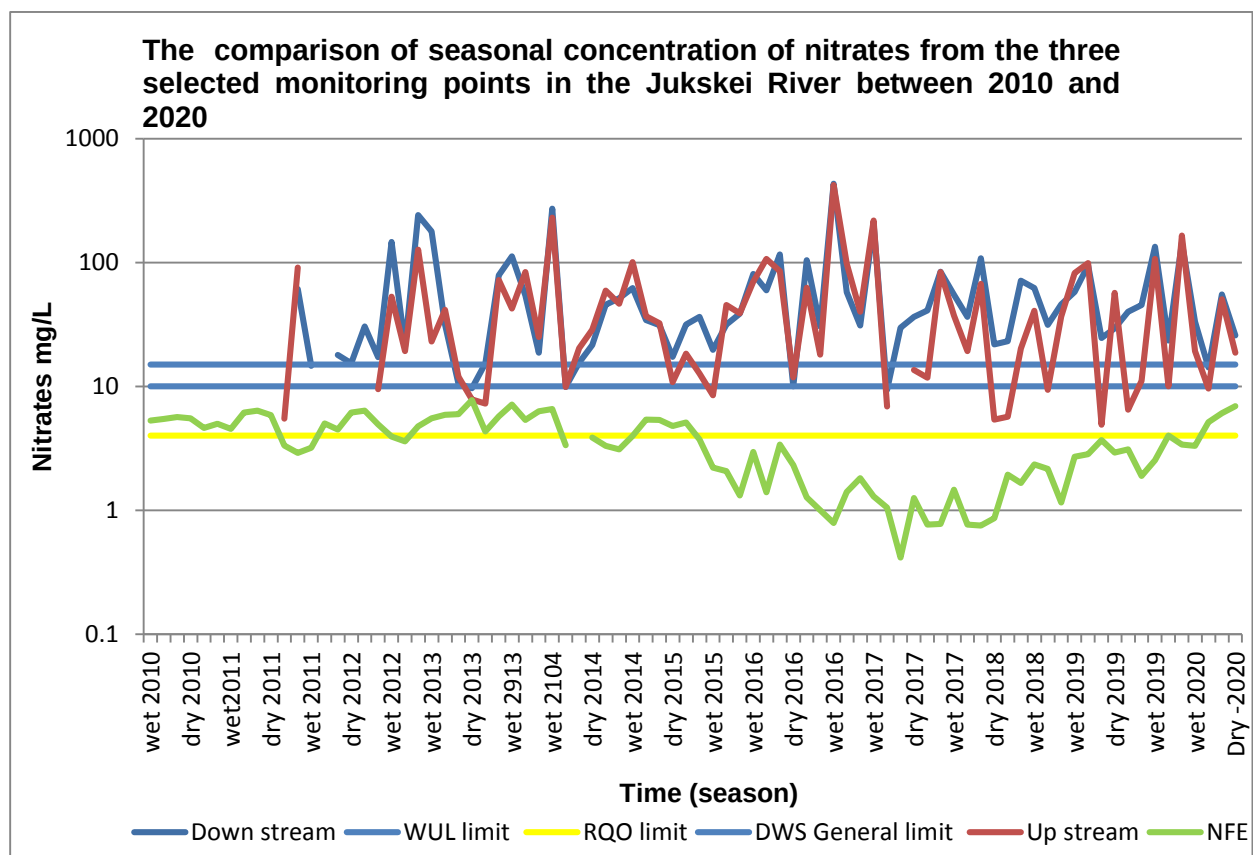


Figure 7: The comparison of the seasonal nitrate concentration of the three selected monitoring points in the Jukskei River between 2010 and 2020.

4.3.1.3 Orthophosphate

The orthophosphate concentrations ranged from 0.1 to 1.6 mg/L upstream, 0.10 to 2.56 mg/L at the discharge point, and 0.10 to 5.8 mg/L downstream. There were gaps in the orthophosphate data obtained from Johannesburg Water. There was no data for upstream and downstream between 2010 and 2011 (Figure 8). The orthophosphate concentration at the upstream point was within the WUL limits, DWS Wastewater discharge, and RQOs limits for both wet and dry seasons. The attention of orthophosphate differed significantly upstream and downstream. According to the findings, there are increasing trends from upstream to downstream. The orthophosphate concentration at the discharge point changed over time (Figure 8).

The results showed that phosphate was within the WUL and DWS general wastewater limits at upstream and discharge points. At the downstream, it is above the WUL limit but within the DWS general wastewater limit (1.1 mg/L), and this could have been caused by partially treated wastewater originating from the WwTW.

The excel results indicated that between 2015 and 2019, the orthophosphate concentration was higher than the WUL limits but lower than the DWS wastewater discharge and RQOs limits. High orthophosphate levels have the potential to harm rivers by causing eutrophication (Morisson *et al.*, 2001). Between 2015 and 2019, the orthophosphate concentration was higher than the WUL limits but lower than the DWS wastewater discharge and RQOs limits. High orthophosphate levels have the potential to harm rivers by causing eutrophication (Morisson *et al.*, 2001) (Figure 10).

The results showed that the difference in mean orthophosphate readings varied significantly between the three sampling sites. Samples from downstream were 0.3 mg/L less than those from upstream ($P < 0.0001$). Orthophosphate readings at downstream were higher on average (difference = 0.5 mg/L, $P < 0.0001$). The mean values between discharge and downstream were also statistically significant (difference = 0.2 mg/L, $P < 0.0001$).

The orthophosphate concentration at the downstream point between 2012 and 2013 was within the WUL limit, DWS wastewater and RQOs limits for both seasons (Figure 8). However, the orthophosphate concentration was above the boundary between the other years, which could have been caused by partially treated wastewater originating from the WwTW. This highlights that the WwTW could not effectively treat effluent orthophosphate concentrations to the required limits.

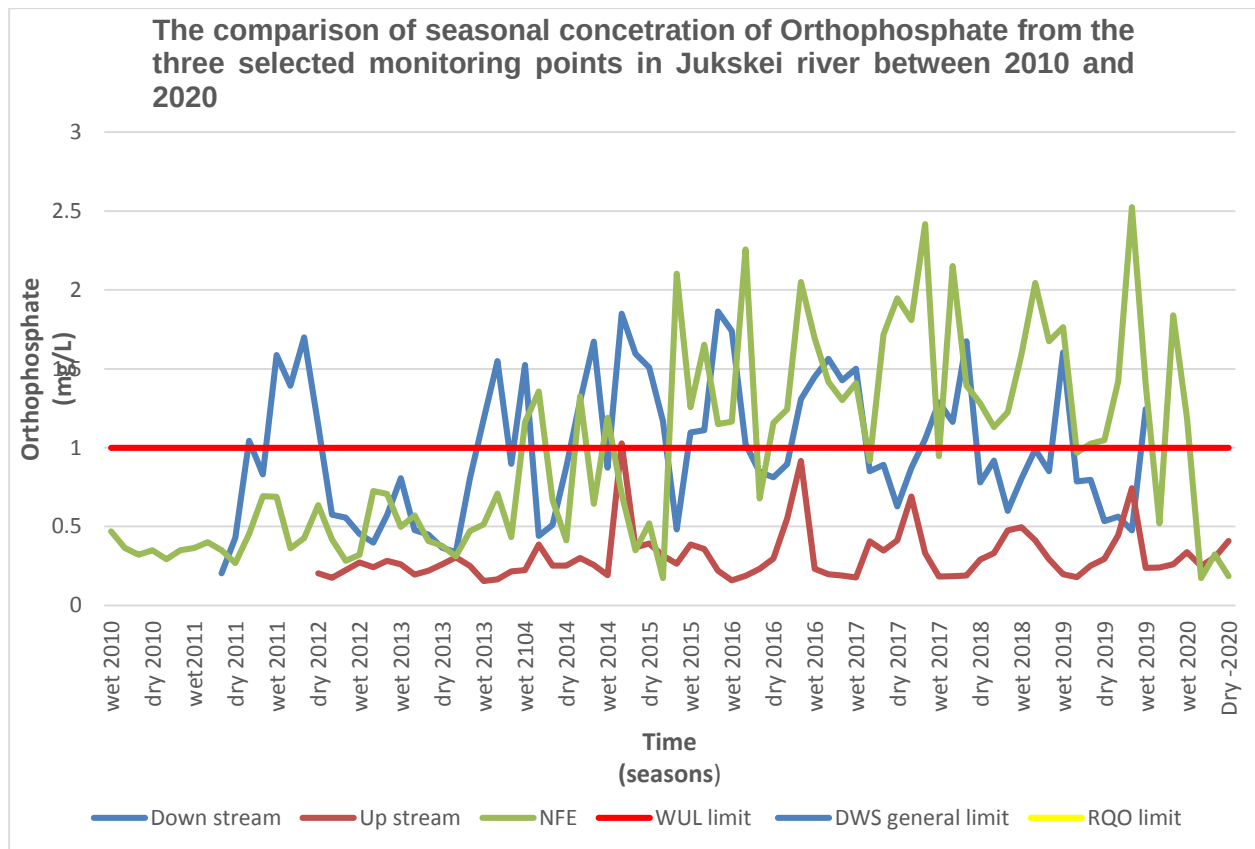


Figure 8: Comparison of seasonal concentration of orthophosphate from three selected monitoring points in the Jukskei River between 2010 and 2020.

4.3.1.4 pH

The pH value of a water sample measures the hydrogen ion activity (DWAF, 1996a). Temperature, inorganic and organic ion concentrations and biological activity all impact pH. pH can affect the availability and toxicity of constituents such as trace metals, non-metallic ions such as ammonium, and essential variables such as selenium. Most of South Africa's freshwaters are relatively well buffered and neutral, with pH levels ranging between 6 and 8 (Thiere *et al.*, 2004).

Compared with the WUL DWS wastewater discharge limits, all the pH values measured throughout the study were within limits. PH would not impact the receiving environment based on the WUL and DWS effluent discharge limits.

The pH value during the study was within the acceptable limit for the WUL and DWS discharge limits. However, there were gaps in the data obtained from Johannesburg Water for upstream and downstream. In 2011 there was no data for all the three sampling points, and between 2011 and 2012, there was no data for upstream and downstream; this could be due to the availability of data, or no data was collected within the period (Figure 9). The pH ranged from 6 to 10.6mg/L

at the upstream sampling point, 6.3 to 8.1mg/L at the discharge point, and 5 to 10mg/L at the downstream end.

The results showed that the difference in mean pH readings varied between the three sampling sites. Samples from downstream were 0.1 less than those from downstream ($p < 0.0001$). pH readings at downstream were higher on average (difference = 0.2, $p < 0.0001$). The difference in mean values between discharge point and downstream was also statistically different (difference = 0.3, $p < 0.0001$) (Table 13).

The pH downstream of the discharge points did not differ significantly from those measured upstream of the Northern WwTW based on average values. It can be concluded that the release of wastewater from the works had no significant impact on the pH of the Jukskei River.

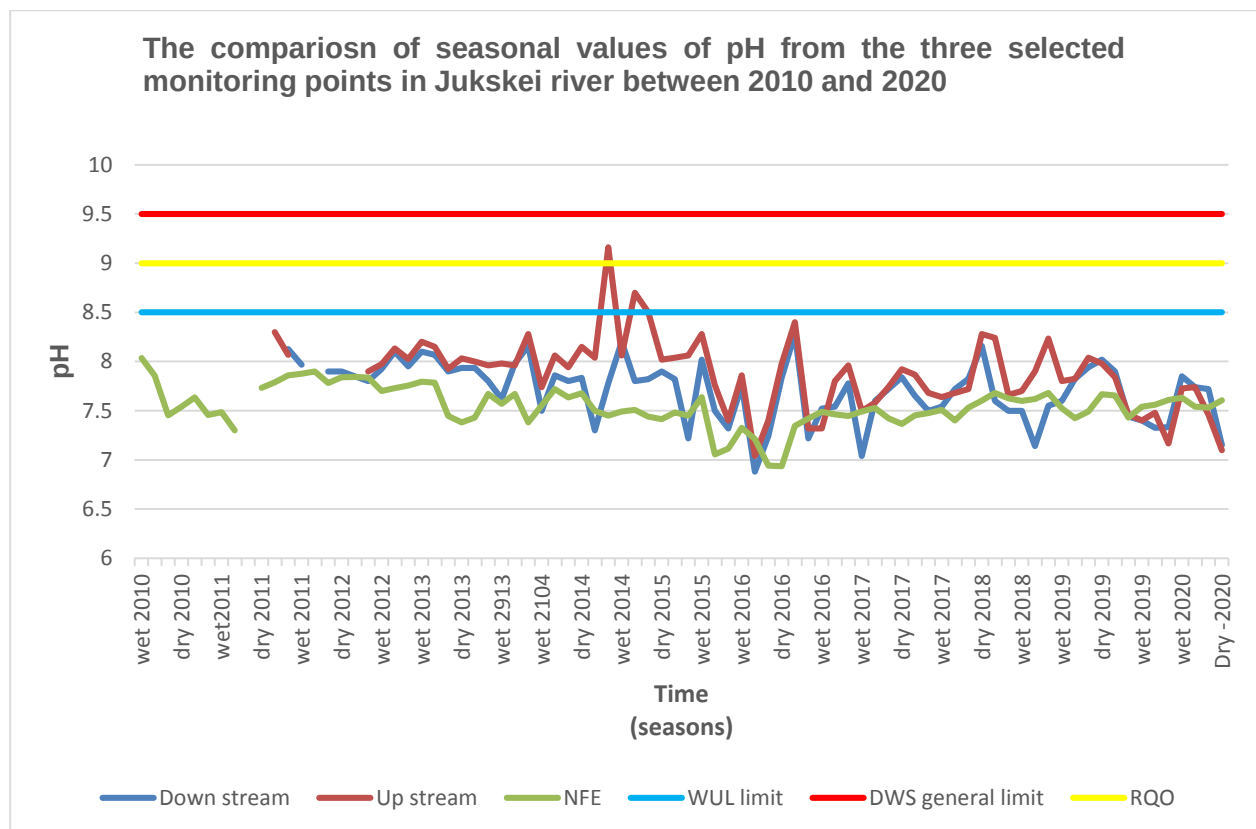


Figure 9: Comparison of the seasonal pH values from three selected monitoring points in the Jukskei River between 2010 and 2020.

4.3.1.5 Electrical Conductivity

The results of excel data showed that there were gaps in the water quality data that was obtained from Johannesburg Water; there was no data for upstream between 2010 and 2011 and the downstream point for 2010. The results indicate that EC was within the WUL limit and DWS

guidelines discharge limits in both seasons but above the RQOs limits. In 2020, the EC exceeded the WUL and DWS wastewater discharge limits. Electrical conductivity concentration ranged from 13 to 85 mS/m upstream, 29 to 1400 mS/m at the discharge point and 14 to 120 mS/m downstream (Figure 10).

The results showed that the EC was within the WUL and DWS wastewater discharge limits of 70 mS/m. This indicates that the Northern WwTW successfully removed some ions from the wastewater before discharge. Any increase in EC pollution could endanger the health of downstream water users.

The results showed that the difference in mean EC readings varied significantly between the three sampling sites. Samples from downstream were 11.5 mg/L less than those from upstream ($p < 0.0001$). The readings at downstream were higher on average (difference = 15.4 mg/L, $p < 0.0001$). The mean values between discharge and downstream were also statistically significant (difference = 46.9 mg/L, $p < 0.0001$).

In 2020, a high EC was recorded at the final effluent point during the wet season; this could be that the Northern WwTW was unable to remove the ions in the wastewater before discharging it into the Jukskei River. Any increase in EC pollution could endanger the health of downstream water users. Dilution and other natural processes occurring along the river system could explain the decrease in EC concentration at the downstream sampling point (Walakira, 2011).

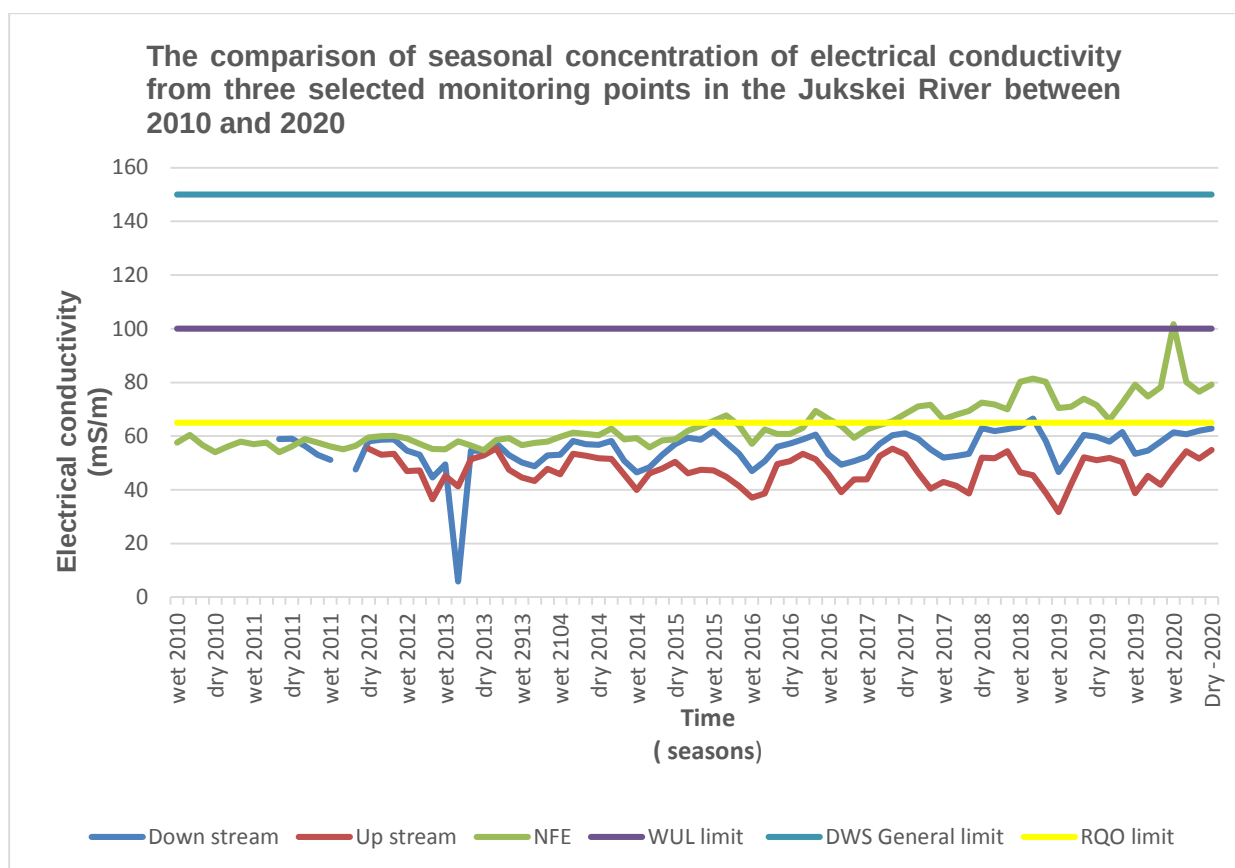


Figure 10: Comparison of the seasonal concentrations of electrical conductivity at three selected Jukskei River monitoring points between 2010 and 2020.

4.3.1.6 Chemical Oxygen Demand (COD)

The COD is a measurement of how much oxygen is likely to be used to degrade organic waste (DWAf, 1996a). When it comes to the historical data, there were gaps in the data; no data were available for the upstream site from 2010-2012, and also no data was available between mid-2013 and 2020; this could be either the data was not captured or misplaced; furthermore, the downstream data also had no data for 2010-2011 and mid-2013 to 2020 (Figure 10).

The COD concentration ranged from 10 to 29mg/L at the upstream site, less than 10 to 58 at the discharge point and less than 10 to 360mg/L downstream of Northern WwTW. High concentrations were discovered both upstream and downstream. This suggests that Northern WwTW's effluent quantity may affect the river health of the Jukskei River. The only point that exceeded the WUL and DWS wastewater discharge limits were upstream (Figure 10).

The results showed that the difference in mean COD readings varied significantly between the three sampling sites. Samples from downstream were 25.3 mg/L higher than those from upstream ($P < 0.0001$). COD readings at downstream were higher on average (difference = 28.5 mg/L, P

<0.0001). The difference in mean values between discharge and downstream point was statistically significant (difference = 0.3 mg/L, $P < 0.0001$).

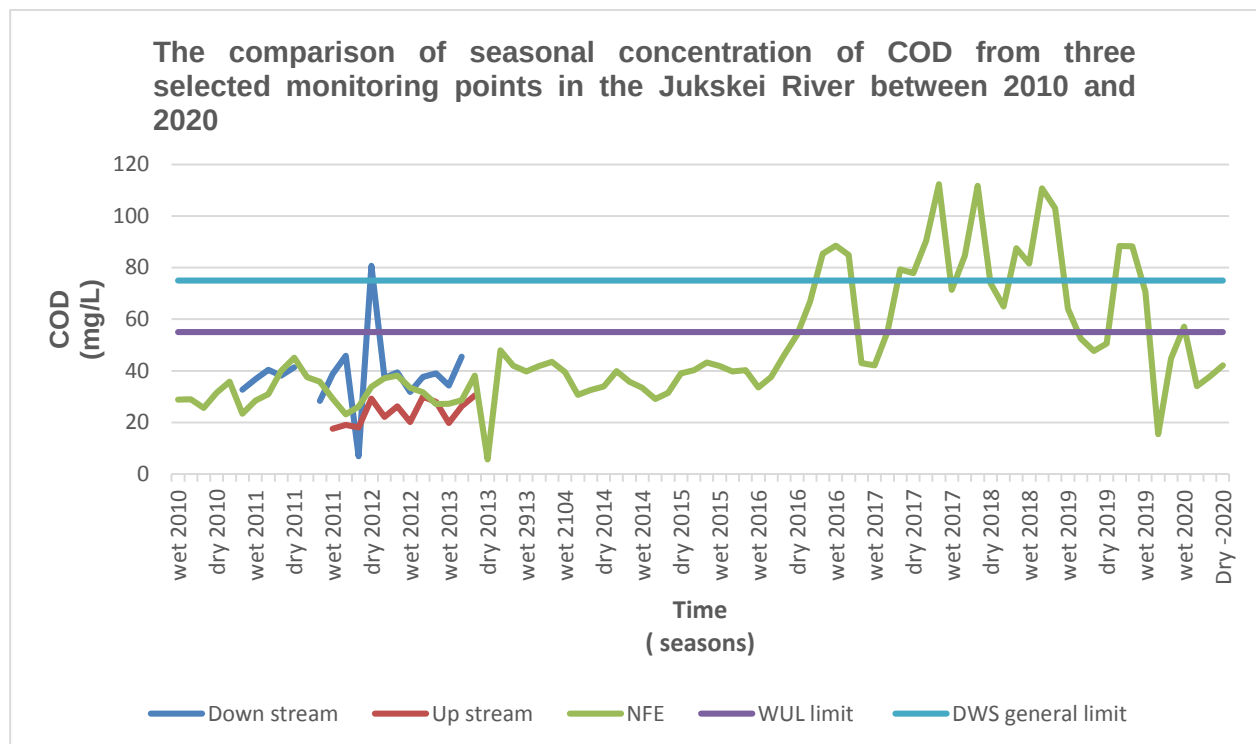


Figure 11: Comparison of the seasonal concentration of COD for three selected monitoring points in the Jukskei River for the period between 2010 and 2020.

4.3.1.7 Suspended Solids

The suspended solids concentration started from <1 to 2000 mg/L for upstream, 1.2 to 2600 mg/L for the discharge point and <1 to 1900 mg/L for the downstream end. The historical data indicated that between 2010 and 2017, suspended solids at NFE point were within the WUL limit and DWS general limit, and 2017 till 2020, it was above the WUL limit; however, it was still within the available limit. This could imply that sludge settled effectively at Northern WwTW during sedimentation (Figure 12).

A high suspended solids concentration was recorded at the upstream point (115.1 mg/L), above the WUL and general wastewater discharge limit, attributed to non-point sources. However, the results showed that the EC was within the WUL and DWS available wastewater limits.

The results showed that the difference in mean SS readings varied significantly between the two sampling sites. Samples from downstream were 7.3 mg/L higher than those from upstream ($p = 0.662$); there was no statistically significant difference. Suspended solids readings at downstream were higher than upstream (difference = 30.5 mg/L, $p < 0.0001$). The mean values between

discharge and downstream point were statistically significant (difference = 37.7 mg/L, $p < 0.0001$) (Table 13).

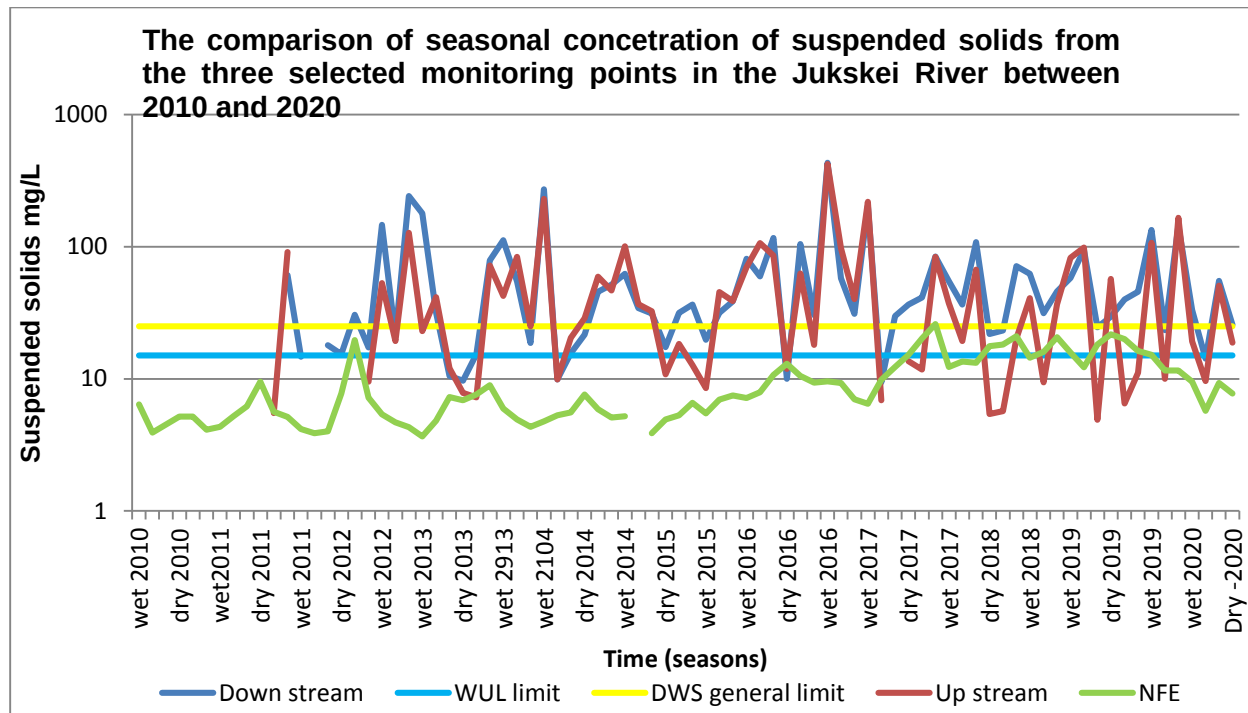


Figure 12: Comparison of the seasonal concentration of suspended solids for three selected monitoring points in the Jukskei River between 2010 and 2020.

4.3.1.8 *Escherichia coli*

The results showed that *E. coli* concentration ranged from 0–240 000 counts/100 mL upstream, 0–240 000 counts/100 mL downstream, 0–240 000 counts/100 mL effluent point. *E. coli* levels in all sampling points exceeded the WUL, DWS wastewater discharge, and RQOs limits between 2013 and 2020. Because this catchment is associated with informal settlements such as Alexandra Township, which sits on the bank of the Jukskei River, other sources of waste may be Jukskei River from various sources. There was also a gap in the data; data for the upstream point began in 2012 and ended in 2020, with no data for the downstream point in 2010 (Figure 13).

In 2003, the Jukskei had a concentration of *E. coli* of 300 000 CFU/mL, which was more than four orders of magnitude higher than the recommended 1 to 2 CFU/mL (DWAf, 2003). Surface water quality issues are not limited to the Jukskei River; in fact, most South African rivers that flow through informal settlements face similar challenges (Van Niekerk, 2000) (Figure 13).

The *E. coli* levels in all sampling points exceeded the WUL, DWS wastewater discharge, and RQO limits. The presence of high *E. coli* levels at discharge point, upstream and downstream

ends could be due to hygienic waste in the wastewater and runoff from non-point sources (Chapman, 1996; Isobe *et al.*, 2004) (Figure 13).

The results showed that the difference in mean E Coli readings varied significantly between the two sampling sites. Samples from downstream were 5974.73 CFU/mL less than those from upstream ($p < 0.0001$), which was statistically significant. E Coli at downstream were lower on average (difference = -47186.37 CFU/mL, $P < 0.0001$). The difference in mean values between discharge and downstream was not statistically significant (difference = -53161.1 CFU/mL, $p = 0.072$) (Table 13).

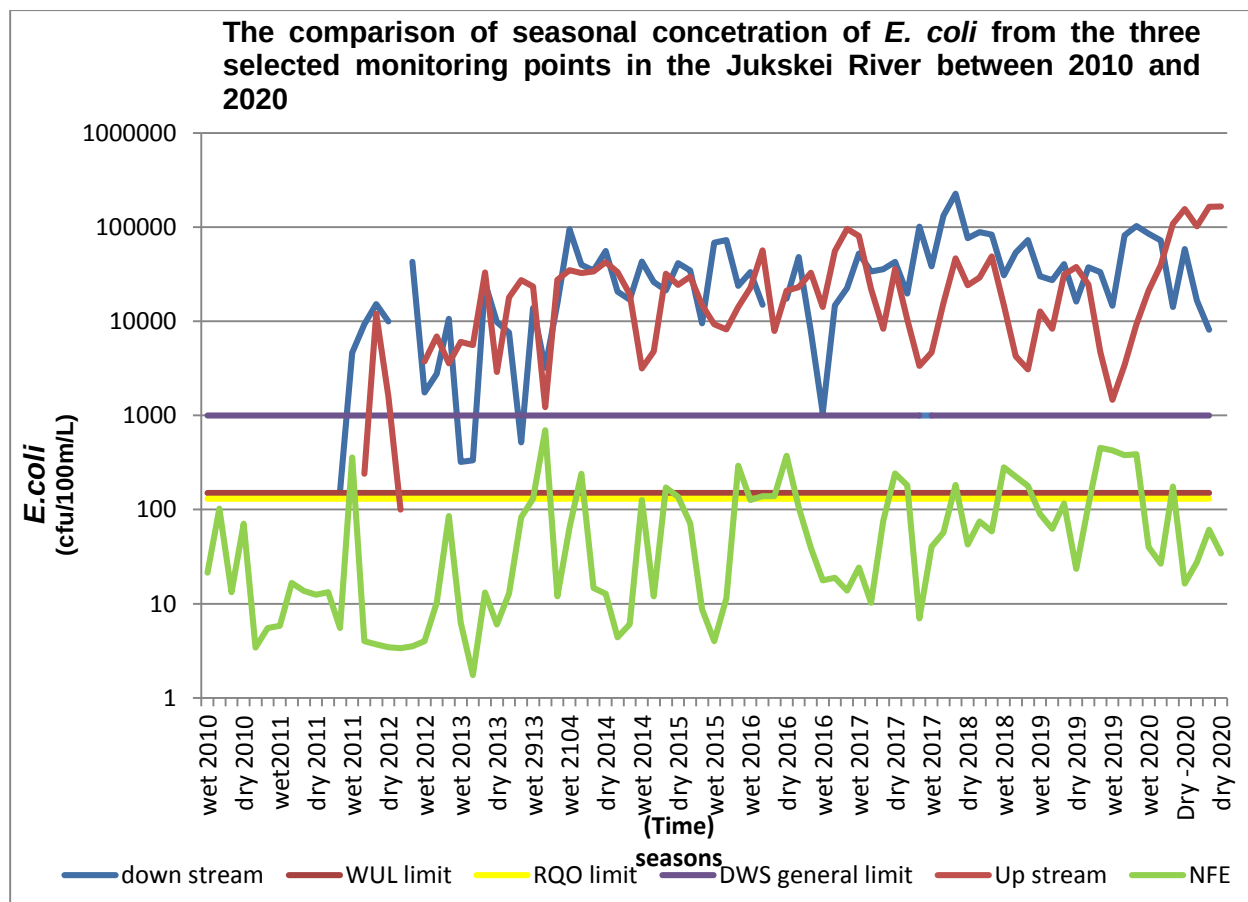


Figure 13: Comparison of the seasonal concentration of *E. coli* from three selected monitoring points in the Jukskei River between 2010 and 2020.

4.3.2 Summary of Biomonitoring Reports Analysis of Secondary Data Collection

The evaluation of biomonitoring reports was undertaken to assess the impacts of the Northern WwTW on the macroinvertebrates. Only nine (9) pieces were obtained from Johannesburg Water and evaluated. The biomonitoring is undertaken twice a year during the low and high flow seasons by Northern WwTW. See below the summary of SASS5 results of the secondary data.

In 2011, SASS5 scores were low at both sites compared to those expected for the Highveld Ecoregion at level 1 (Dallas, 2007) (Figure 14). The lowest SASS5 score was recorded at the downstream site, consistent in the dry and wet season surveys (Table 14). The number of taxa was higher at upstream site point in comparison to the downstream site during the April 2011 (wet season) survey but only marginally during the September 2011 (dry season) survey, and this could be associated with the Northern WwTW effluent; this could be as a result of anthropogenic activities particularly at the upstream during the September 2011 survey. Aquatic macroinvertebrates indicated moderate biotic integrity upstream (C category) and seriously/critically modified integrity downstream (E/F category) during the April 2011 wet season and the September 2011 dry season survey.

The upstream site had higher ASPT values in April 2011 than the downstream site, indicating more intolerant taxa identified at the upstream area. However, the ASPT value at upstream was lower than downstream in September 2011, but it improved again in April 2012, so the ASPT was the same at both sites. There was little change in the ASPT scores for September 2012 and only a slight increase in the ASPT score at the upstream site in February 2013. The low ASPT scores at both sites have shown that macroinvertebrate communities at these sites are in decline, dominated by tolerant taxa.

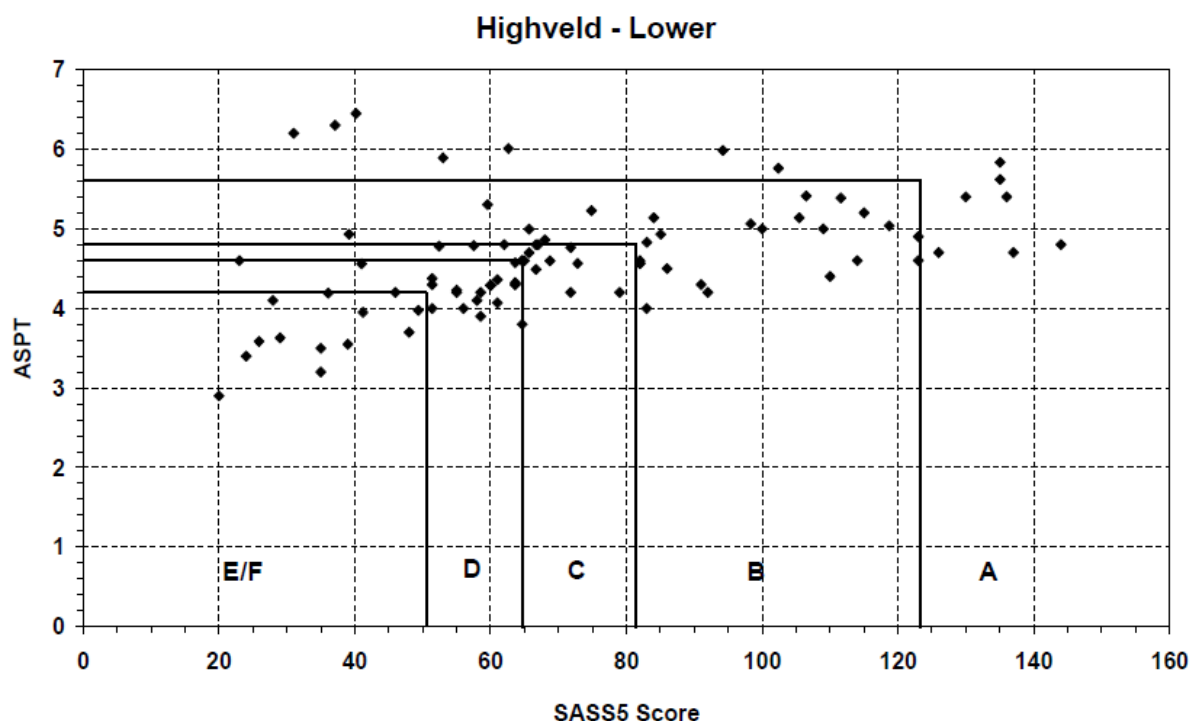


Figure 14: Biological Bands for the Highveld – Lower Ecoregion (Dallas, 2007).

Compared to previous years, the SASS5 scores recorded during the February 2013 survey (DWJ27 and J5) were at their highest. However, the scores were still low compared to what was expected for the Highveld Ecoregion level 1 (Figure 14). Downstream of the Northern WwTW effluent discharge, the SASS5 score decreased. This could be attributed to high nutrients and low DO from effluent point and cause impoverished macroinvertebrates assemblage at the downstream point. According to USEPA (1999) and USEPA (2004) studies, wastewater treatment plants use chlorine, ozone, or ultraviolet light as disinfectants, resulting in a high chlorine concentration at the effluent point.

In 2013, taxon diversity and ASPT decreased downstream of the WwTW. The low ASPT scores (5) at both sites showed that the macroinvertebrate assemblages were primarily tolerant taxa, indicating a degraded system. The biotic integrity of the Jukskei River was seriously compromised (Class E/F) at both upstream and downstream sites, with few taxa present and the loss of most intolerant forms. Not only do the results show poor biotic integrity, but they also show that biotic integrity is deteriorating further downstream of the effluent discharge point (Table 15).

In 2014, SASS Guidelines (Dallas, 2007) interpreted SASS 5 information collected during the survey. The guidelines method utilises natural variation in SASS score and ASPT to determine preliminary biological bands. Northern WwTW falls within the Level 1 Ecoregion for the Highveld, and the SASS5 score and ASPT values were evaluated according to Ecoregion bands (Figure 14).

The SASS score and ASPT were used to determine the Ecological Category (EC) for the Jukskei River (DWJ 27 and J 5). According to the data, both the sites had a very low SASS score and ASPT with a dominant presence of pollution-tolerant invertebrate species. Considering long-term biomonitoring data, this system has remained seriously and critically modified since 2005.

In 2015, the ecological category for upstream was in category C (Seriously Modified), and downstream indicates a category E/F (Seriously/critically modified system). In November 2014, the upstream site improved from a Category E/F to a Class C in May 2015 with the most insensitive species, *Leptophlebiidae* (Prongilis) (Table 14), with a SASS score of 47 was obtained, with 10 taxa recorded during the survey for upstream. The ASPT score of 3.9.

In 2015, the downstream point had a very low SASS score and ASPT with a dominant presence of pollution-tolerant macroinvertebrate species. The change in the ecological category could indicate the Northern WwTW wastewater effluent released into the Jukskei River downstream of the final effluent discharge.

The ecological category for upstream point and upstream indicated a category D (Largely Modified). The upstream end had deteriorated to a category D since May 2015. The most pollutant-sensitive taxon was *Baetidae* (> 2sp). The downstream point was found to have improved to an essentially modified state since May 2015. There was an improvement at the downstream point of the final discharge point in 2016. However, not all the parameters were within the required limit, this could be attributed to partially treatment of wastewater.

In 2017, a SASS score of 34 was recorded across seven taxa with an ASPT of 4.9, categorising the Jukskei River as an ecological category C (Moderately Modified). In 2018, a SASS score of 47 was obtained, with 12 taxa recorded during the survey for upstream. The ASPT score of 3.9 obtained placed the Jukskei River into a Present Ecological State (PES) of Category E (Severely Modified). The PES of Category F (Severely Modified) is deteriorating from Category C (Moderately Modified), which could be due to the impact of effluent from the WwTW.

In 2018, a SASS score of 47 was obtained, with 12 taxa recorded during the survey for upstream. The ASPT score of 3.9 obtained placed the Jukskei River into a Present Ecological State (PES) of Category E (Severely Modified).

In 2019, the biomonitoring was not conducted due to floods; the ecological state has remained the same from the December 2018 survey. In 2020, the overall ASPT score of 3.4 obtained placed the site into a PES of Category F (Severely Modified). The PES of Category F (Severely Modified) is deteriorating from Category C (Moderately Modified), which could be due to the impact of effluent from the WwTW.

In 2020, the overall ASPT score of 3.4 obtained placed the site into a Present Ecological State (PES) of Category F (Severely Modified).

Table 15: Summarised SASS5 results of secondary data

Date	Upstream point				Downstream point			
	SASS5	No of Taxa	ASPT	Class	SASS5	No of Taxa	ASPT	Class
2011	28	6	4.7	C	5	2	2.5	E/F
2012	6	3	2.0	E/F	5	2	2.5	E/F
2013	50	12	4.2	EF	35	10	3.5	E/F
2014	25	7	3.6	E/F	14	5	2.8	E/F
2015	47	10	4.7	C	19	6	3.2	E/F
2016	55	13	4.2	D	47	11	4.3	D

2017	34	7	4.9	C	26	7	3.7	E/F
2018	47	12	3.9	E	3	2	1.5	F
2019								
No data								
2020	17	5	3.4	F	2	1	2.0	F

4.2.3 Summary of compliance with Northern Works WUL wastewater discharge limits

The selected eight variables were categorised as compliant or non-compliant using the study area water use licence's wastewater discharge limits. The results showed that out of eight variables, only five variables were compliant with WUL discharge limits (EC, COD, nitrate, orthophosphate, and pH) and the other three (Ammonia, suspended solids, *E coli*) were not compliant with the WUL's wastewater discharge limit. This could be attributed to partially wastewater treatment and pollution from non-point sources (Table 16).

Table 16: Summary of compliance with WUL Wastewater discharge limits

WUL Variables	Frequency	Percentage
Ammonia		
Discharge point (NFE)		
Compliant	1047	30.39
Non-compliant	2398	69.61
Nitrate		
Discharge point (NFE)		
Compliant	114	97.44
Non-compliant	3	2.56
Suspended Solids		
Discharge point (NFE)		
Compliant	465	69.40
Non-compliant	205	30.60
pH		
Discharge point (NFE)		
Compliant	463	95.27
Non-compliant	4	0.82
Orthophosphate		
Discharge point (NFE)		

Compliant	504	80.25
Non-compliant	124	19.75
Chemical Oxygen Demand		
Discharge point (NFE)		
Compliant	2,436	71.27
Non-compliant	982	28.73
Electrical Conductivity		
Discharge point (NFE)		
Compliant	653	99.54
Non-compliant	3	0.46
<i>Escherichia coli</i>		
Discharge point (NFE)		
Compliant	75	11.72
Non-compliant	565	88.28

4. 5 Discussion

The data obtained from Johannesburg Water had gaps. The Johannesburg Water collects samples at the designated monitoring points daily in compliance with water use licence requirements. However, the data had gaps could have been from Johannesburg Water failure to collect, analyse, or capture the data. In some months, there were incomplete data sets for upstream and downstream monitoring sites making it difficult to compare individual selected monitoring points with WUL, general wastewater limit and ROQs. According to Dube (2020), poor water quality data makes it difficult to make informed decisions or even determine the impact in most cases.

Although the data had gaps, the data was enough for the study to determine whether Northern WwTW effluent has a long term impact on macroinvertebrates and water quality in the Jukskei River as the primary data was also collected to validate the secondary data to see if the WwTW effluent was within the same range during the same seasons. The majority of variables were in the same range in the same season. The study by Mothetha (2016) found that the water quality results were in the same range with the same loads of concentration.

The study found that out of eight parameters secondary data, only five were compliant with the WUL wastewater discharge limit, and the other three were not compliant. The statistical data also suggest statistically significant differences within the seven variables except for E. coli. The results

indicate that the Jukskei River is severely modified due to different human activities within the catchment. According to Da Silva (2016), the Jukskei River is in a built-up and populated Johannesburg North area. It has been historically exposed to many water quality issues, particularly of a bacterial nature, and other non-point pollution sources. The results have also shown that there is a high level of pollution upstream of WwTW compared to the discharge point (pH, SS and E. coli), which indicates that the WwTW alone is not contributing to the pollution load in Jukskei River, there are other sources upstream of the WwTW.

The Northern WwTW is adjacent to Diepsloot Township, where there is a mushrooming of informal settlements without proper sanitation and small-scale farms. This could be another contributing factor to the contamination of the Jukskei River.

According to the available data, the Jukskei River's water quality deteriorated over time. According to the national general wastewater guidelines, RQOs, and WUL wastewater limits, the wastewater quality discharge parameters exceeded critical quality indicators. The outcome of the analysed data indicated that pollutant concentration is high in three selected sampling points. The ANOVA results have shown no significant differences at all three monitoring chosen points, which indicated that other non-point sources along the Jukskei River contributed to the deterioration of Jukskei River EC, as high pollutant concentrations were also recorded upstream of the WwTW. The impact of poor water quality was visible in the Jukskei River's severely altered PES.

The biomonitoring results indicated an increase intolerant and decline in intolerant macroinvertebrates, which indicates the modified Physico-chemical conditions and poor physical conditions within reach. The PES deteriorated from category C, recorded in 2011, to E/F in 2020, seriously modified. All of this points to the Jukskei River's poor water quality. According to Dabrowski (2018)'s study for upper Jukskei River catchment rehabilitation, all sites were rated as E/F, severely impacted.

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study looked into the long-term effects of the Northern Wastewater Works effluent on the macroinvertebrates and water quality in the Jukskei River. The primary objectives of this study were to assess whether the wastewater effluent from Northern Works had an impact on macroinvertebrates and water quality of the Jukskei River system as a receiving environment; analyse collected primary water quality results and historical water quality trends of selected monitoring points for a period of 10 years; compare water quality trends with Water Use Licence (DWS) discharge parameters, DWS Wastewater Quality Guideline and Resource Quality Objectives (RQOs) limits; and, reach the current and historical macroinvertebrate community found at the selected monitoring points.

The overall results have indicated a long-term impact due to the Jukskei River catchment, which is critically modified due to non-point pollution sources and partial wastewater treatment at the Johannesburg Water Northern WwTW. It was evident from the water quality results obtained from the JW Lab that the Northern Works did not fully comply with the WUL wastewater standard, general limits and RQOs. The ANOVA has also shown statistically significant differences in seven variables. The posthoc test has indicated that only *E coli* was not statistically significantly different. The results showed that out of eight variables, only five were compliant with WUL limits (EC, nitrate, COD, Orthophosphate and pH), and the other three (ammonia, suspended solids, *E. coli*) were not compliant with WUL's wastewater discharge limit.

Over ten years, the water quality has deteriorated, and thus the tolerant macroinvertebrates increased while the intolerant macroinvertebrates decreased. The PES has changed from category C to E/F, which seriously modified the Jukskei River. The primary data also indicated that the poor water quality has contributed to a poor community of macroinvertebrates. It was the dominant driver for the modified state of the Jukskei River. The absence of intolerant taxa indicated changed physicochemical conditions within reach. The tolerant species that were present were *caenidae* and *Simuliidae*.

The overall results demonstrated the Northern WwTW's partial effectiveness in treating wastewater discharged into the Jukskei River for the three selected monitoring points' analysed parameters. These could result from equipment failure or a high inflow that exceeds the capacity of the Northern Works.

5.2 Recommendations

There were gaps in the data set that was obtained from JW. The data gaps were potentially due to data not being collected or recorded. The findings also revealed no statistically significant difference between upstream and downstream for *E. coli* in water quality within the Jukskei River. However, the *E. coli* at the discharge point was below the upstream, giving a different indication about the river condition. The availability of intolerant macroinvertebrates has decreased. The results indicated that the Jukskei River's current ecological state is E/F, showing that it has been significantly modified. This requires JW to continue with daily monitoring and other stakeholders such as DWS to undertake effective measures by monitoring and reporting of non-point pollution sources that are discharging the pollutants upstream of the river to ensure that the PES at least is restored to category C or D for water quality to improve and become favourable for the aquatic ecosystem.

Following are the recommendations:

- In the absence of robust monitoring data on microbiological indicators before discharge, treated water quality should be checked daily. When partially treated waste, particularly from sewage treatment works and food processing plants, is poorly treated and discharged into river systems, it may contain residual pathogenic microorganisms that pose health risks. To enhance the quality of effluent discharged into the Jukskei River, an investigation within the works is required to determine what is causing these lapses to occur more frequently.
- The outcome of the water quality tests revealed that the effluent from the works was partially compliant with the WUL, RQOs, and DWS general wastewater limits that are discharged into the Jukskei River. According to Johannesburg Water WRAP (2018), the current flow measurement indicates that the combined capacity of the Northern basin will exceed the Northern WwTW capacity shortly. Furthermore, Northern WwTW is approaching its maximum design capacity (Johannesburg Water WRAP, 2018). The available treatment capacity of the Works is recorded as 405ML/d against a designed capacity of 450ML/d. This could be due to insufficient ability to handle influent volumes due to population growth and equipment failure during the treatment processes. It is recommended that Johannesburg Water conduct daily equipment inspections to identify the problems immediately before equipment failures. They should also consider expanding and including new technology with better treatment so that the works meet licence requirements while improving the poor water quality of the Jukskei River and its present ecological state.

- Maintain the daily collection of water samples and data capture for all selected monitoring points of the WwTW by JW for the main variables linked to evaluating the standard of treated wastewater discharged into the Jukskei River. The daily monitoring would assist in picking up failures and non-compliance with the WUL wastewater discharge effluent limits. This will help the WwTW's to become proactive and undertake corrective actions whenever there is an issue. The City of Johannesburg, internal JW environmental section, and DWS must conduct regular compliance audits to ensure that JW is adhering to the terms of the issued WUL.
- Undertaking more research into the impact of wastewater discharged from the works on water resources, focusing on primary data. Future studies that may benefit may include assessing wastewater works' performance in treating wastewater and the use of new technology at the works.

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APPENDICES

Appendix A: Ethics Clearance Letter from North-West University



Date: 17 February 2020

Dear Mr Thendo Makuya

Ethics consideration for Mr Thendo Makuya, student nr 23726369

The Scientific Committee of the Sub-programme 4: Environmental Management in the Unit for Environmental Sciences and Management has carefully considered your research proposal. The scientific committee has found that your project proposal entitled: *"The long-term impact of Northern Wastewater Treatment Works effluent on macroinvertebrates and water quality in the Jukskei River"*, under supervision of Dr Wynand Malherbe, is in accordance with the scientific method and adheres to the required standards as set out in the Academic Rules for Master's and Doctoral Students at North-West University. The proposed methodology does not pose any ethical risk/poses no risk to human participants, hence the study is recommended for expedited ethical review by the FNAS Ethics Committee.

Your proposal is regarded as satisfactory and is therefore recommended for acceptance by Board of Faculty.

Yours sincerely



Prof Francois Retief
Chair of the Scientific committee

Scientific Committee:

Prof. Francois Retief, Mr. Reece Alberts, Dr. Claudine Roos, Dr. Wynand Malherbe, Mr. Theunis Meyer

Appendix B: Authorization letter from the Johannesburg Water Ltd (Pty)



City of Johannesburg

Johannesburg Water SOC Ltd

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19 March 2021

Dr Wynand Malherbe,
North West University
Faculty of Natural and Agricultural Science

LETTER OF APPROVAL: ACCESS TO INFORMATION

PROPOSED PROJECT: Long-term Impacts of Northern Wastewater Treatment Works effluent on Macroinvertebrate and water quality in Jukskei River

Johannesburg Water (JW) received a request for access to information from Mr Thendo Makuya for a Masters Study. JW has scrutinised the proposal content in line with internal policy and processes.

The Study has been granted access to information through the Innovation and Technology office. It is also requested that engagement with JW for this project be conducted via the Innovation and Technology office, which will then facilitate the process with the relevant information source division.

Please do not hesitate to seek any clarification.

Yours sincerely,

Dr Zakhele Khuzwayo
Manager: Innovation and Technology

Directors:

Mr Sibusiso Buthelezi (Chairperson), Mr Ntshavheni Mukwevho (Managing Director), Mr Johan Koekemoer (Financial Director),
Dr Jack Maduna, Ms Ndivhuho Sekoba, Ms Rachel Kalidass, Professor Clinton Aigbavboa, Ms Mpusi Mangena, Mr Dingane Khesuoe,
Ms Roslynn Greef, Mr Sabelo Mtolo, Ms Gugu Phakathi, Ms Thembi Maseko, Mr Mveleli Booi

Ms Kethabile Mabe (Company Secretary),
Johannesburg Water SOC Ltd
Registration Number: 2000/029271/30