ASSESSMENT OF THE POSSIBLE RELATIONSHIPS AND INFLUENCE OF CLIMATE VARIABILITY AND WATER FLOW ON WATER QUALITY IN MAJOR RIVERS OF THE KRUGER NATIONAL PARK

by

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DECLARATION

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Assessment of the Possible Relationships and Influence of Climate Variability and Water Flow on Water Quality in Major Rivers of the Kruger National Park

I declare that the above dissertation is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

I further declare that I submitted the dissertation to originality checking software and that it falls within the accepted requirements for originality.

I further declare that I have not previously submitted this work, or part of it, for examination at Unisa for another qualification or at any other higher education institution.

17/02/2024

Nicole Carys Christie **Date**

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ABSTRACT

Water is a vital resource required by all living organisms for their continued survival, however current trends indicate that water resources, especially in semi-arid regions such as South Africa, are becoming more stressed alongside the prevalence of climate change. The Kruger National Park (KNP), a prime conservation area in the east of South Africa is no exception to these challenges and has, for several decades, been subject to persistent water quality and flow issues, putting vulnerable ecosystems at risk. This research undertook to establish the historic trends and current state of water quality of the seven major rivers that flow through the park, as well as to determine the influence of regional climate variability upon these water resources. Mann-Kendall (MK) Time Series Trend Analyses were compiled to determine temporal water quality trends for the rivers and revealed that approximately 75% of all water quality observations - indicated by eleven parameters - exhibited a deteriorating trend over time. Of particular significance were the ions responsible for salinisation and wastewaters responsible for microbial pollution. Acidification was a secondary concern for many of the water quality monitoring sites. Spearman's Rank Correlation Analyses were compiled to establish the relationships between various climate, water quality and water flow parameters. The results indicated that variations in water quality were most strongly associated with climate variability at monitoring sites further south (e.g.: Crocodile and Sabie Rivers) due to a higher average annual rainfall impacting water flow, and therefore the dilution capacity of the rivers. Subsequently, various solutions were recommended, involving a combination of political, environmental and management strategies and activities to address these water quality issues and ensure good quality water for the KNP well into the future.

Key terms: water quality; water flow; climate variability; Kruger National Park; water degradation; South African rivers.

OKUCASHUNIWE

Amanzi awumthombo obalulekile futhi zonke izinto eziphilayo ziyawadinga ukuze ziqhubeke ziphila; kodwa-ke, izimo zamanje zikhomba ukuthi ilokhu incipha imithombo yamanzi, ikakhulu ezindaweni eziwugwadule njengeNingizimu Afrika, kanjalo nokuphazamiseka okudalwa ukuguquguquka kwesimo sezulu. Isiqiwi esaziwayo i-Kruger National Park (KNP), okuyindawo esempumalanga yeNingizimu Afrika, nayo iyathinteka ngalokhu. Lesi siqiwi sinenkinga yokuswela amanzi kanjalo nezinga lawo elingagculisi, nokubeka engcupheni inhlaliswano yezinto eziphilayo. Lolu cwaningo lwenzelwa ukuthola izimo obekwenzeka ngazo phambilini nesimo samanje ngezinga lamanzi emifula eyisikhombisa emikhulu egeleza e-KNP, kanjalo nomthelela ongaba khona emifuleni yesifunda ngenxa yokuguquguquka kwesimo sezulu. Lapha kusetshenziswe ucwaningo i-Mann-Kendall Time Series Trend Analyses ukuze kutholakale izimo zesikhashana zezinga lamanzi emifuleni, kanti-ke lokhu kukhomba ukuthi cishe izinga lokugeleza kwamanzi liku-75% - uma kuhlolwa izinga lamanzi kusetshenziswa amapharamitha ayishumi nanye efizikhokhemikhali nemayikhrobiyo –- kuvela ukuthi amanzi aya ngokuya encipha kakhulu. Okubaluleke kakhulu ama-ion asebenza ukukhuculula amanzi kanye namanzi angcolile ahambisana namagciwane. Izimo zesikhathi eside ze-E. coli zibonise ukuthi amanzi omfula awamukelekile ekutheni asetshenziswe ezintweni ezihlukahlukene. Ukufakwa kwe-esidi emanzini kuvele njengenkinga yesibili esezindaweni eziningi okuhlolwa kuzo izinga lamanzi. Kuphinde kwasetshenziswa i-Spearman's Rank Correlation Analysis ukuze kutholakale ubudlelwano phakathi kwezinga lamanzi ahlukahlukene adalwa isimo sezulu kanye nalawo manzi azigelezelayo. Imiphumela iveze ukuthi ukuhluka kwezinga lamanzi kuhlobene kakhulu nokuguquguquka kwesimo sezulu ezindaweni okuhlolwa kuzo eziseningizimu (isib., umfula i-Crocodile kanye ne-Sabie), ngenxa yemvula yonyaka engaphezu kwesilinganiso, enomthelela ekugelezeni kwamanzi, nokube nomthelela emazingeni okuhlanjululwa kwamanzi emifula. Amagrafu akhombisa ukugcinwa kwesimo aveza ukuhlukahluka kwesikhathi eside kwezimo zezindawo maqondana nokufanelekela ukusetshenziswa, ikakhulu ukwehla kwezinga lamanzi nokuba sengozini kwezinto ezifundisa ngamanzi kuhluke kakhulu futhi kumaphakathi nesifunda ngasinye. Ngemuva kwalokho, kuye kwanconywa izixazululo ezehlukene ezisekelwe yingqikithi, okuhlanganisa inhlanganisela yamasu nemisebenzi yezepolitiki, ezemvelo nezokuphatha, ukuze kubhekwane nalezi zinkinga zezinga lamanzi kanjalo nokuqinisekisa ikusasa elihle lezinga lamanzi e-KNP. Kusenethuba lokwenziwa

kocwaningo olwengeziwe, ukuze kube nokuqonda ngokwanele maqondana nobudlelwane phakathi kwesimo sezulu nemithombo yamanzi ezindaweni eziningi zokongiwa kwemvelo nangokwezifunda.

ISISHWANKATHELO

Amanzi ngumthombo obalulekileyo ofunwa zizo zonke izinto eziphilayo ukuze ziqhubeke ziphila; nangona kunjalo, iintshukumo zangoku zibonisa ukuba imithombo yamanzi, ingakumbi kwimimandla eyomileyo efana noMzantsi Afrika, iya isiba noxinzelelo ngakumbi kunye nokuxhaphaka kokutshintsha kwemozulu. IKruger National Park (KNP), eyona ndawo iphambili yolondolozo lwendalo esempuma yoMzantsi Afrika, ikwanjalo. Ixhomekeke kumgangatho nakwimiba yokuhamba kwamanzi eqhubekayo, ebeka indalo esesichengeni emngciphekweni. Olu phando lwenziwe ukumisela iintshukumo zembali kunye nemo yangoku yomgangatho wamanzi wemilambo esixhenxe emikhulu ehamba kwiKNP, kunye nempembelelo enokubakho yokuguququguquka kwemozulu yommandla kwimilambo yayo. I*Mann-Kendall Time Series Trend Analyses* iqulunqwe ukuze kuqinisekiswe iintshukumo zomgangatho wamanzi zexeshana emilanjeni, kwaye oku kutyhile ukuba malunga ne75% yayo yonke imigqaliselo yomgangatho wamanzi – ebonakaliswe yimilinganiselo elishumi elinanye ekujongwa ngayo umgangatho wamanzi omlambo eyaziwa ngokuba yi-*physicochemical and microbial water quality parameters* -- ibonise intshukumo ewohlokayo ngokuhamba kwexesha. Eyona nto ibibaluleke kakhulu ibiziiayonzi (*ions*) ezinoxanduva lokuzisa ityuwa emanzini kunye namanzi amdaka anoxanduva longcoliseko lweentsholongwane. Iintshukumo zentsholongwane ebangela isifo sorhudo i*E. coli* zexesha elide zibonise ukuba amanzi omlambo awamkelekanga ukuba asetyenziselwe iindlela ezahlukileyo. Ukufakwa kweasidi kuye kwayinkxalabo yesibini kwiindawo ezininzi zokuhlola umgangatho wamanzi. Kuqulunqwe i*Spearman's Rank Correlation Analyses* ukuze kuqinisekiswe ubudlelwane phakathi komgangatho wamanzi kwiimozulu ezahlukileyo kunye nemilinganiselo yokuhamba kwamanzi. Iziphumo zibonise ukuba ukuguququguquka komgangatho wamanzi bekunxulunyaniswe kakhulu nokuguququguquka kwemozulu kwiindawo zokubeka iliso ezisemazantsi (umzekelo, iCrocodile neSabie Rivers), ngenxa yokuna kweemvula zonyaka ezingaphezulu komyinge, ezibe nefuthe ekuhambeni kwamanzi, zibe nefuthe kumthamo wokuhamba kwamanzi emilambo, kwaye zanegalelo kumthamo wongxengo wale milambo. Iigrafu zokuthotyelwa kwemimiselo nemigangatho ziphinde zabonisa iintshukumo ezahlukileyo zesithuba zexesha elide ngokokufaneleka kokusetyenziswa, ngakumbi kugxininiswa ukuba umgangatho wamanzi kunye nokuba sesichengeni kwawo kwizingeneleli zemozulu nokuhamba kwamanzi emhlabeni ukhethekile kakhulu kwaye ubekelwe kumbindi wommandla ngamnye. Emva koko, kuye kwacetyiswa ngezisombululo ezahlukileyo ezisekelwe

kwimeko, ezibandakanya indibaniselwano yezopolitiko, izicwangcisoqhinga nemisebenzi yolawulo lokusingqongileyo, ukujongana nale miba yomgangatho wamanzi nokuqinisekisa ikamva lomgangatho olungileyo wamanzi eKNP. Amathuba ophando olongezelelweyo akhona, ukwandisa ulwazi olukhoyo kubudlelwane phakathi kwemozulu kunye nemithombo yamanzi kwiindawo zolondolozo kwimilinganiselo eyahlukileyo yemimandla neyeengingqi

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AMD:	Acid Mine Drainage
DWA:	Department of Water Affairs
DWS:	Department of Water and Sanitation
EC:	Electrical Conductivity
EFR:	Environmental Flow Requirements
GHG:	Greenhouse Gas
IWRM:	Integrated Water Resource Management
KNP:	Kruger National Park
KNPRRP:	Kruger National Park Rivers Research Programme
m.a.s.l:	Metres Above Sea Level
NMP:	National Monitoring Programme
NRW:	Non-Revenue Water
NWQMP:	National Water Quality Monitoring Programme
NWRS:	National Water Resource Strategy
RQIS:	Resource Quality Information Services
SAWS:	South African Weather Service
TDS:	Total Dissolved Solids
TWQRs:	Target Water Quality Ranges
WMA:	Water Management Area
WWTWs:	Wastewater Treatment Works
UNESCO:	United Nations Educational, Scientific and Cultural Organization

CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1. Introduction and Context

Water is a natural resource which by virtue of its fundamental physics is in a state of flux rather than occurring as a stock, and is fugitive in nature (Turton, 2008; Pollard et al., 2011). It is a vital resource on which all living organisms on earth rely for their survival. Water is essential for meeting basic human needs and is also a strategic economic resource necessary for promoting socio-economic interaction (SADC, 2008; UNEP, 2016; du Plessis, 2019). Although the total volume of water available on earth is constant over time, its distribution and form (solid, liquid, gaseous) are dictated by physics and the hydrological cycle (Turton, 2008). Water resources are further influenced by various natural and anthropogenic factors which all combine to determine the quality, quantity, and availability of freshwater for various uses, and if not in a state of equilibrium, can lead to water-related stress and water scarcity. Changes to hydro-climatic and socio-economic conditions have increasingly put pressure on freshwater resources and have exacerbated water-related challenges on various scales (Veldkamp et al., 2016). Additionally, as with the human population, not all water resources are equally distributed across the globe, and most are unsuitable for human consumption (du Plessis, 2019).

Current global trends indicate that water resources have become stressed (Munia et al., 2016; du Plessis, 2019) and many areas are already classified as water scarce (Veldkamp et al., 2016). Global water demand has been increasing at a rate of about one percent (1%) per year as a function of population and economic growth (UN Water, 2018). Under a scenario based on average growth, with no efficiency gains assumed across the water use sectors, global water requirements could, by 2030, increase from 4 500 billion m^3 to 6 900 billion m^3. This is approximately 40% above the current reliably accessible supply. At the current withdrawal rate of 4 500 billion m^3 per annum, global withdrawals are already close to their maximum sustainable levels (WRG, 2009; UN Water, 2018). In addition to the demand for water for consumption purposes, water is also treated as a means by which to discard of waste products, and therefore carries a double burden. The availability of water is largely determined by its quality because polluted water cannot be used for human consumption, nor conservation (van der Merwe-Botha, 2009; du Plessis, 2019). Approximately two million tonnes of sewage and wastewater effluent are discharged into the world’s water resources every day, and each year, the world produces six times more wastewater than there is water contained in its rivers (du Plessis, 2019). Approximately 80% of this wastewater is currently not collected or treated (UNEP, 2016).

Currently, over two billion people already live in water stressed regions. By 2030, approximately one third of the world's population will live in water basins with a water deficit greater than 50%, with 107 countries not on track to achieving water sustainability by 2030 (WRG, 2009; WRG, 2021). The number of people living in water scarce areas for all, or part of the year, is set to increase from approximately 4.8 to 5.7 billion by 2050 (Munia et al., 2016; UN Water, 2018). Additionally, more than one billion people are currently living without access to a safe source of drinking water and approximately 2.6 billion people are living without access to safe sanitation (du Plessis, 2019).

Furthermore, water is the primary medium through which the effects of climate change are felt, and it is expected that the impacts will continue to intensify indefinitely (IPCC, 2014). Additional stress on water resources will have consequences for livelihoods and wellbeing and could exacerbate the availability and quality issues of water in many countries, especially those classified as naturally water stressed (Dallas et al., 2019). Climate change predictions indicate that three to four billion people will be exposed to physical water scarcity if global average temperatures increase between 2 - 4˚C from current levels (IPCC, 2022). Water quality will be impacted by changes in the ambient air temperature, and the increase of events such as floods and droughts (Delpha et al., 2009; Tanner et al., 2022). These events alter the dilution of dissolved substances in water, thereby modifying the quality of water. Reduced water quality will threaten the potable water supply, even with improvements in treatment capacity (IPCC, 2014; IPCC, 2022). Furthermore, freshwater biodiversity is expected to decrease proportionally to the degree of warming, in line with reduced water availability (IPCC, 2022).

Therefore, because of its state of flux, its fugitive nature, as well as its drivers, such as economic development, population growth, and poor management practices, water as a natural and economic resource presents several challenges, which need to be considered to ensure water security into the future. This research aims to address such challenges on a local, South African scale, within the context of the KNP, by evaluating the quality of its river water, and the possible influence that water flow and climate variability have on water supplied through rivers for conservation.

The KNP is a savanna ecosystem situated in the Mpumalanga and Limpopo provinces of South Africa and is traversed by a set of large and biologically diverse transboundary river systems (Riddell et al., 2019a). These rivers, in order from north to south, are the Limpopo, Luvuvhu, Shingwedzi, Letaba, Olifants, Sabie and Crocodile rivers. Owing to the presence of mining, agriculture, industrial production, and various domestic water uses along their reaches, these rivers are widely regarded as some of South Africa's most degraded freshwater resources (Marr et al., 2017a). According to the DWS (2019), the KNP and its rivers are positioned within the Drainage Region A (Limpopo), Drainage Region B (Olifants) and Drainage Region X (Inkomati-Usuthu). Due to its location in a semi-arid region, characterised by highly variable water regimes, the management of surface water resources of the KNP should be underscored by knowledge of the long-term trends in climate and hydrological processes. These measures become highly relevant for the management of the conservation area under the potential threat of climate change, and its influences on, and risks for the natural environment and ecosystems sustained by freshwater (Riddell et al., 2020).

This research therefore set out to evaluate the state of water quality in KNP rivers and determine how these water resources are possibly influenced by the variability of the regional climate and water flow. This will shed further light on the possible long-term impacts on the environmental, social, and economic sustainability of the KNP. A statement of the research problem now follows.

1.2. Problem Statement and Rationale

The inefficient management of water resources has emerged as a worldwide trend, with an overall deterioration in the quality and quantity of water being a far-reaching consequence. Despite water playing a central role in sustaining life and maintaining economic activities, it has become one of the most abused resources in the world. Countries are struggling to meet the rapidly changing water requirements, while concurrently attempting to solve various challenges associated with its sustainability such as pollution, over-abstraction, non-revenue water (NRW), and increased climate variability. Currently, various water management areas (WMAs) in South Africa are already experiencing moderate to large water deficits; natural ecosystems and freshwater resources are under severe pressure by various water use sectors; and water quality in general is steadily declining (Ashton et al., 2001; du Plessis, 2014; Oberholster et al., 2017; du Plessis, 2019).

Standards governing the quality and flow of river water have been set at multiple governmental levels to achieve improved access and sustainability (du Plessis, 2019). However, there is a shared concern amongst government officials, decision makers, investors, researchers, and the public, that despite South Africa's achievements under an integrated water resources management (IWRM) approach, the health of rivers is generally poor and rapidly deteriorating (van der Merwe-Botha, 2009; Baker & Greenfield, 2019).

Meeting human needs for freshwater resources in an expanding world has come largely at the expense of inland freshwater ecosystems, such as rivers, and has led to the growing need to manage freshwater more sustainably. Globally, freshwater ecosystems are facing rates of biodiversity loss which exceed those of terrestrial habitats, possibly positioning them as the most endangered ecosystems in the world. Ultimately, the deterioration of rivers has a detrimental impact on freshwater habitats downstream, as well as on the biodiversity that they support (Enoch, 2018; Baker & Greenfield, 2019), thereby inhibiting both urban development and tourism (van der Merwe-Botha, 2009).

In South Africa, where water is limited by climatic conditions and excessive anthropogenic pollutants, rivers still provide most of the water to various water use sectors (Huizenga, 2011). South Africa's reliance on river water as an exploitable source of freshwater is primarily due to the limited existence of large, permanent water bodies, such as dams and lakes, and the currently limited use of groundwater aquifers. Although the country appears to have an extensive network of river systems, many of these are small and shallow, or flow only during the rainfall season (Barker, 2006). Despite conservation water requirements in South Africa accounting for approximately only one percent (1%) of the total water consumption (van Vuuren, 2017a), protected areas face cumbersome management challenges in terms of ensuring a healthy flow of river water to support ecosystems, and ultimately nature-based tourism. Protected areas are not 'islands' and are, therefore, not isolated from the growing water crisis in South Africa (Pollard et al., 2011). River ecosystems are also not divisible from the landscape and cannot be contained in man-made boundaries or separated from outside influences (van Vuuren, 2017a). Therefore, while protected areas have a vital role to play in the adaptive water management processes of a country, they are also amongst the users that are most at risk (Pollard et al., 2011).

The KNP, the primary focus area of this research, located in the north-eastern portion of South Africa, straddles two transboundary river basins positioned between Mozambique and Zimbabwe. The KNP forms part of the Greater Limpopo Transfrontier Park and comprises a total area of approximately 35 000 km² (Viljoen, 2015; Biggs et al., 2017). It is a leading international conservation area and a major tourist destination for both South Africans and foreigners (O'Keeffe & Davies, 1991; Barker, 2006; Viljoen, 2015; Nhamo & Dube, 2019). Freshwater is a key ecosystem service to the park, the surrounding protected areas, and the local human settlements (Biggs et al., 2017). Both the maintenance and good health of ecological processes and systems that support the preservation of genetic and species diversity within the park are the responsibility of the park, as is the sustainable utilisation of these resources (Moore et al., 1991; Gerber et al., 2015; Baker and Greenfield, 2019). The KNP's water supply is obtained mainly through boreholes and from both perennial and non-perennial rivers originating in the higher-lying areas to the west where they are first highly utilised by various industries and already highly impacted upon. In a South African context, the KNP is therefore the furthest downstream user of these water resources and frequently receives water via in-stream flows that is of a sub-standard quality (du Toit et al., 2003; Riddell et al., 2019a).

The park has a history of water quality and river flow issues which can be traced back as far as a century ago (de Villiers & Mkwelo, 2009; Riddell et al., 2019a; Riddell et al., 2019b). Van Vuuren (2017a) states that since its establishment in the early nineties, the lack of available water resources has been a prime consideration for the management of the KNP. Pienaar et al. (1997) has highlighted the series of pollution incidents that the perennial rivers flowing into the park have sporadically been subjected to since the early 1920s, as well as the increased siltation which has contributed to further water quality degradation since the mid-1940s. Pollard et al. (2011) and Shikwambana et al. (2021) affirm the continuing decline in water quality in these rivers since the 1960s and highlight the adverse effects of these issues on the KNP ecosystems. The cumulative effects of altered water quality and flow regimes over many decades are evident in aquatic ecosystems, and in the dependent flora and fauna. One of the first signs of this deterioration was identified when flows in the previously perennial Letaba River, and later in the Luvuvhu and Olifants Rivers, ceased periodically (Pienaar et al., 1997; Pollard et al., 2011). Declined flows were largely attributed to increased withdrawals for industrial and agricultural expansion, and to heavy silting and drought (Pienaar et al., 1997). The degradation and loss of aquatic ecosystems and other related biodiversity in the park, resulting from declined flow, heavy pollution, and invasive species, have plagued the various rivers in the park and the associated catchment areas, especially over the past three decades (Pollard et al., 2011).

Some of the primary freshwater-related issues in the KNP include, but are not limited to, water flow and availability, as well as water quality related challenges. Firstly, the flow of major rivers has been significantly influenced by abstractions, altered flow regimes and high evaporation losses, resulting in many of the rivers displaying high levels of seasonal variability. The Limpopo, Shingwedzi, Letaba and Crocodile Rivers, are highly influenced by the regional climate (high spatio-temporal rainfall variability) and upstream abstractions. These factors have resulted in flow declines to near zero in the winter months and multi-annual droughts, episodic flow, and water abstraction requirements consistently exceeding availability (Ashton et al., 2001; Barker, 2006; Jury, 2016; Louw et al., 2018; DWS, 2019). A distressing occurrence that has highlighted these main water flow challenges in the WMAs of the KNP was the drying up of the lower reaches of the Olifants River in late 2005. The dry spell lasted for 78 days and restricted critical ecosystem services in the KNP (Biggs et al., 2017).

Secondly, the major rivers are prone to a common array of water quality challenges, which have been steadily degrading riverine ecosystems over the past few decades (DWS, 2019). The Olifants River, for instance, has been regarded as one of the most polluted systems in South Africa (Gerber et al., 2015). The river has been polluted to the extent that there have periodically been several “unexplained” fish and crocodile deaths (de Villiers & Mkwelo, 2009; Ferreira & Pienaar, 2011). This particular issue has led to a significant research response, which continues today, although no absolute conclusions have yet been drawn (Biggs et al., 2017). Primary forms of land use in the catchments include agriculture and mining, although the quality of the water is also influenced by both urban and rural settlements, industrial wastewater, and tourism (DWS, 2019). These activities give rise to several issues, such as erosion and sedimentation, increased salinity, and excessive nutrient levels - resulting in the eutrophication of water bodies - and acidification that alters the natural state of rivers and water bodies (Ashton et al., 2001; Ferreira & Pienaar, 2011; Pollard et al., 2011). By far the most prominent and widespread issue is that of eutrophication and the proliferation of harmful algal blooms, caused primarily by rising nutrient contents and microbial contamination from failing wastewater treatment works (WWTWs) (Fouché & Vlok, 2012; Louw et al., 2018; DWS, 2019). Research conducted on the various rivers has at times exposed the presence of *microcystin-LR* at double the limit regarded as safe by the World Health Organisation (WHO) (Petersen et al., 2014; Gerber et al., 2015). Harmful algal blooms and cyanotoxins may be consumed by wildlife and are said to be the cause of poisoning of wildlife in the KNP and possibly the fish and crocodile deaths (de Villiers & Mkwelo, 2009; Ferreira & Pienaar, 2011; Gumbo et al., 2016).

There is consequently a growing concern related to the potential long-term effects of water pollution and reduced river flows for ecosystems in the KNP, as well as for the quality of water subsequently entering Mozambique (Marr et al., 2017a). A more up-to-date analysis, evaluation, and monitoring of trends, patterns and future potential impacts is required to supplement the existing knowledge and to allow for the implementation of relevant mitigation and/ or adaptation strategies to reduce vulnerabilities and future probable risks. This research aims to contribute to the existing body of knowledge by providing an updated analysis and evaluation primarily related to the possible influence of climate variability on the flow and water quality of the KNP's primary rivers.

In 2015, freshwater system degradation outside of the protected area and global climate change were listed by SANParks as the two environmental threats of greatest concern to the KNP (Petersen et al., 2015). It is therefore clear that despite the KNP having been at the forefront of applied river ecosystem research for over 30 years, each of the park's rivers was exhibiting unique water quality and flow challenges that arose from anthropogenic influences in the surrounding catchments. Notwithstanding some recent improvements in areas near the KNP, it is likely that owing to increased climate variability, a multitude of water quality and river flow issues persist and might even intensify (Riddell et al., 2019a).

The park's climate, which oscillates between wet and dry cycles, between seasons and across decades, has further exacerbated the need for a stabilised water supply (van Vuuren, 2017a). Anthropogenic influences have for many years adversely affected the hydrological cycle, leading to changes in the atmospheric moisture content and precipitation patterns (IPCC, 2014; IPCC, 2022). Water acts as the agent that delivers climate change related impacts to the world, increasing potential vulnerabilities and risks. Changes to components of the hydrological cycle resulting from climate change and seasonal variations in a country's climate can therefore lead to a diverse set of impacts further conditioned by interactions with non-climatic drivers (IPCC, 2014; IPCC, 2022). These impacts challenge the KNP's ability to maintain the viability of aquatic ecosystems and its ecological diversity, and therefore need to receive continued and concerted attention (Riddell et al., 2019a).

Apart from the climatic impacts on water availability and the hydrological risks, the consequences of climate change for water quality in conservation areas have not yet been studied in-depth (Delpha et al., 2009; Nkhonjera, 2017). This research represents one of the few attempts to examine the possible consequences of climate variability on freshwater river systems in a South African conservation area and is based on the interplay between physicochemical and microbial water quality parameters, water flow and regional climatic trends (Dallas et al., 2019).

1.3. Aim and Objectives

The preceding rationale and statement of the research problem informed this research and can be summarised as follows: Human activities have had a series of progressively aggravating impacts on scarce water resources in South Africa. These have been accelerated by rapid population and economic growth over the last few decades, and the changes have and will continue to be influenced by variations in the regional climate (Oberholster & Ashton, 2008). The KNP's river water supply is provided by several rivers in the Limpopo, Olifants and Inkomati-Ususthu WMAs, which have been highly affected by various anthropogenic activities along the respective river reaches. Over the course of a century, these conditions have resulted in a deterioration in water quality and a decline in the volume of river flow into the park, which has in turn led to a multitude of environmental catastrophes for the sensitive ecosystems and the biodiversity which they support. As such, it is appropriate to take stock of the current situation regarding the possible water-related challenges in the park, and to consider - up to the completion of this research - the possible effects that increased regional climate variability has had.

The primary aim of this research is therefore to evaluate long-term water quality trends and identify the possible influences of water flow and climate variability on river water quality in the KNP.

The following objectives have been developed to achieve the stipulated research aim and include the following:

- Establish the long-term trends in water quality for the rivers traversing the KNP.
- Determine suitability for various uses according to the stipulated South African water quality guidelines and standards.
- Identify possible influences of climate variability and water flow on KNP river water quality according to the established relationships

- Determine the high risk and/or priority areas for water degradation and susceptibility to climatic influence.

The primary research question has thus been established as follows: Does climate variability and water flow influence the water quality of river water resources located within the relevant WMAs supplying water to the KNP?

As such, the research sub-questions include the following:

- What are the dominant trends in river water quality for the observed time periods at each of the selected water quality monitoring sites?
- Can these freshwater resources be considered “fit for use” as per the water quality guidelines set out in South Africa for domestic use, irrigation, and aquatic ecosystems?
- Does the regional climate, water flow and their variability, influence the water quality of these rivers over the observed time periods for selected sites?
- What are the locations (sites) that are at high risk and should be considered a priority for remediation?
- What further research is required to fully understand the state and possible influences of increased climate variability on the freshwater resources of the WMAs situated in the KNP?

1.4. Significance of the Research

South Africa is a country characterised largely by arid to semi-arid conditions and with water resources that are classified as “scarce”, the latter factor is forcing more attention to be directed to improving the overall management of these resources. The management of water quality and flow and the issue as to how these parameters relate to regional climates are inextricably linked. The effective and equitable management of a particular water resource requires a thorough knowledge and understanding of the interaction of climatic factors with physicochemical parameters, and their individual and combined impacts on water quality and flow (Ashton et al., 1995). The burgeoning water-related stresses are thus high priorities on global scientific research and political agendas and owing to increased water stress caused by numerous factors, including increased climate variability, this matter should receive more attention within the South African context (UNEP, 2016).

Current research indicates that more countries are experiencing severe water shortages, and there is evidence of ever-increasing limitations on freshwater reserves (Munia et al., 2016; Veldkamp et al., 2016). A country is said to be water stressed when the demand for water exceeds the available volume during a specific period, or when poor water quality restricts its use (Munia et al., 2016). Water scarcity therefore refers to the ongoing inability to meet the demand for water (Veldkamp et al., 2016). The increase in the demand for water as well as the projected change in climatic conditions is expected to intensify the issue of water scarcity in South Africa even further (Veldkamp et al., 2016). This will impact on the freshwater resources emanating from South Africa's limited river network and will affect the viability of these rivers to deliver ecosystem services to strategic conservation areas (Jury, 2016; Marr et al., 2017a).

Being highly susceptible to common forms of anthropogenic pollution, rivers are amongst some of the most threatened ecosystems on earth (Baker & Greenfield, 2019). Over-exploitation, water pollution, flow modification, habitat destruction and alien invasive species are some of the environmental changes that are placing increasing pressure on freshwater river systems in South Africa (Darwell et al., 2009; Petersen et al., 2014; Baker & Greenfield, 2019). The impacts are felt to varying degrees throughout all catchments in the country and, depending on the surrounding land use, have different implications for people and the environment. As such, there has been an increase in the demand for the holistic monitoring of rivers to examine long-term trends and quantify the impacts of various outside influences on these water resources (Antonopoulos et al., 2001; van Vuuren, 2020). From the perspective of scientific research, one of the most important steps in better managing and protecting these resources is the spatio-temporal analysis of various aspects of the freshwater environment, including, but not limited to water quality, water flow and the effects of climate variability on these aspects (Bhat et al., 2014).

The freshwater lifelines of arid and semi-arid regions would not exist without rivers, nor would much of the local and regional biodiversity. River health assessment is of the utmost importance in South Africa and research aims to be of such value that it may be incorporated into future and on-going management strategies. There is currently a knowledge gap in terms of some of the river's responses to the changing regional climate and the possible resultant effects on water users and ecosystems dependent on these rivers (Stolz, 2018). Consequently, it is both a research and management priority to protect riverine ecosystems and the biodiversity that they support. It is critical that, in the face of climate change, water resource managers should attempt to:

- gain a better understanding of how river systems are changing;
- improve on planning for these changes; and
- include predicted change scenarios into river and protected area management policies (Thompson & Lipsett, 2015).

To successfully carry out its conservation role, the KNP requires a specific standard of consistent water quality and flow. However, despite the enabling contribution that legislative frameworks have made for water reform and environmental flows since 1998, the ecological integrity of most rivers flowing into the KNP has not improved. River water in the transboundary basins continues to deteriorate - a problem which is exacerbated by increasing climatic pressures. Given that all the rivers form part of a transboundary, international system, the implications of continued water degradation and increased water stress are of wider significance than to South Africa alone (Pollard & du Toit, 2011).

This research was thus initiated in the light of the severity of the water quality and river flow issues afflicting the freshwater resources in the WMAs of the KNP (Riddell et al., 2019a). It is of significance across various scales: locally, with respect to the conservation practices of the KNP; nationally, in terms of the protection of water resources and sustainable development in South Africa; and internationally, with respect to the water governance agreement between South Africa and Mozambique (Fouché & Vlok, 2012; Stolz, 2018). The quantification of the hydrological challenges faced by these rivers, together with their response to increased climate variability, is essential to the sustainability of the KNP, which supports the maintenance of critical South African biodiversity and economic development through nature-based tourism (Marr et al., 2017a; van Vuuren, 2017a; Riddell et al., 2019b). The degradation of these natural resources could be expected to be accompanied by widespread negative effects on the riparian and aquatic ecosystems, the heterogeneous landscape, and the wildlife of the KNP, and will ultimately lead to economic losses through a declining ecotourism sector (van der Merwe-Botha, 2009; Marr et al., 2017a).

Understanding the temporal and spatial characteristics of a region’s climate and water resources would therefore be essential in promoting informed decision-making in water resource management (Saraiva-Okello et al., 2015; UNEP, 2016; Mosase & Ahiablame, 2018). Such a knowledge resource would also be indispensable to SANParks in terms of maintaining the viability of the KNP as a leading conservation area and tourism destination. Furthermore, knowledge of the spatio-temporal patterns in the WMAs of the KNP is key to understanding natural ecosystem flux and the impacts of anthropogenic inputs upstream.

While pollution, low flow trends and their impacts on aquatic ecosystems have been focused upon and are well understood for the Olifants and Crocodile Rivers (Ashton et al., 1995; Ashton & Dabrowski, 2011; Biggs et al., 2017; Marr et al., 2017a; Oberholster et al., 2017), an understanding of the numerous impacts on the other five major rivers is far from extensive. In fact, relatively speaking, these have been understudied. In addition, despite the well-established fact that the KNP is regularly subject to harsh, extended periods of drought, followed by short bursts of intense rainfall, little is known regarding the historical interaction between water quality, water flow and climatic variability in the region.

Climate change poses a serious threat to protected areas, as they are often isolated in fragmented landscapes and confined within stringent park boundaries (MacFayden et al., 2018). The decline in the state of river water resources in the KNP poses a threat to sustainable economic development in the region. If left unchecked in the long-term, such trends may result in a decline in the quality of the water for human consumption and irrigation. Reductions in ecotourism revenues could occur as a result of the degradation of riparian and aquatic ecosystems in the KNP and its neighbouring private game reserves (Marr et al., 2017a). The country's capacity to provide sufficient water of an appropriate quality to meet developmental needs, while ensuring environmental sustainability, is directly threatened by the degradation of all its water resources (Heath et al., 2010). The fact that only 16% of the country's water sources are formally protected in the form of nature reserves or parks is also concerning. Protected areas, such as the KNP, need to be secured and well managed to ensure long-term water security, and, as such, problems in these areas should raise red flags (du Plessis, 2019).

By quantifying the extent of the pollution and water flow problem in the KNP rivers, and their response to a changing climate, it is possible to make improvements in the spheres of planning and managing water resources in the KNP region (du Plessis, 2014). The research therefore focuses on providing a detailed evaluation of the long-term water quality trends of rivers relevant to the KNP, and their possible responses to water flow and regional climate variability. Through this research, high risk areas for pollution and climatic influence and/or priority areas requiring immediate attention, urgent remediation or further investigation were identified. This research will also assist water resource decision makers to develop and implement appropriate strategies and responses to address the identified water-related issues. The knowledge gained from this research will ultimately support a scientifically sound form of reasoning for improved integrated water management and informed decision-making in the various catchments of the KNP.

1.5. Brief Overview of the Literature Review

The literature review implements a “top-down” approach, first discussing the critical aspects of water quality and availability in a global and national (South African) context. The first section evaluates and highlights the primary challenges related to global water scarcity, primary water quality issues and the identified and predicted impacts of global climate change on freshwater resources. An overview of the current state of surface freshwater resources in South Africa is included and provides a review of the availability and use of surface freshwater resources in South Africa, as well as explains how these have been impacted by the regional climate. The primary water quality and scarcity challenges in South Africa are also discussed. More specifically, the chapter includes a discussion on the importance of healthy, functioning riverine ecosystems in South Africa and their inextricable link to supporting ecosystem processes in the KNP, as well as to ecotourism.

The chapter concludes with a discussion of previously established relationships between water quality, water flow, and climate variability, and lastly, a discussion of the selected water quality parameters as per the Target Water Quality Range (TWQR) guidelines established in South Africa for measuring the state of water quality and flow parameters.

1.6. Brief Overview of the Methodological Considerations

This research used water quality and flow data, which are publicly accessible upon request from the Department of Water and Sanitation (DWS) Resource Quality Information Services (RQIS) database. The data were requested by sending an email to the DWS. Supplementary water quality data were obtained from SANParks, and climatology data, including temperature and rainfall figures, were obtained from the South African Weather Service (SAWS). The water quality and flow data used spanned various time periods specific to each water quality monitoring site. The climatology data obtained from SAWS covered average monthly minimum and maximum measurements of rainfall and temperature and spanned various time periods at five different climate monitoring sites.

The data obtained from the DWS are available to the public and therefore presented no ethical issues for consideration as this research was primarily conducted as a desktop study. Data obtained from the SAWS, however, required the signing of a disclosure statement (Appendix I).

The additional water quality and flow data obtained from SANParks are not openly accessible and required the registration of the project with SANParks and the completion of a non-disclosure and spatial data agreement (Appendix II).

The research methodology employed in this research project is empirical and quantitative, as it attempts to make planned observations of phenomena (in this case, water quality parameters, climatic parameters, and water flow measurements) through a systematic and rational process (Dan, 2017; Patten, 2017). Empirical methods involve the systematic collection and analysis of data and are, as such, typically used in quantitative research designs. Research which allows data to be structured and interpreted using statistical analysis, and which measures variables and describes the relationship between those variables using statistics, is quantitative by nature (Rockinson-Szapkiw, 2012). The research philosophy is ultimately positivist, in which empirical research methodologies and quantitative designs are rooted (Dan, 2017). Positivist research philosophies are characterised by their highly structured nature, the large samples that are involved, and the quantitative measurements that are made (Dudovskiy, nd). Positivist research focuses on a strict scientific empirical method design to yield data and facts that are uninfluenced by bias and subjectivism (Saunders et al., 2009).

This research attempts to identify and explain the statistical relationship between several parameters and is therefore classified as a multi-factorial non-experimental correlational (causal comparative) form of research. In addition, the parameters are not manipulated in any way. This correlational research is retrospective as it makes use of archival data, which were obtained from the DWS, SANParks and from SAWS (Price et al., 2015). To achieve the aim and objectives, the research methodology is differentiated into three phases, as follows (Figure 1.1):

Phase 1 **Data Collection, Structuring And Cleaning**

- Collect data from SAWS, SANParks and DWS.
- Clean data by identifying extreme, inaccurate or missing values and apply interpolation.
- Structure data in databases and calculate monthly averages for each monitoring site and parameter.

Phase 2 **Data Analysis**

- Establish the temporal and spatial trends by identifying changes in rainfall, temperature, water flow and water quality over the study period for the specified sites.
- Identify the parameters that occur outside of the TWQRs.
- Identify the possible influence of rainfall and temperature on water quality and flow.

Phase 3 **Interpretation of Results**

- Evaluate the temporal and spatial trends by identifying important and significant variations in the selected water quality and flow parameters.
- Discuss the significance of parameters that occur outside of the TWQRS.
- Evaluate the relationships between water quality, water flow and climate parameters and discuss their significance.
- Evaluate the current state of water resources in the study area for the time period.

Figure 1.1: Phases of the research methodology process.

The data were processed and analysed using statistical analysis software XLSTAT Basic Plus. The data were first subjected to basic statistical analysis (measures of central tendency, standard deviations, and variance). The percentiles, mean and standard deviations of each parameter were tabulated. This enabled the spatial comparison of parameters between sites. Inferential statistical analyses were conducted to determine the reliability of the data and the validity of the findings. Mean monthly water quality was graphed in time series trend analyses with a Sen's slope to determine temporal changes in the parameters. Results of the time series trend analyses were then compared with the TWQRs and compliance graphs for each WMA were compiled. Measures of the relationship (correlation) between the water quality, water flow and climatic parameters were determined through the application of a Spearman's Rank Correlation Analysis (R). Water quality and flow sites were chosen according to the proximity to the KNP, as well as to the relevant climate monitoring site(s).

1.7. Scope of the Research

This research considers the relationships between water quality, water flow, and climate variability in the KNP region to identify and evaluate dominant trends and quantify the impacts of various drivers on the water resources. Although land use and land change influence water resources, and were considered during data analysis, a detailed exploration of this relationship was beyond the scope of this research. The research aimed to provide a long-term evaluation of the trends in KNP river water quality, evaluating their suitability for use and high-risk areas for remediation, as well as the impacts of water flow and climate variability on the selected water quality parameters. A retrospective research approach was applied to determine whether an association exists between various factors, and to determine the nature of the relationships. Such research is essential for the development of future studies and interventions.

1.8. Structure of the Dissertation

Chapter 1 highlights the core themes of the research in the context of freshwater and river research in South Africa's leading conservation area, the KNP. The chapter discusses the current challenges associated with water quality and flow in the KNP, and the concerns associated with the impending impacts of climate change on these water resources. The problem statement is described, the research aim, research objectives, as well as the research questions, are also included, and the significance of the research is discussed. A brief overview of the literature, methodology and primary scope of this research are clearly laid out to form the framework on which this research is based.

Chapter 2 describes the background to the selected study area by providing a general overview of the characteristics of the environment in which the research was conducted and informs the physical context of the research problem. The chapter includes descriptions of the various geographical and hydrological features of the WMAs relevant to the KNP. It provides a detailed description of the natural processes that influence the river resources in and around the park, including, but not limited to the geology and soils, topography, hydrology, the climate, and vegetation. The chapter concludes with a description of the land use practices and general characteristics of the WMAs and their relevant sub-catchments.

Chapter 3 presents a detailed Literature Review, and thus examines the primary themes linked to freshwater resources globally and in South Africa, where they would affect the KNP, the study area of this research. The chapter includes critical knowledge and key concepts associated with the topics of water quality, water availability and river flow, and climate change. This chapter critically reviews fundamental literature sources regarding previously established relationships between the various water-related variables, as well as South Africa's main water quality and availability challenges. The chapter concludes with a discussion on the importance of riverine ecosystems in South Africa; and presents the selected water quality parameters and flow requirements as per the TWQRs guidelines established for measuring the status of water resources in South Africa.

Chapter 4 explains the methods used in this research to achieve the specified aim and objectives. It describes the research design, relevant ethical considerations, the complete set of methodological tools, the approaches and the resources used to analyse the specified data.

Chapter 5 discusses the results of the data analyses and interprets these results to present an overview of the current challenges related to water resources in the KNP as they pertain to the research objectives. The chapter sets out to answer the associated research questions and includes the following main themes:

- A discussion of the observed trends and patterns in river water quality. Significant findings in terms of spatial and temporal variability are highlighted.
- A discussion of each of the selected research sites regarding each one's suitability, according to South African standards, for providing water for consumption. The areas of greatest concern are highlighted and evaluated.
- A discussion of the relationship between climate parameters, water quality and flow, as well as the observed consequences.

Chapter 6, the final chapter of this dissertation, contains a synthesis of significant results and observations, and provides suitable recommendations regarding the management steps which need to be taken within the study area. Furthermore, it makes recommendations for future research pertaining to the influence of climate variability on water resources in protected areas.

1.9. Conclusion

Water is earth's most important natural resource and is ultimately vital for supporting all forms of life. However, it is constantly changing and is distributed unevenly across political borders. Ongoing changes to hydro-climatic and socio-economic conditions are increasingly putting pressure on freshwater resources across the globe. The degradation of water resources and increasing stress and scarcity are consequences of global climate change, economic development, and exponentially growing populations. Therefore, society faces a mounting number of water-related challenges to ensure water security into the future.

Conservation areas are at the forefront of these water resource challenges, which are particularly prevalent in South Africa, a semi-arid to arid country, where there are already moderate to large water deficits. Only one percent (1%) of South Africa's water consumption can be attributed to conservation requirements, yet, as a result of upstream impacts, these users bear the brunt of decreased flows and poor quality. The KNP is one such area that has a long history of water quality and flow issues. The park's water requirements are mainly met through the provision of freshwater by the various rivers which flow in from its western borders. The cumulative effects of altered water quality and flow regimes in the rivers over many decades are evident for the park and jeopardise the park's ability to successfully sustain biodiversity over the long-term.

Therefore, this research can be of great value since past research has highlighted the relevance of quantifying the current situation regarding the KNP's river water resources and determining the possible effects that increased regional climate change has brought. This research ultimately aims to evaluate trends in the quality of water received by the rivers of the KNP and to identify the possible influences of water flow and climate variability over the long-term. The establishment of these relationships will enable the identification of high-risk areas and priority areas requiring urgent remediation Rivers are amongst some of the most threatened ecosystems on earth and especially within South Africa. Therefore, from a scientific research perspective, the spatio-temporal analysis of various aspects of the freshwater environment - and the effects of the drivers ultimately contributing to these water-related challenges - is one of the most important steps in improving the management and suitable protection of these resources. A detailed description of the background to the study area now follows.

CHAPTER 2: DESCRIPTION OF THE STUDY AREA

2.1. Introduction

The selected study area for this research is described and consequently sets the context for the research at a regional scale. A discussion of the various attributes and features of the KNP and the relevant WMAs and rivers is included. The topography, hydrology and climate of the park is briefly described, followed by a discussion of the general characteristics of the seven rivers that comprise the study area. A brief description of the history and general characteristics of the KNP now follows.

2.2. The Kruger National Park

The KNP (Figure 2.1) started as a small area in the Lower Sabie catchment more than 100 years ago, in 1898. Shortly after this, in 1903, the Shingwedzi Game Reserve was added. Over the years, additional sections were added to the initial piece of conservation land as they became available, incorporating parts of different ecosystems and landscapes. The KNP came into being on the 31st of May 1926 when the National Parks Act was promulgated through the Parliament of the then Union of South Africa (O'Keeffe & Davies, 1991; Pienaar et al., 1997).

The KNP lies in the north-eastern part of South Africa and borders Zimbabwe to the north and Mozambique to the east (Ferreira & Pienaar, 2011). It is found in the provinces of Mpumalanga and Limpopo between the north-eastern lowveld of South Africa, the low-lying area between the foot slopes of the Drakensburg Great Escarpment, and the Mozambique coastal plains in the east (Petersen, 2012; Riddell et al., 2019a). Together with the surrounding private nature reserves, the KNP constitutes one of the world's most extensive and highly valued conservation areas. Its width is just under 60 km from west to east (at its widest part), however it spans approximately 325 km from north to south (Barker, 2006). The KNP is part of the Great Limpopo Transfrontier Park alongside the Limpopo National Park in Mozambique and the Gonarezhou National Park in Zimbabwe. Altogether, the transfrontier park covers 35 000 km^2 (Nhamo & Dube, 2019), making it the largest safari park in South Africa (Sappa et al., 2018). The KNP also forms part of the United Nations Educational, Scientific and Cultural Organization's (UNESCO) Kruger to Canyons biosphere reserve (Nhamo & Dube, 2019).

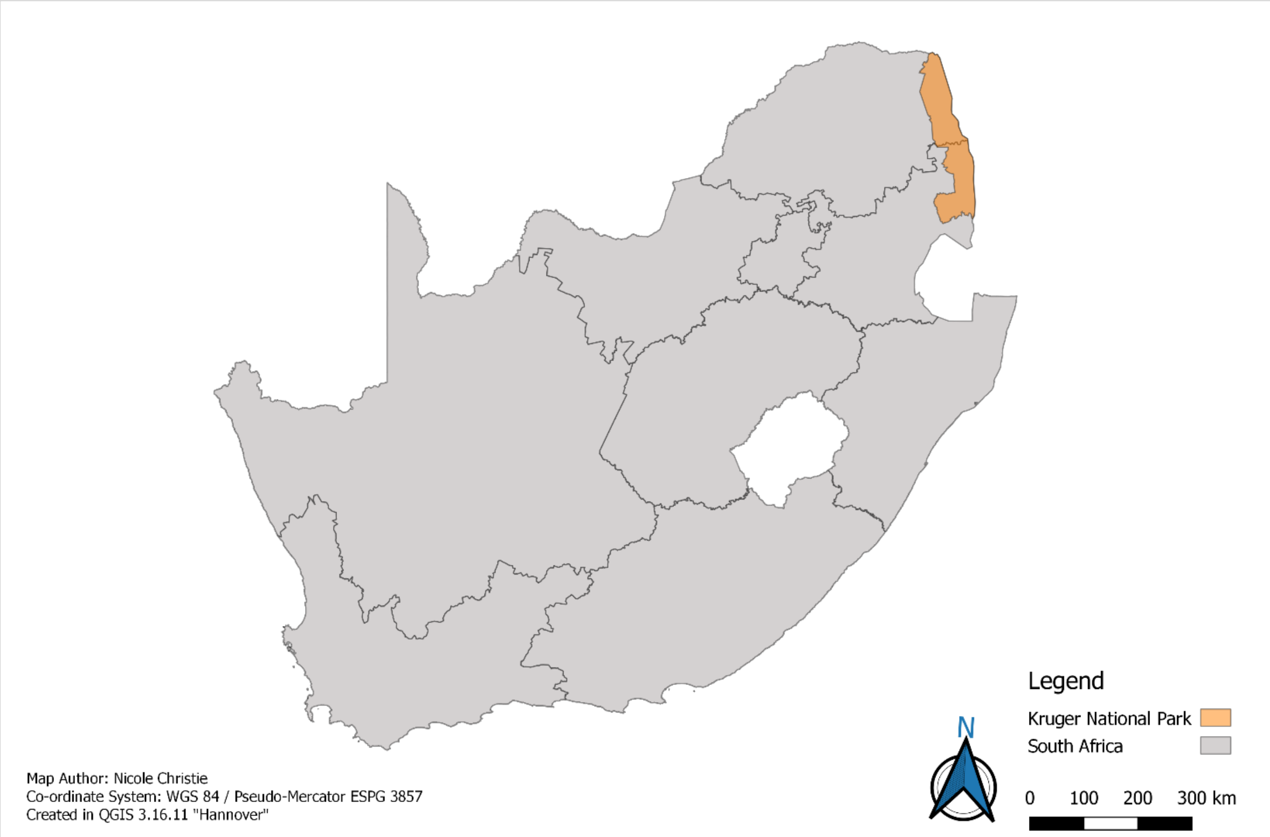

Figure 2.1: The location of the South African portion of the Kruger National Park in north-eastern South Africa.

The KNP is best known for its biodiversity and abundance of wildlife (Viljoen, 2015; van Vuuren, 2017a), and being South Africa's largest nature reserve, the park plays an important role in ecotourism and conservation. The KNP is abundant in both flora and fauna. Almost 2 000 plant species have been identified. There is an inventory of around 500 species of birds, and 255 faunal species inhabit the diverse plant life. This includes the "big five", and endangered species such as the wild dog and cheetah. At least 45 freshwater fish species have been identified in the park's rivers, many of them endemic to the area (van Vuuren, 2017a; van Vuuren, 2017b).

In 2017, the KNP received approximately 1.9 million tourists and accounted for 26% of all tourist visits to South African National Parks. At least two million people live within 50 km of the KNPs western borders and around half a million people live within 50 km of the eastern boundary (Pollard et al., 2011).

Although the park was not originally established with the protection of its water resources in mind, the management thereof has become a central function (van Vuuren, 2017b). Biodiversity is highly dependent on the surrounding landscape and the naturally occurring water in the park. Likewise, groundwater and surface water recharge are highly influenced by the physical characteristics of the KNP environment (Petersen, 2012). The rivers that flow into the KNP are undoubtedly affected by the diverse range of natural factors such as the geology, soils, morphology, hydrology, and climate. These characteristics play a vital role in determining the ecological processes within the various river systems (Venter, 1986; Muller & Villet, 2004; Barker 2006; Viljoen, 2015; Stolz, 2018). A short description of the topography, hydrology, and climate of the KNP now follows. The geology and land use of the WMAs are described at catchment levels (Section 2.3) thereafter.

2.2.1. Topography

The Drakensberg Escarpment to the west and part of the Soutpansberg to the north divides the South African Highveld and Lowveld, with the KNP situated in the latter (Pollard & du Toit, 2011). The region's terrain is mostly flat, and the elevation is low, varying between 260 to 440 metres above sea level (m.a.s.l.), except for various mountain ranges with the highest summit, the Khandizwe Mountain, reaching an elevation of 840 m.a.s.l. (Viljoen, 2015; van Vuuren, 2017b; Sappa et al., 2018). The landscape is mostly plains with a gentle slope from west to east, broken up by the Lebombo Mountain range which runs along the park's eastern border adjoining it to Mozambique (Muller & Villet, 2004; Sappa et al., 2018). The Lebombo Mountains inside the KNP reach a maximum height of 497 m.a.s.l. (Petersen, 2012). Various ridges and koppies to the west, formed by isolated rhyolite flows and granophyre, run parallel to these mountains (Schutte, 1986). The Malelane Mountains are a prominent feature of the south-western region and average a height of approximately 800 m.a.s.l. (Petersen, 2012). Between these protrusions lies a gently undulating landscape, except south of Pafuri where the Nwambia Sandveld hosts a flat landscape (Schutte, 1986).

Numerous watersheds and valleys resulting from the granitic rocks of the western KNP serve as tributaries for the rivers draining west to east. Rivers cutting through resistant rhyolite ridges of the Lebombo Mountains create the Shingwedzi, Olifants, Nwaswitsontso and Sabie gorges. Where the main rivers span homogenous rock formations such as the Red Rocks of the Shingwedzi River, a range of pothole-like structures can be found (Viljoen, 2015).

2.2.2. Hydrology and Water Chemistry

Water has two very important functions in the KNP. Firstly, the form and quantity in which water is available largely determines the suitability of habitats and therefore contributes towards the maintenance of structural and species diversity. The spatial and temporal distribution of water is also a determinant of the viable number of species in the park and their population dynamics (Pienaar et al., 1997). Secondly, aquatic and amphibious species are dependent on water for the provision of their habitats which are just as important as terrestrial habitats from a conservation perspective (Pienaar et al., 1997). Pienaar et al. (1997) states that water-based ecosystems are a high priority in terms of conservation because they host flora and fauna unique only to them, in addition to the larger mammals such as hippo and otters, avifauna, reptiles and amphibians.

Water in the KNP is naturally available in the form of both seasonal and perennial rivers, pools of water of varying sizes and permanence, including isolated springs and pans (Pienaar et al., 1997). By virtue of its position, the KNP receives water from several rivers which enter through its western boundary and flow eastwards through the park to Mozambique. The rivers arise on or above the escarpment that divides the eastern lowveld from the central interior plateau (Biggs et al., 2017). The nature of these rivers varies significantly. Some rivers have broad sand beds with gently sloping banks, and dense and/ or sparse riparian vegetation. Others have steep banks with dense and/ or open vegetation and rocky gorges, for instance. Along the same river there may be a variety of vastly different characteristics present, with several gradations from one extreme to the other (Pienaar et al., 1997; van Vuuren, 2017b). The main KNP rivers drain a total combined area of approximately 88 600 km^2 (Barker, 2006) and include the Limpopo, Luvuvhu, Shingwedzi, Letaba, Olifants, Sabie and Crocodile Rivers (Venter & Bristow, 1986). The rivers are influenced mostly by rainfall outside of the KNP as well as by various human developments, forestry, agriculture, and dams that affect flow (Pienaar et al., 1997; Gerber et al., 2015; Gerber et al. 2016). Due to their presence in a semi-arid area, and the upstream anthropogenic influences, all the major rivers have highly variable flow regimes, with some ceasing intermittently throughout the drier seasons. When these rivers are active, they experience large sediment loads due to the highly erodible soils within the catchments (Viljoen, 2015).

The geomorphological conditions underlying freshwater rivers are key determinants of the natural water quality (Eze & Knight, 2018). In general, the inorganic chemistry of South African rivers is largely controlled by the chemical weathering of rocks due to the poorly developed, thin soil cover. Bicarbonate ions are released into surface waters as a result of incongruent and congruent silicate and carbonate weathering reactions.

Bicarbonate and cations such as calcium and magnesium result mainly from mineral weathering, while chloride, sulphate, nitrate and phosphate tend to have alternative sources. The typical pH of 8 to 8.5 of South African surface water results from the release of bicarbonate in weathering reactions (Huizenga, 2011). Additionally, the semi-arid climate in South Africa, i.e., low rainfall and high evaporation rates, tends to increase the organic chemical species in surface freshwaters. Huizenga (2011) developed an inorganic chemistry index (ICI) for South African waters based on the pollution index introduced by Pacheco and van der Weijden circa 1996. The index characterises the water chemistry of the various drainage regions in South Africa. According to Huizenga's (2011) classifications, the water quality in the primary drainage regions in which the KNP rivers are located is predominantly controlled by chemical weathering. A more detailed analysis enabled a further division based on the average contribution of chloride, sulphate, and the sum of phosphate and nitrate towards the ICI.

In the Limpopo WMA and Inkomati-Usuthu WMA, natural water quality is controlled by chemical weathering and the contribution of mostly sulphates followed by chloride. These drainage areas have typical total dissolved solid (TDS) contents below 500 mg/ℓ but increasing to between 500 and 1 000 mg/ℓ, for some samples. Surface water chemistry in the Olifants WMA is also predominantly controlled by chemical weathering, as well as by other factors that contribute mostly chloride followed by sulphate. The TDS values vary from between 500 and 2 000 mg/ℓ (Huizenga, 2011). Thus, due to the complex geology and irregular nature of the basement areas in the KNP area, natural water quality can fluctuate considerably between locations within close proximity to one another, laterally and with depth (Petersen, 2012). This baseline water quality is an important consideration for this research as it will inform the analysis of data and influence the interpretation of the results in terms of the possible anthropogenic and climatic influences on water quality and flow in the relevant KNP catchment areas.

The main anthropogenic factors affecting water quality in the KNP catchments are a combination of point source and diffuse sources of pollution. Overgrazing, agriculture and sand mining in the catchments create erosion which leads to the sedimentation of riverbeds, and impacts water quality and freshwater ecosystem health. River flow is mainly impacted by impoundment and abstraction (Shikwambana et al., 2021). The DEA (2012) states that the Crocodile and Olifants River catchments are the most affected by heavy abstraction. In 2005, the Olifants River stopped flowing, prompting widespread concern for all the easterly flowing rivers in South Africa, particularly those that flow through the KNP. Current levels of abstraction in the upper catchment areas results in inconsistent flows and poor quality freshwater in the middle and lower catchments, which threatens the health of in-stream biota (SANParks, nd; Pollard & du Toit, 2011). Despite some more recent improvements in the KNP locality, it is still highly probable that water resource degradation persists due to upstream impacts (Riddell et al., 2019a). South Africa's Ecological Reserve benchmark defines a dynamic quantity and quality of flow regimes for water resources to sustain healthy freshwater ecosystems (Pollard & du Toit, 2011). Reporting back on the Shared Rivers Initiative - an action-research programme funded through the Water Research Commission - Pollard and du Toit (2011) note that none of the primary rivers of the KNP met the reserve requirements for environmental flows.

2.2.3. Climate

Two main climatic zones characterise the KNP. The southern and central portions of the park fall into the Lowveld bushveld zone, and the northern section falls into the arid bushveld zone (Petersen, 2012). The KNP is a summer rainfall area situated in the Savanna biome with semi-arid to sub-tropical and tropical climate systems (Petersen et al., 2014; Sappa et al., 2018). The region is influenced by anticyclonic systems moving semi-rhythmically from west to east over Southern Africa. In summer, anticyclonic conditions in the South African interior create hot and dry conditions. These are usually followed by the development of a low-pressure cell which brings in warm, moist equatorial air and thunderstorms. In winter months the anticyclonic system in the South African interior results in mild conditions over the lowveld, giving way to cooler conditions when cold frontal systems enter from the southern polar regions (Venter & Gertenbach, 1986). During the coldest month of June, daily temperatures vary from an average minimum of 7.81°C to an average maximum of 26.11°C, while in the warmest month of February, minimum temperatures are around 21.51°C with maximum temperatures reaching 33.51°C (Ferreira & Pienaar, 2011). However, temperatures in summer have been known to reach up to 44°C or more and seldom fall below freezing in winter. Frost is thus rare (Venter & Gertenbach, 1986).

The majority of the region experiences hot wet seasons that last from four to eight months, with a warm dry season occurring in the remaining months. Summers are hot and humid, while winters are predominantly dry (Venter & Gertenbach, 1986; Barker, 2006). Rainfall plays an essential role in the natural processes of the park, including river health (MacFayden et al, 2018). The entire park experiences a mean annual rainfall of 530 mm, well below the world average of 880 mm (Petersen, 2012; van Vuuren, 2017b). However, this figure ranges quite significantly from north to south and from west to east (Venter & Gertenbach, 1986), leaving the north and south-east regions of the park generally dry (Nhamo & Dube, 2019). Rainfall in the northern-most section of the park can be as low as 350 mm on average, increasing to as much as 750 mm on average in the park's southern-most regions (van Vuuren, 2017b). Some parts on the eastern side and in the south-west region of the park receive a higher-than-average rainfall of around 750 to 900 mm per annum (Nhamo & Dube, 2019). Approximately 80% of the rainfall occurs between October to March (Ferreira & Pienaar, 2011; van Vuuren, 2017b). Annual average rainfall figures can however be misleading as the park's climate fluctuates between dry and wet cycles approximately every ten years, with periods of drought interspersed by periodic flooding (van Vuuren, 2017b; MacFayden, 2018). The KNP also experiences long-term oscillations of about 80 to 100 years in terms of rainfall (Venter & Gertenbach, 1986; Pienaar et al., 1997). There is a difference of about 26% between the average annual rainfall of wet and dry cycles (Venter & Gertenbach, 1986).

Recent research indicates that high and low rainfall periods in the KNP appear to mostly match the La Niña and El Niño cycle (MacFayden, 2018). Thompson and Lipsett (2015) found that the climate of the KNP is strongly influenced by El Niño. This results in the KNP experiencing periods of drought approximately every two to seven years and persisting for approximately 18-month periods. Conversely, non-drought periods are characterised by heavy floods, particularly in more recent years. Thompson and Lipsett (2015) further revealed that there is a correlation between the El Niño cycle and periods of 'low flow' of certain KNP rivers. However, there is currently very limited research which examines the influence of climate variability on freshwater resources of the KNP (Thompson & Lipsett, 2015).

According to Nhamo and Dube (2019), climate change and the extreme weather events that coincide with it, pose a threat to wildlife and tourism across Africa (Nhamo & Dube, 2019). Climate change has been observed to have disrupted the natural balance in conservation areas through changing wildlife migration patterns and reduced biodiversity. Extreme weather events in South Africa have been increasing (Nhamo & Dube, 2019), and it is therefore important to understand the local effects of climate on these areas and the threats to wildlife tourism. The placement of the KNP in a semi-arid region of South Africa makes its particularly vulnerable to climate change (Nhamo &

Dube, 2019). Most noticeably, the short and medium-term seasonality of rainfall is shifting both spatially and temporally with rainfall often occurring outside of the typical wet periods. High rainfall seasons are receiving even more rainfall than before, while low rainfall seasons are experiencing even less. The north-western regions of the park are receiving significantly more extreme precipitation and flooding, and regions to the far north and south show the greatest changes in seasonality (MacFayden et al., 2018).

2.3. Water Management Areas and Secondary Catchments of the KNP

Institutional requirements provide for the management of water through Catchment Management Agencies across WMAs which are divided further into sub-catchments (DWS, 2016a). The WMAs related to the KNP study area are shown in Figure 2.2.

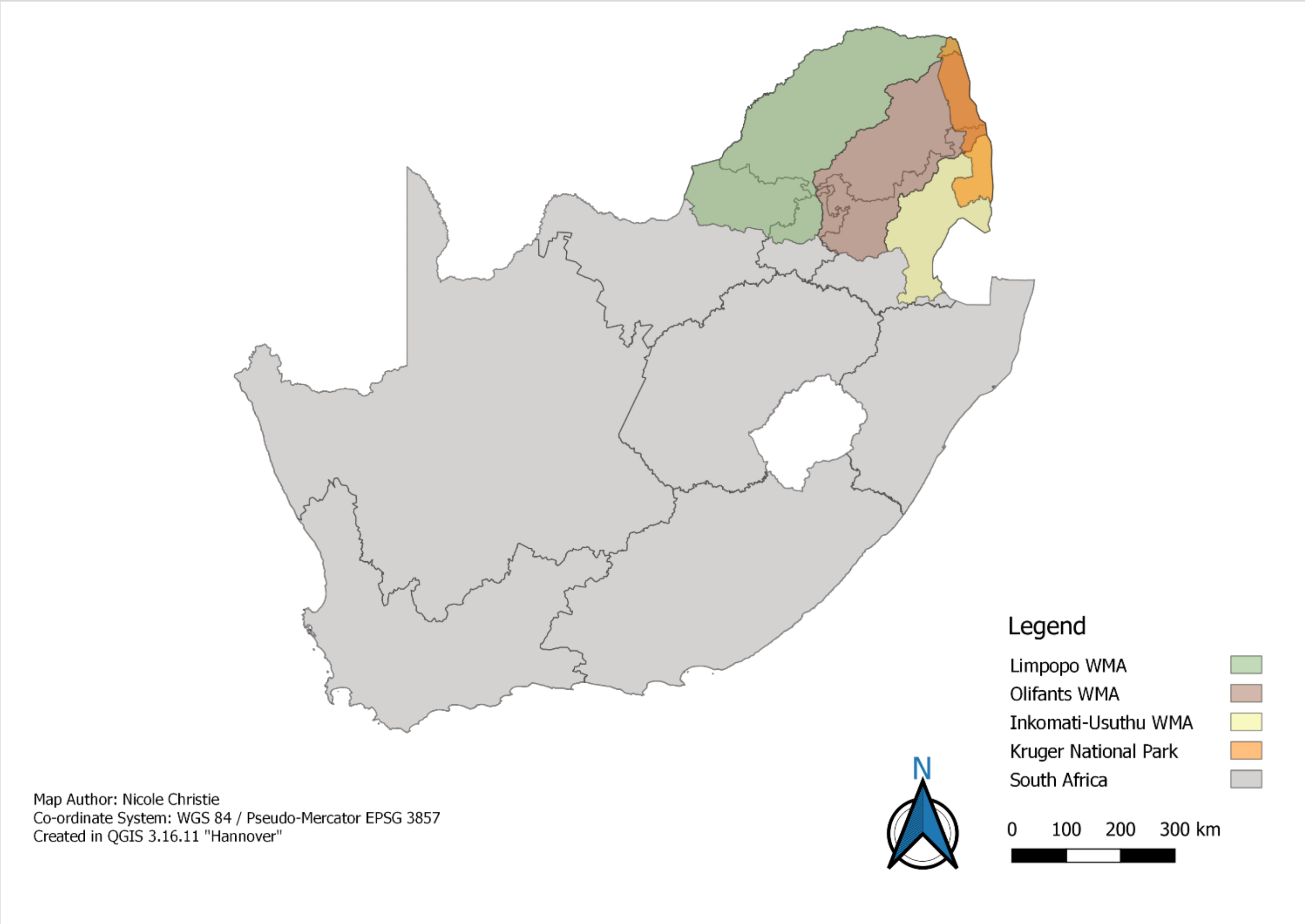

Figure 2.2: The location and delineation of the Limpopo, Olifants and Inkomati-Usuthu WMAs in South Africa and in relation to the KNP.

The KNP straddles three primary drainage regions, or WMAs, namely:

- the Limpopo WMA or Drainage Region “A”;

- the Olifants WMA or Drainage Region "B", and;
- the Inkomati-Usuthu WMA or Drainage Region "X" (DWS, 2019).

The Limpopo, Luvuvhu, Letaba, Shingwedzi and Olifants Rivers contribute to the international Limpopo Basin while the Sabie and Crocodile Rivers contribute to the international Inkomati Basin (Pollard & du Toit, 2011). These main rivers typically drain from west to east (Muller & Villet, 2004). The majority of the KNP rivers are historically perennial, and only one river, the Shingwedzi is naturally seasonal, flowing only after sufficient rains. The largest of the seasonal rivers that form part of this research is the Shingwedzi (van Vuuren, 2017b). However, both the Luvuvhu and the Letaba Rivers are often treated as temporary rivers due the significant alteration to their flow (Muller & Villet, 2004).

The characteristics of the main rivers are unique and distinct; nonetheless, they do share some similarities based on their catchment characteristics and anthropogenic impacts. The Luvuvhu, Letaba, Olifants, Crocodile and Sabie River catchments span a large section of the Limpopo and Mpumalanga provinces. All the main rivers, except for the Olifants, have their source in the Great Escarpment, either the Soutpansberg or Drakensberg, where up to 80% of their runoff is generated. The Olifants River rises in the Highveld (van Vuuren, 2017a; van Vuuren, 2017b). The total length of each of the rivers and the portion that falls within the KNP is indicated in Table 2.1.

Table 2.1: The length of the study area rivers inside and outside of the KNP boundaries (SANParks, nd).

River / Catchment	River Length in SA (km)	River Length in KNP (km)	% River in KNP
Limpopo	736	29	4
Luvuvhu	225	79	35
Shingwedzi	159	100	63
Letaba	481	125	26
Olifants	704	98	14
Sabie	178	102	57
Crocodile	316	113	36

The upper reaches of the KNP rivers are located outside the jurisdiction of the park authorities. The KNP, like many other protected areas, faces several management challenges of which ensuring a healthy flow of these rivers into the park is key. The progressive deterioration in the quality and flow of water received from these rivers, along with the growing impacts of a changing climate, has been problematic for the park for some time (Pollard et al., 2011; Petersen et al., 2014; Gerber et al., 2015; Gerber et al., 2016; Biggs et al., 2017). Increasing human populations west of the park and the associated growth of urban settlements, agriculture, and industry to support these populations throughout the region has undoubtedly placed enormous pressure on the water resources of rivers. All the rivers have, to varying degrees, experienced flow and quality modifications due to these growing upstream demands, with agriculture and mining being the biggest influencers (SANParks, nd; Angliss, 2005; Pollard et al., 2011; Gerber et al., 2015; Gerber et al., 2016).

A detailed description of each of the seven catchments in the three WMAs, and their relevant rivers now follows.

2.3.1. Limpopo River Catchment

The Limpopo River catchment is one of nine secondary drainage regions in Drainage Region A or the Limpopo WMA (DWS, 2019). DWS water quality and flow monitoring sites in this secondary catchment are situated both inside and outside of South Africa. The Limpopo River is one of the largest and most important transboundary rivers in South Africa. It has a total drainage area of approximately 415 000 km^2. The river flows across the Kalahari Plains between South Africa, Botswana and Zimbabwe and then descends through Mozambique towards the Indian Ocean (Ashton et al., 2001; Jury, 2016; Mosase & Ahiablame, 2018).

The river has several tributaries with mostly seasonal or episodic flows, making the entire river system a dense network. The Limpopo River used to be a strongly flowing perennial river, however it is now regarded as having a weak flow and largely dries up in periods of drought, so that there is little to no surface flow along the middle and lower reaches of the river (Ashton et al., 2001; Jury, 2016). Due to the arid climate, groundwater is used extensively in the catchment, and very few sites are available for the construction of major dams (du Plessis, 2019).

The landscape in the catchment consists mainly of plateaus interrupted by low elevation mountains and hills as well as deeply incised valleys (Limpopo River Awareness Kit, nd). The geomorphology, particularly the high elevation, has a distinct effect on the climate in the area impacting precipitation patterns and the distribution of rainfall (FAO, 2004).

The Limpopo River comprises part of the Limpopo Basin, and therefore encompasses an important ecological transition zone that marks the junction of four separate bio-climatic zones. The Basin is also an important area for floral and faunal biodiversity and supports a very large rural population with a high poverty ratio (Ashton et al., 2001). The upper portion of the catchment hosts mainly rain fed agriculture, meaning that water abstraction has been relatively steady, and is more affected by climatic factors than anthropogenic influences (Jury, 2016). Game keeping, livestock rearing, and irrigation farming are the main land uses in the catchment, although various mining developments are beginning to increase. There are already large mining areas in the form of coal and platinum mining operations located close to Lephalale. The catchment varies from having highly developed urban areas, to rural communities who rely on subsistence farming (du Plessis, 2019).

2.3.2. Luvuvhu River Catchment

The Luvuvhu River catchment is one of nine secondary drainage regions in Drainage Region A, or the Limpopo WMA (DWS, 2019). The river rises in the Soutpansberg Mountains just south of Louis Trichardt, and flows east toward the KNP, where it joins with the Limpopo River (Ashton et al., 2001; Barker, 2006).

The catchment covers a total area of 3 800 km^2. It is drained by the Luvuvhu River and the tributaries which include the Latonyanda, Mutshindudi and Mbwedi rivers (Barker, 2006; Pollard & du Toit, 2011). The catchment supports important ecosystems such as those in the Luvuvhu Gorge and the Pafuri Flood Plain located in the KNP (Pollard & du Toit, 2011). Mainly veld type vegetation such as tropical forest, tropical bush and savannah are found here (Barker, 2006).

The northern boundary of the Luvuvhu River catchment is formed by the Soutpansberg Mountains which influences the hydrology of the river by effecting higher rainfall through their topographic influence (Pollard & du Toit, 2011). Geology in the Luvuvhu River catchment consists mainly of sedimentary rocks to the north and metamorphic rocks in the south. Tshikondeni and the northern parts of the KNP host a high quality set of coal deposits. A small portion of the southern part of the catchment hosts the Bushveld Igneous Complex (Pollard & du Toit, 2011). In the upper regions of the catchment a variety of acidic, instructive granites and gneisses of the Sand Formation occur, while further downstream, the catchment is underlain by mostly silicified sandstones and quartzites of the Soutpansberg Group (Ashton et al., 2001).

Thoyandou is the main urban area in the catchment (Monyai et al., 2016). The Luvuvhu River catchment is located mostly within agricultural and rural areas with the lower portion forming part of the KNP. Altered flow regimes and changes in habitat have resulted due to erosion and sedimentation (DWS, 2019). Land use in the form of agriculture takes up one third of the catchment in the west. Four percent (4%) of the catchment is dedicated to commercial forestry, 10% is dedicated to commercial dry land agriculture, 3% to agriculture, 50% to range land cover, 30% to conservation and 3% to urban areas (Odiyo et al., 2014). The higher lying Soutpansberg Mountain Range area of the catchment is dominated by forestry. Fruit farming and several smallholding developments take place in the upper reaches of the catchment, while the middle is densely populated with urban, semi-urban and rural settlements practicing subsistence farming (Pollard & du Toit, 2011; DWS, 2019). The lower most reaches of the catchment comprise smaller conservation areas as well as a section of the KNP (Pollard & du Toit, 2011).

Four large dams and approximately 180 smaller dams are located in the Luvuvhu River catchment. These dams are used to supply water for both domestic use and livestock watering. A portion of the available water supply is transferred out of the catchment to supplement the very dry Sand River catchment (Ashton et al., 2001).

2.3.3. Shingwedzi River Catchment

The Shingwedzi River catchment is a secondary catchment area in the Primary Drainage Region B, or Olifants WMA (DWS, 2019). It is the largest of the seasonal rivers in the park, flowing only after sufficient rains (van Vuuren, 2017b). Although the Shingwedzi River is not a perennial river, it is considered one of KNP’s major rivers (Wray & Venter, nd).

The river drains one of the drier secondary catchments. It is largely due to this aridity in conjunction with poor water use practices, that the Shingwedzi River does not have a perennial flow (Barker, 2006). The river originates near the town of Malamulele and covers an area of around 5 300 km^2 (Fouché & Vlok, 2012). The river rises in low hills and flows through the Limpopo Province. Most of its catchment area and its tributaries lie within the KNP boundaries.

The upper reaches of the Shingwedzi River catchment are underlain mainly by basalts of the Letaba formation from the Lebombo Group and Karoo Supergroup. The middle reaches consist of potassium-poor quartz-feldspar of the Goudplaats Gneiss Basement, while the lower reaches consist of mainly Goudplaats Gneiss and Makhuttswi Gneiss. This results in highly erodible soils throughout the catchment (Fouché & Vlok, 2012).

Economic activity and land use in the catchment is characterised by irrigation, afforestation, tourism, as well as commercial and subsistence farming. Just outside the KNP, land use is dominated mostly by subsistence farming and small industrial developments (Fouché & Vlok, 2012). Water use in the catchment is therefore focussed on subsistence agriculture and wildlife conservation, with boreholes providing water to the tourist accommodations in the KNP (Ashton et al., 2001). There are no large urban areas situated on or near the river, as most of its reaches occur within conservation regions (Barker, 2006).

A few small dams are located on the Shingwedzi River where it rises, and supply water for domestic consumption to a few small settlements and mines. Borehole water is used regularly to supplement supply, particularly in the catchment area that falls within the KNP (Ashton et al., 2001; Barker, 2006).

2.3.4. Letaba River Catchment

The Groot Letaba River arises in the Northern Drakensburg Mountains from where it meanders down the slopes in a north-easterly direction until it meets the Little Letaba in the KNP (Barker, 2006; DWS, 2019). From this confluence the river becomes known as the Letaba River, which flows east across the park to where it joins the Olifants River. The Letaba River catchment falls within the Primary Drainage Region B. The Letaba River catchment drains an area of approximately 13 500 km² (DWS, 2019). The river is perennial in the Great and Middle Letaba reaches, becoming more seasonal as it flows towards the KNP (Barker, 2006; Ashton et al., 2011).

The most prominent geology in the Letaba River catchment is that of granites that allow shallow weathering and the development of sandy soils and numerous diabase dykes (Barker, 2006; Pollard & du Toit, 2011). The upper reaches of the catchment are underlain mostly by the Transvaal Sequence. The dolomitic outcrops which dominate the lithology are important sources of good quality water in the upper catchment. Rocks of the Gravelotte Group and the Rooiwater Complex outcrop as visible hills to the north-east and east of the catchment. The Rooiwater Complex is also prominent in the south-west, hosting a variety of felsites and gabbros at the foot of steep hills. In the south, the Murchinson Greenstones are prominent formations and contain antimony and gold deposits (Ashton et al., 2001).

The DWS (2019) indicated that the Letaba River was found to have monitoring sites that were largely modified. The Groot Letaba River is influenced by commercial plantations, sand mining and erosion which evidently have an impact on the Letaba River downstream (DWS, 2019). Urban areas in the catchment include Tzaneen, Nkowakowa and Giyani. Land use in the catchment is a variety of agricultural practices including intensive commercial and irrigated agriculture in the upper regions. Mostly citrus, tropical fruit and vegetables are grown. Commercial forestry covers a large area of the Drakensberg Escarpment and the Soutpansberg Mountain area (Pollard & du Toit, 2011). As a result, water quality in the upper section of the catchment is generally good, but noticeable declines occur towards the lower reaches. This is mostly due to salination from natural sources such as the underlying geology and mineral leaching, but also from anthropogenic nutrient enrichment emanating from treated domestic wastewater and agricultural runoff (Pollard & du Toit, 2011).

Surface waters in the Letaba River catchment have been developed extensively. Several small to large dams have been constructed to meet a variety of water use demands including domestic, irrigation and industrial needs (Barker, 2006; Pollard & du Toit, 2011). Many of these dams are heavily silted and therefore do not fulfil the irrigation needs for which they were intended (Barker, 2006). Irrigation is the most intensive water use in the catchment, followed by forestry. Agricultural development has significantly influenced water supplies in the Letaba River catchment, necessitating the addition of dams in recent years (Pollard & du Toit, 2011). Water demand in the catchment exceeds availability despite several storage reservoirs providing water for industrial and domestic activities (Ashton et al., 2001).

2.3.5. Olifants River Catchment

The Olifants River catchment falls within three provinces including the western part of Gauteng, the majority of Mpumalanga, and a portion in Limpopo. The river itself is one of the largest in South Africa and originates in the east of Johannesburg, flowing in an easterly direction towards the KNP. The entire catchment drains an area of approximately 54 570 km^2. It joins the Limpopo River in Mozambique before entering the Indian Ocean. The main tributaries of the Olifants River are the Wilge, Elanda, Ga-Selti, Klein Olifants, Steelpoort, Blyde, Klaserie and Timbavati Rivers. This extensive river falls into Primary Drainage Region B, or the Olifants WMA; with the lower reaches near the KNP forming the secondary catchment area “B7”. The majority of the secondary catchment falls into the KNP (DWS, 2019). The river rises in the Highveld and flows in a north-easterly direction and joins the Letaba River before it flows into Mozambique (Ashton & Dabrowski, 2011).

In terms of geology, the Karoo System is represented in a large portion of the upper catchment, alongside much younger sedimentary and crystalline rocks such as sandstones, carbon-rich mudstones, conglomerates and shales (Ashton & Dabrowski, 2011). There are also rich coal deposits in the upper areas of the catchment which give rise to extensive mining and electricity production. In the central part of the catchment the geology consists mostly of hard igneous rock of the Bushveld Igneous Complex. A large dolomite intrusion extends along the Blyde River in Mpumalanga and follows a north-westerly direction along the WMA boundary (Pollard & du Toit, 2011). As in the upper catchment, the southern portion of the catchment hosts extensive, carbon-rich sedimentary rocks of the Karoo System making the area a prime site for intensive coal mining (Ashton & Dabrowski, 2011).

While the eastern portion of the catchment is under conservation, other major land uses outside of the KNP borders include irrigated commercial agriculture, afforestation, livestock and game farming, mining, and small-scale, rain-fed agriculture (Ashton & Dabrowski, 2011; Biggs et al., 2017; Mirzabaev et al., 2019). The main urban areas in the catchment include Witbank, Lydenburg and Phalaborwa (Pollard & du Toit, 2011). Coal has been mined in the upper parts of the catchment for over a century resulting in a multitude of abandoned mines decanting Acid Mine Drainage (AMD) into surrounding water resources. Economic activity is also focussed on coal combustion power plants, smelters, and various industrial developments (Oberholster et al., 2017). There are nine active coal fired power stations in the catchment whose pollution impacts are theoretically managed through licensing procedures (Pollard & du Toit, 2011; Oberholster et al., 2017). However, atmospheric emission deposition has been acknowledged to cause salinity in the catchment. Economic activity in the lower portion of the catchment is centred around mining in Phalaborwa (Pollard & du Toit, 2011).

Surface waters are highly developed. Numerous small and major dams have been constructed to meet the needs of a growing urban and rural population, irrigation, mining, and industry. The entire WMA is under stress with ongoing water deficits even without allowances for the Ecological Reserve. Irrigated agriculture is the largest water use sector in the catchment (Pollard & du Toit, 2011).

Over the years, the declining state of water resources in the Olifants WMA has received a lot of attention. Increased mining activity and poor waste and wastewater management have resulted in the deaths of fish and crocodiles in the lower Olifants River (Ferreira & Pienaar, 2011; Pollard & du Toit, 2011). The discharge of untreated and poorly treated wastewater from numerous sources combined with AMD from extensive mining operations have led to steadily rising nutrient concentrations resulting in the river becoming increasingly eutrophied (Ashton & Dabrowski, 2011). The Olifants River is one of South Africa's most extensive and important rivers but is also now one of the most polluted (Marr et al., 2017a; Oberholster et al., 2017).

2.3.6. Sabie River Catchment

The Sabie River catchment is one of four secondary drainage regions in Primary Drainage Region X, or the Inkomati-Usuthu WMA. (DWS, 2019). The Sabie River is the most contained within the KNP of all the rivers, with just less than 110 km of its 180 km length falling within the park (SANParks, nd; Pollard et al., 2011). The Sabie River catchment drains a total area of around 7 096 km² and is part of an international drainage basin, the Inkomati Basin (Barker, 2006; van Vuuren, 2017b). The Sabie River has its origins in the town of Sabie on the eastern Drakensberg slopes. It flows eastward and confluences with the Nkomati River in Mozambique. The river is fast-flowing, which results in its fairly cool temperature where it enters the KNP (van Vuuren, 2017b). The Sand River is a major tributary of the Sabie River and converges with the Sabie River inside the KNP (Erasmus, 2018).

The Sabie River catchment has a diverse geomorphology consisting of sedimentary, intrusive, and extrusive igneous as well as metamorphic bedrocks (Erasmus, 2018). This bedrock lithology is highly varied, ranging from metamorphic rocks such as quartzite; intrusive and extrusive igneous rocks such as granite; and sedimentary rocks such as shale. The upper reaches of the catchment host dolomite, limestone and granite, the middle reaches host a range of granites and gneisses, while the lower reaches host sandstone, basalt, and rhyolite (Moon & Heritage, 2001; Eze & Knight, 2018). Soils in the catchment are naturally rich in calcium and magnesium and low in phosphorus due to the dolomitic geology. These soils are also characterised by a higher pH (Heritage & Moon, 2000; Stolz, 2018). The Basement Complex traverses the upper and middle reaches of the catchment, while the Karoo sequence and Transvaal sequence underlay the eastern and western parts of the catchment respectively. The geology is superimposed by natural vegetation ranging from grasslands to inland tropical forest, tropical bush, and savannah (Barker, 2006).

The Sabie River catchment is mostly affected by land uses such as commercial forestry, agriculture, rural and urban development. The main stem of the river is classified as being in a largely natural condition, except upstream of the KNP where its health declines to moderately/largely modified (DWS, 2019). Approximately 71 000 ha or 16% of the catchment has been converted for forestry, mostly in the upper catchment where exotic tree species are planted. Approximately 11 300 ha of the catchment is covered by irrigated crops mostly consisting of bananas, avocados, citrus, papaya, and vegetables (Barker, 2006).

Biologically, the Sabie River is one of the most diverse in South Africa, largely due to its temperature and generally good water quality (van Vuuren, 2017b; Riddell et al., 2019a). The river includes species found nowhere else in the country, including the Lowveld largemouth kurper (van Vuuren, 2017b). Despite the quality of water in the Sabie River catchment being of high standard, the catchment is in a water deficit due to shortages in the Sand River catchment (Pollard & du Toit, 2011). Historical evidence indicates that the Sabie River water quality was previously adversely affected by mining pollution, leading to the river becoming sterile. It was only after radical action by the Mining Department in the 1940s that pollution in the river was combatted effectively and it was restored to a more biologically diverse state (Barker, 2006; Riddell et al., 2019a).

2.3.7. Crocodile River Catchment

The Crocodile River is part of the Inkomati-Usuthu WMA and covers approximately 10 450 km^2 (van Vuuren, 2017b; DWS, 2019). The river has several tributaries, with the Elands River being its largest. The river is itself a tributary of the Nkomati River (van Vuuren, 2017b).

The terrain in the Crocodile River catchment is relatively uniform spanning plateaus of undulating plains in the Highveld to areas of low relief in the central portion of the catchment, and a moderate relief in the lower regions. The geology of the catchment is highly diverse (Enoch, 2018). This slow-flowing river is underlain by mainly dolerite intrusions, basaltic lava bedrock and sandy pools (Kleynhans et al., 2013; Roux et al., 2018). The volcanic intrusive rock of the Bushveld Igneous Complex covers a large portion of the catchment and contains the largest platinum group metals in South Africa. As a result, this area has been targeted for vanadium, chrome, and platinum mining operations (Enoch, 2018).

Irrigated agriculture and forestry account for the greatest water demand in the Crocodile River catchment (Pollard & du Toit, 2011). The catchment is impacted by a variety of land uses including commercial forestry, agriculture (fruit orchards, vegetables, and sugar cane), as well as urban and rural settlements (Roux et al., 2018; DWS, 2019). At the river's head waters, a number of conservation, trout rearing and fishing operations can be found. Commercial forestry occurs mostly in the headwaters of the Crocodile River's tributaries, however there are several large towns situated along the Crocodile's reaches including Dullstroom, Mbombela, Malelane and Komatipoort (Roux et al., 2018).

The catchment has one large dam, namely the Kwena Dam, in the upper catchment, and several smaller farm dams in the central portions (Pollard & du Toit, 2011; Roux et al., 2018). The catchment is highly stressed, with water requirements consistently exceeding availability. Although there is policy to not issue any further water use licenses, irrigation demands have been increasing since the 1990s, and there is likely some unlawful development (Pollard & du Toit, 2011).

The Crocodile River is second only to the Sabie River in terms of its biological diversity. The river hosts at least 49 fish species. This is largely due to its wide range of riverine habitats, ranging from cold mountain streams in the Drakensberg to the Lowveld where slow-flowing temperate waters are found (Roux et al., 2018). It provides habitat for a number of invertebrate species and rare fish such as the air breathing shellear, Inkomati suckermouth and the Southern barred minnow (van Vuuren, 2017b). Downstream from Nelspruit the steep sided riverbanks are densely covered with riparian vegetation and reed beds (Roux et al., 2018).

2.4. Conclusion

The KNP is located on the Lowveld of South Africa and is well known for its biodiversity and abundance of wildlife including the "big five". Together with the adjoining reserves it constitutes one of the world's most extensive and highly valued conservation areas. The climate is mostly hot and dry with droughts being endemic to the region. Therefore, the park relies on the inflow of water from several large rivers as well as groundwater which recharges predominantly in the short, wet seasons. Seven major rivers across three WMAs arise in the Lowveld interior and flow in an easterly direction across the KNP. Biodiversity is highly dependent on this inflow, and the rivers themselves are undoubtedly influenced by a range of geology, soils, and morphology. These characteristics play a vital role in determining the ecological processes within the various river systems and suggest the presence of a heterogeneous range of biotypes that support wildlife.

Over-abstraction, various point and non-point pollutants, and a variety of artificial changes threaten the ecological integrity of the rivers. The Luvuvhu, Shingwedzi and Letaba Rivers no longer have a perennial flow, and even the larger Crocodile and Olifants Rivers exhibit declining flows in winter months that must be supplemented through groundwater recharge. In particular, the Letaba, Olifants, and Crocodile Rivers all receive a diverse inflow of pollutants, while the Sabie River remains the least disturbed system. Nevertheless, the Sabie River system as well as the other rivers already under pressure, will be threatened further through multiple regulations, upstream alterations, and additional influxes of pollutants in the next five years if current trends continue.

To fulfil its conservation role in eastern South Africa, the KNP requires a certain standard and flow of water. Despite the enabling of legislative frameworks for water reform and environmental flows since 1998, the ecological integrity of most rivers flowing into the KNP has not improved. South Africa's capacity to provide sufficient water of appropriate quality to meet developmental needs while ensuring environmental sustainability is directly threatened by the degradation of water resources. Therefore, protected areas such as the KNP need to be secured and well-managed to ensure long-term water security, and problems in these areas should raise red flags. Consequently, it is of high priority that these riverine ecosystems and the biodiversity that they support be protected. It is critical that, in the face of the multiple threats, we attempt to gain a better understanding of how these river systems are changing over time, improve planning and accommodate these predicted changes into protected area management policies.

CHAPTER 3: LITERATURE REVIEW

3.1. Introduction

This research is focussed upon establishing the possible influence of climate variability on water quality and flow in rivers of the KNP as well as the spatial and temporal patterns associated with water quality for the park as discussed in Chapter 1. Various aspects of water quality, including the numerous contaminants and pollution plaguing water resources on a global scale and in South Africa, are therefore focussed upon in this chapter and discussed in detail. Factors affecting the quantity and availability of water resources and consequently freshwater river flows are also discussed. The impacts of climate change and climate variability are highlighted and discussed as a key challenge to water resources on both a global and South African scale. Lastly, the physical and chemical parameters used to determine the health of water resources, and which relate to commonly experienced water quality problems in South Africa, are briefly discussed. The Chapter concludes with a synthesis of the reviewed literature.

3.2. State of Global Water Resources

Freshwater is a vital natural resource which underpins healthy, stable, and productive societies and ecosystems (Gain et al., 2016). People and ecosystems require an adequate quantity and quality of freshwater to survive. Freshwater is essential to meeting basic human needs, such that access to water has been entrenched in constitutions globally as a fundamental human right. Water as an economic resource is vital for promoting socio-economic interaction and is therefore of strategic importance (SADC, 2008; UNEP, 2016; du Plessis, 2019). Additionally, the importance of the provision of a certain amount and quality of freshwater for supporting nature has been highlighted in policy and planning through concepts such as the Ecological Reserve or other environmental flow requirement concepts (Pollard & du Toit, 2011).

By virtue of fundamental physics, freshwater resources are constantly in a state of flux rather than a stock. Freshwater resources are fugitive in nature, thus while the volume of water present on earth is always constant, its distribution and availability are driven by an unpredictable hydrological cycle (Turton, 2008; Pollard et al., 2011).

Approximately 75% of the earth's surface is covered by water. Approximately only 3% of this is freshwater and 72% is salt water, which is unfit for most types of consumption. Of the 3% of freshwater on earth, only 0.5% is available, while the remaining 2.5% is stored in other forms such as ice and snow. The 0.5% of available freshwater is stored in the earth's rivers, lakes, aquifers, reservoirs and ultimately in the hydrological cycle (du Plessis, 2019). Water is therefore an important resource across the globe for all sectors and is increasingly under threat by numerous anthropogenic activities. These activities together with increased climate variability can in turn exacerbate current water scarcity and threaten future water security in different regions across the globe.

While water scarcity can be interpreted from a demand driven perspective or population supply perspective, water security usually refers to the availability of an acceptable quantity and quality of freshwater for health, livelihoods, ecosystems, and production. This is usually viewed in conjunction with an acceptable level of water-related risks to people, environments, and economies. Ensuring water security in this way has been deemed one of the major challenges of the 21st Century (Gain et al., 2016), and as such has been an international priority for several years (UNEP, 2016). This is evident in various policies and practical efforts such as the United Nation's recognition of the need to ensure water security through Goal 6 of the Sustainable Development Goals (SDGs) (Gain et al., 2016). Yet, it has been widely documented that an increasing number of countries are experiencing water shortages and limitations to their freshwater resources (UN Water, 2018). In the past, priority has been given to ensuring water security through improving access and increasing the quantity of safe water that is available for consumption. However, the quality of freshwater is another dimension of water security that is becoming increasingly important as the world's rivers are going through important changes that may decrease the usability of these resources. Goal 6 of the SDGs specifically calls for stricter sustainable withdrawals and marks the first acknowledgement, on a global scale, of the need to protect aquatic ecosystems and to preserve ambient water quality (UNEP, 2016).

Despite the increasing strain on global water resources, the earth is not running out of water, and most countries theoretically have enough to meet their population's needs and sustain environmental flow requirements. Often it is the mismanagement of these water resources that threaten economies, human welfare, and natural ecosystems. Water stress is therefore often rooted in poor or reactive decision making, lack of informed management, lack of suitable skills and the failure to fully value water as a political and economic resource (WRG, 2009; UN Water, 2021).

The current state of water resources highlights the need for improved management and the recognition and accurate measurement of the value of freshwater to enable the establishment of sustainable and equitable practices on a global scale (UN Water, 2021). The following sections therefore focus on the use and availability of the world's water resources, the current state of water quality, and predicted possible effects of climate change and/ or increased climate variability. A brief description of the world's water availability and scarcity now follows.

3.2.1. Water Availability and Increased Scarcity

Freshwater resources on earth are very limited, with as much as 99% of all water already being saline, and more of it becoming so through anthropogenic actions (van der Merwe-Botha, 2009). Current trends indicate that freshwater resources, that sustain important ecosystems and growing populations, have become stressed (Munia et al., 2016; du Plessis, 2019). Around the world, water resources are being degraded by various contaminants, rendering them unsuitable for use, or are drying up due to both natural and human impacts. Numerous drivers including increasing population growth, demographic changes, urbanisation, and climate change are currently the most prominent threats to a secure water supply in the future (du Plessis, 2019). As a result, 25 African countries are projected to be water stressed by 2025. This statistic has almost doubled since 1995. Additionally, 25 out of the 48 countries expected to experience water shortages by 2025, will be African (Loewenson, 2020).

The successful harnessing of the world's freshwater over many decades has been achieved through the building of dams, extensive irrigation systems, and innovative infrastructure. This has allowed the human population to expand, adding pressure to these water systems and resulting in some of earth's largest rivers running dry (WWF, 2016). During the last five decades, the world population has doubled, resulting in the growth of not only the Gross Domestic Product (GDP), but also urbanisation, agriculture, and industrial output (WRG, 2009). In the last 100 years, global water demand has increased by a factor of 6, and since 1980 has been increasing at a rate of about 1% per annum as a function of this growth (UN Water, 2018; UN Water, 2021). Under a scenario based on average economic growth, with no indication of possible gains in efficiency, global water requirements could grow from 4 500 billion m^3 to 6 900 billion m^3 by 2030. This is approximately 40% above the current sustainable supply. At the current 4 500 billion m^3 per annum withdrawal rate, global withdrawals are already near maximum sustainable levels (WRG, 2009; UN Water, 2018).

Renewable freshwater resources and the human population are unevenly distributed across the globe, which means that already two to three billion people live in water stressed areas (Munia et al., 2016; UN Water, 2018). Although more than 80 countries are characterised by water scarcity, the sub-Saharan African region has the largest number of water scarce countries than any other region in the world (du Plessis, 2019). The world population is expected to increase to between 9.4 and 10.2 billion by 2050. Therefore, the number of people living in water scarce areas for all, or part of the year could increase to approximately 4.8 - 5.7 billion by 2050 (Munia et al., 2016; UN Water, 2018). Approximately up to 56% of the global population could be exposed to annual water scarcity by 2080 (Veldkamp et al., 2016). The WRG (2009) found that there was a high correlation between projected population and economic growth, and the extent of the gap between projected water demand and current supply. This indicates that high growth countries are vulnerable to particularly severe water scarcity issues in the next few decades (WRG, 2009). Various attempts to project water demand trends have reached different conclusions. The WRG (2009) projected that there would be a 40% global water deficit by 2030 under a business-as-usual scenario. Similarly, the Organisation for Economic Co-operation and Development (OECD) projected that demand would increase by 55% between 2000 and 2050; and independent research found that global water use would increase by 20 to 30% above the sustainable level by 2050 (UN Water, 2021). Mexico, the Western United States of America (USA), Northern and Southern Africa, Southern Europe, Middle East, India, China as well as Australia are areas that are most at risk.

Economic growth and development are fundamental drivers of the challenges surrounding water resources. The agricultural sector currently accounts for approximately 69 to 71% (this number varies according to different sources) or 3 100 billion m^3 of global water withdrawals (UN Water, 2018). This is mainly used for irrigation, as well as livestock watering and aquaculture (UN Water, 2021). Without efficiency gains, this is expected to increase to 4 500 billion m^3 by 2030 but will constitute an overall slight decline to 65% of water withdrawals among sectors. Water-related challenges, food production and trade are intimately linked. The world's agricultural hubs are home to some of the poorest subsistence farmers and these areas are where withdrawal is projected to grow. For instance, India's agricultural withdrawals are expected to reach 1 195 billion m^3, in Sub-Saharan Africa withdrawals are expected to reach 820 billion m^3, and China will reach 420 billion m^3 by 2030, putting some of the world's poorest communities at risk of water scarcity (WRG, 2009; UN Water, 2018).

Industrial water use accounts for approximately 20% of global withdrawals and is dominated by the energy production sector. The energy sector constitutes 75% of industrial withdrawals, with the remaining 25% being used for manufacturing (UN Water, 2018). Industry account for 19% of freshwater withdrawals, which has been projected to increase to 24% by 2050 with Asia and Europe accounting for the largest increases (UN Water, 2020).

In terms of the domestic water use sector, expected withdrawal is likely to increase significantly over the period leading up to 2050 due to population growth and increased rural-urban migration. Domestic water currently accounts for roughly 10% of the remaining use and will increase in all regions across the world except for Western Europe where it should remain constant due to low population growth. African and Asian sub-regions will experience the greatest increase in use, where it could almost triple. The majority of this growth will be attributed to increased access to water in urban settlements (UN Water, 2012). One of the major concerns is that increased water scarcity may intensify competition between people and sectors and therefore lead to conflict in some areas. This is especially a concern where river basins cross political boundaries and lead to problems of allocation. Approximately 40% of the global population live in shared river basins that comprise two or more countries. This is of particular importance because upstream water use in transboundary basins increases water scarcity for downstream users (van der Merwe-Botha, 2009; Munia et al., 2016).

Although awareness of the environmental limitations to growth has increased in the last two decades, the operational integration of environmental quality objectives and efficiency principles into water resource planning remains a major weakness (Hirji et al., 2002; Onu et al., 2023). Poor water resource planning, investment and management has led to a steady decline in the availability and quality of the world's water resources, rendering large portions of freshwater unsuitable for various uses and unable to sustain sensitive ecosystems (Edokpayi et al., 2017; du Plessis, 2019). A brief description of the primary water quality and pollution problems on a global scale now follows.

3.2.2. Primary Water Quality and Pollution Problems

Alongside the importance of making adequate water available for people and ecosystems, is the importance of that water being of good quality. Together these criteria are necessary for achieving food and water security for growing populations and essential ecosystems. The availability of water is largely determined by its quality (van der Merwe-Botha, 2009; du Plessis, 2019), because polluted water cannot be used for drinking, basic hygiene, industrial purposes or agriculture and causes damage to human health and ecosystem services and functioning. Furthermore, poor water quality disrupts the balance of aquatic ecosystems and results in large scale changes to the abundance and distribution of aquatic species (UNEP, 2016). Therefore, the rising environmental pressures on freshwater resources associated with drivers such as urbanisation, industrialisation, mining, and agriculture are global concerns which urgently require more committed remedial action (Oberholster et al., 2017). The recognition of the need for good quality water has predominantly focussed on the direct uses for domestic and productive purposes, and it is only in recent years that there has been a shift towards maintaining healthy freshwater reserves for the sake of aquatic ecosystems (UNEP, 2016). Unfortunately, global water quality data remains sparse and inconsistent due to the lack of monitoring and reporting capacity, particularly in less developed countries. Despite a lack of rigorous monitoring, numerous trends concerning various types of pollution problems and persistent water quality issues exist (UNEP, 2016; UN Water, 2021).

Approximately two million tonnes of sewage and wastewater effluent is discharged into the world's water resources every day, and each year, the world produces six times more wastewater than there is water contained in its rivers (du Plessis, 2019; Bhat & Qayoom, 2021). Approximately 80% of industrial and municipal wastewater is not treated before being released into the environment. This ratio is higher in less developed countries where the capacity for treatment, and the provision of sanitation is lacking (UN Water, 2021). Since the 1990s, water pollution in the global South (South America, Africa and Asia) has worsened and is expected to decline further in the near future, posing risks to human health, the environment and overall future sustainability (UNEP, 2016). Between 1990 and 2010, the level of pathogen pollution and organic pollution worsened in more than 50% of river reaches in South America, Africa and Asia and impacted one third of rivers on these continents (UNEP, 2016). The expansion of sewerage systems that discharge untreated wastewater into rivers has been highlighted as one of the primary causes (UNEP, 2016; UN Water, 2018).

In the global South, one seventh of rivers are also affected by severe organic pollution, with limited data projecting a worsening trend. Organic pollution results from the addition of large amounts of decomposable organic compounds into water resources. As these compounds break down, they reduce the level of dissolved oxygen (DO) in the water body, restricting oxygen required by fish and other aquatic fauna (UNEP, 2016). Organic pollution therefore severely impacts freshwater fisheries and ultimately food security and livelihoods. Organic pollution plays a significant role in nutrient loading and often leads to eutrophication of the water body, which is globally considered to be one of the most serious threats to freshwater ecosystems (de Villiers & Thiart, 2007; UN Water, 2021). Nutrient loading usually occurs when anthropogenic additions of phosphorus and nitrogen become so high that it disrupts the natural processes of a water body (UNEP, 2016). Agriculture, which accounts for most water withdrawals is also the predominant source of nitrogen and phosphorus pollution due to the sector's return flows containing fertilisers and pesticides (de Villiers & Thiart, 2007).

Saline pollution is less widespread than pathogen and organic pollution, however salinity levels have increased in rivers of the global South by around one third over the past two decades. One tenth of rivers are currently threatened by moderate to severe salinisation. This type of pollution is the result of dissolved salts and other substances being loaded into water bodies in such concentrations that it impairs the use of the water for irrigation and industry. Although most rivers naturally have some salt content as a result of the underlying geology and lithology of the drainage basin, various activities (e.g.: the addition of domestic wastewaters and runoff from mines and agriculture) have consequently increased salt concentrations in water that is naturally not saline (UNEP, 2016; Cañedo-Argüelles et al., 2019).

While an increase in wastewater discharge is the immediate cause of escalating water pollution, ultimately it is population growth, economic activity, intensification and expansion of agriculture, and growth of urban settlements that negatively influences the quality water resources. Although water pollution in the global South is serious, swift action could circumvent any further major declines and help to easily restore affected rivers. What is needed to achieve this is a better understanding of the scope and intensity of water pollution through more widespread and improved monitoring coverage, as well as a thorough assessment of the of water quality on various local scales which will identify the priority locations and actions required to improve pollution control (UNEP, 2016).

The quality of water in a particular location is also influenced by natural factors in relation to the water body's location. The primary natural influences include the geochemical and climatological location of the water (IPCC, 2014; UNEP, 2016). Changes to the climate across regions will affect water quality in various ways. One of these ways include the spatio-temporal changes to rainfall patterns across the region. Rainfall affects surface flows and therefore the dilution capacity of surface water. During extreme rainfall events, larger pollutant concentrations will flow into water bodies causing increased pollution. Higher water temperatures can cause DO to deplete faster (IPCC, 2014). Several studies indicate that higher water temperatures and reduced flow rates during summer months may lead to pollutants having a greater impact on rivers (Hosseini et al., 2017). A detailed discussion of the aforementioned trends, observations and impacts of increased climate variability and climate change on freshwater resources now follows.

3.2.3. Global Climate Change and Freshwater Resources

Climate can be defined as the average weather conditions of a region, usually measured over a period of more than 30 years. Climate variability refers to the spatio-temporal deviations above or below the mean climate statistics, due to natural external processes outside the earth system, or as a result of natural or anthropogenic internal forcing. Climate change is therefore the shift in average climate over time due to either anthropogenic factors or natural variability (Sinha & Kumar, 2015). The human influence on the global climatic system has been receiving increased attention and has consequently become one of the world's biggest environmental challenges for a number of decades, even though its impacts on valuable freshwater resources are only just beginning to be understood (SADC, 2008; IPCC, 2014). The most recent report by the IPCC (2022), for instance, indicates with high confidence that anthropogenic influences can be directly attributed to severe droughts in Southern Africa.

The established and predicted impacts of climate change have become a widespread concern mostly due to its effects on water resources, and in turn its indirect effects thereof on people's livelihoods, wellbeing, and overall environmental health. Climate change affects the spatio-temporal patterns of water resources, has various feedback effects, and impacts human-environment interactions in multiple and complex ways (UN Water, 2020).

There is an overwhelming scientific consensus that anthropogenic activities have activated a relentless warming of the global climate system. The ongoing emission of Greenhouse Gases (GHGs) and carbon dioxide, which have steeply increased since the pre-industrial era, has led to imbalances in the atmosphere that give rise to changes in weather and water patterns. Most warming has taken place in the last three decades, with five of the warmest years being recorded since 2010. The average surface temperature of the earth has risen by 0.9°C since the beginning of the 19th century. Annual precipitation trends influenced by climate change are less certain than temperature trends, however even small changes in temperature can have significant impacts on the availability and quality of water (UN Water, 2020; Zak et al., 2021). Climate change has stimulated an increased occurrence of droughts, floods, and other extreme weather events, all of which have the potential to reduce water availability, thereby increasing water stress. These changes will become more significant for freshwater resources as GHG concentrations increase (du Plessis, 2019; UN Water, 2021).

Changes to the climatic system also reduce the predictability of water resources in terms of their availability as well as quality (UN Water, 2020). Climate change is likely to increase the seasonal variability of naturally occurring water bodies, exacerbating problems in areas that are already water scarce, and possibly creating water stress in areas where it has not yet been a frequent occurrence (UN Water, 2021). Unfortunately, the possibility and severity of impacts at individual river basin levels are still uncertain and difficult to quantify (Dallas et al., 2019). However, most projections indicate that water availability will decrease in many mid-latitude and dry subtropical regions, where most of the developing world is found, and increase in many high latitude and humid mid-latitude regions (IPCC, 2014; UN Water, 2020). In addition, the 100-year flood line is expected to be three times higher by the end of the 21st century due to continued emissions.

In 2014, the most vulnerable regions in terms of climate change were predicted to be South Asia and Southern Africa. By 2030, these regions are predicted to experience food shortages mainly attributed to the effects which accompany climate change. Central and Southern Europe is projected to experience some water stress by 2070, and summer flows in Southern and Eastern Europe are expected to decrease by 80% (IPCC, 2014). Such decreases in the terrestrial water budget affect the availability of water for agricultural withdrawals, industrial and domestic supplies, as well as for in-stream uses and the environment (UN Water, 2020).

Water quality will also be impacted negatively and is likely to cause the degradation of many freshwater ecosystems through various physical, chemical, and biological processes related to changes in temperature and rainfall patterns (IPCC, 2014; Nosrati, 2015; IPCC, 2022). Some of the main climatological determinants affecting water quality are ambient air temperature and the increase in hydrological events such as droughts and floods. These events tend to cause changes to the dilution capacity of rivers, or the concentration of dissolved substances in the water body, thereby modifying water quality further. In general, when river flow is low (naturally or in a drought scenario) the concentration of dissolved substances increases, and the amount of DO decreases (Delpha et al., 2009; IPCC, 2014; IPCC, 2022). As mentioned previously, a reduction in the DO content within a water body, inhibits the functioning of most freshwater organisms. Conversely, in heavy rainfall scenarios, water quality is usually impacted by the flushing of organic matter into rivers, increased runoff from urban and agricultural areas and the transportation of solid materials into rivers (Delpha et al., 2009). Alterations to the flow regimes of rivers and the building of infrastructure on various water bodies will exacerbate the ecological effects of climate change much more than previously indicated. For instance, flow regime variability could impact the food chain, resulting in the loss of large-bodied top predators as well as nutrient concentrations in river water (IPCC, 2022). Reduced water quality will threaten potable water supply even with improvements in treatment capacity, particularly for rural populations that still rely on direct access to rivers and dams. Temperature increases, increased sedimentation, nutrient, and pollution loading from heavy rainfalls are the main reasons for this (IPCC, 2014).

It is however important to remember that climate change is only one factor affecting the quality of water. Land use, deforestation, urban expansion, and various other factors also play a significant role (Delpha et al., 2009). It should also be highlighted that few projections related to the possible impacts of climate change or increased climate variability on water quality have been made, and where predictions exist, there is often a high degree of uncertainty. Projections on the localised effects of climate change on water quality depend highly on local conditions, climatic and environmental assumptions, and the current state of pollution within the specific area (IPCC, 2014).

In conclusion, many countries are already experiencing water scarcity conditions and will likely have to cope with lower water availability in the years to come. The world's resources are often shared between countries and the availability for downstream users in individual basins will need to be taken into consideration to ensure an equitable supply and avoid potential conflicts. Regional cooperation will therefore be essential to addressing critical water quality issues between nations within transboundary river basins. Although agriculture will remain the largest overall freshwater user, industrial and domestic demand for water will likely grow much faster due to population growth, rural-urban migration, expansion of urban areas and continued pursuit for economic growth.

Low and middle-income countries can expect to experience the largest increases in exposure to pollutants, primarily due to higher population and economic growth rates in these regions, and the associated lack of infrastructure and proper management. Most rivers in South America, Africa and Asia are showing a declining trend in terms of water quality, posing risks to human health, the environment and future sustainability. The continued decrease in water quality in these mentioned areas will place millions of people living in rural settlements at highest risk of water scarcity as well as water-related diseases mainly due to pathogen pollution.

The abovementioned impacts will be exacerbated as a result of climate change and/ or increased climate variability. Climate change has stimulated more frequent and severe droughts, floods, and other extreme weather events, all of which have the potential to reduce water availability, negatively influence quality and ultimately increase water stress. Climate change is therefore an important factor which needs to be accounted for when assessing the future of water resources, especially in regions such as Southern Africa where water-related challenges are already widespread.

South Africa falls under the Southern African region where rainfall is already low, drought a regular occurrence, and a lack of knowledge, monitoring networks and appropriate infrastructure already affecting the provision of enough quality freshwater for its population and the environment. An overview of the state of South Africa's water resources is thus necessary to provide context and understanding of the current trends and water-related challenges. A discussion of the use, availability, primary water challenges and the predicted effects of climate change in South Africa thus follows.

3.3. State of Water Resources in South Africa

South Africa has undergone significant reform in terms of how it manages its water resources through adopting the IWRM system (van der Merwe-Botha, 2009). However, the country is rapidly approaching the full utilisation of its water resources whilst the demand for water continues to increase across all sectors largely due to continued economic and population growth (DWA, 2010a). Securing the country's water resources for future growth and the development of its people has therefore become a national priority. Underpinning water security in South Africa is the effective management of the quality and quantity of available water resources (van der Merwe-Botha, 2009). In the future, large quantities of water will be required to meet urban growth demands, the generation of electricity and mining developments (DWA, 2010a). However, the country has failed to develop the enablers that allow it to fully implement the appropriate policies and strategies and uphold or enforce the existing legislation, leaving the country at high risk in terms of water scarcity and stress under significant climate change projections (van der Merwe-Botha, 2009).

Much of South Africa's available water is tied up in storage facilities such as dams and reservoirs, as well as in over-utilised rivers that are increasingly under pressure from withdrawals and pollution. The country is dependent on this infrastructure for national water security as well as on significant inter-basin transfers and transfers from other SADC countries (van der Merwe-Botha, 2009; Donnenfeld et al., 2018; DWS, 2018). Despite its innovative infrastructure, more than half of the country's WMAs are in deficit after the allocation of enough water for environmental flow requirements. This indicates the intensity with which water resources are already utilised and highlights the ongoing sustainability challenge in the country (van der Merwe-Botha, 2009; Donnenfeld et al., 2018).

The status of water quality in surface waters throughout South Africa varies considerably between WMAs and within catchments and their rivers. Some of the most contaminated river systems include the Vaal, Crocodile West (Limpopo), Umgeni and Olifants Rivers (van der Merwe-Botha, 2009; Marr et al., 2017a). Freshwater resources are prone to multiple water quality issues due to persistent degradation by all water use sectors. Diminishing quality also affects the availability of freshwater, especially in conjunction with the occurrence of high water losses and longer periods of drought, with the consequence that water restrictions are regularly implemented and enforced. For the country to secure its water resources in the near future, it needs to improve its overall management approaches and invest in technologies that will improve efficiency of use and treatment ability (du Plessis, 2019). A discussion of the country's water availability and use, water scarcity and possible impacts of increased climate variability on its water resources now follows.

3.3.1. Water Availability and Use

As is the situation worldwide, the amount of water available in an area is dependent on the sustainability and management of the resource at a local scale due to the interconnected factors of climate, annual average surface flows and groundwater recharge. South Africa is a semi-arid to arid country with an annual average rainfall totalling only 50% less than the world average. The country receives an average rainfall of only 490 mm per annum and around 80% of rainfall occurs in the span of five months. South Africa's rainfall is the primary input to its water resources although it is highly seasonal and variable (WWF, 2016). South Africa is also located in a negative runoff zone, meaning that annual evaporation exceeds rainfall by a factor of 1.2 - 4 and only 8 - 10% of its rainfall is converted to useable runoff (de Wit & Stankiewicz, 2006; Oberholster & Ashton, 2008; Turton, 2008; DEA, 2012). This poor conversion rate is a serious development constraint for the country, making it a "hostage to its own hydrology" (Turton, 2008, p. 2). The country also receives 10% of its runoff from Lesotho and shares most of its water resources with other countries in the Southern Africa region (WRG, 2009; du Plessis, 2019). Water resources in South Africa consist of 77% surface water, 14% return flows and 9% groundwater (Kahinda & Boroto, 2009; DEA, 2012). It is for these reasons that increased climate variability is such a serious concern for the region and the country, and even small perturbations in the distribution of moisture from the Inter-Tropical Convergence Zone (ITCZ) down to South Africa can cause major shifts in this final conversion ratio (Turton, 2008; DEA, 2012).

South Africa's rivers are small and shallow, limiting opportunities for large scale storage of water resources (WRG, 2009; Donnenfeld et al., 2018). Water availability is inconsistent across the landscape and varies between catchments. Large inter-basin transfers between catchments are necessary to supplement metropolitan areas such as Johannesburg, not located close to major water resources (DEA, 2012). These water transfers between basins form an essential part of the country's water supply. In seven out of South Africa's nine provinces, more than half of the water provision relies on inter-basin transfers (van der Merwe-Botha, 2009). Almost 25% of water supplies, approximately 30 m^3/second, are also transferred from Lesotho into the Upper Orange basin and then downstream to support a number of other basins (WRG, 2009; Prasad et al., 2016). This demonstrates the intensity with which available water resources are already being used. Efficient storage of water resources is thus critical to ensure year-round supply and provide regulated, more consistent flows and fewer floods. South Africa currently has approximately 4 718 dams registered with the Dam Safety Office. This infrastructure stores the country's water resources and is responsible for getting water to settlements, agricultural areas, industry, and wastewater systems, and is critical for maintaining water security. However, these storage facilities also cause the disruption of natural flow regimes, inadvertently degrading the natural state of rivers (WWF, 2016).

South Africa's water resources are already being intensively used and controlled (DEA, 2012). Capacity for further development of water resources is highly limited, with only a few small prospects remaining (du Plessis, 2019). Despite its world-renowned water transfer schemes and storage infrastructure, the country has reached a point where its developmental demands are outstripping its capacity to supply water. The National Water Resource Strategy (NWRS) had determined that, by 2004, around 98% of the total national water resources had been fully allocated, with some of the WMAs being over-allocated by as much as 150% (Oberholster & Ashton, 2008; Turton, 2008). This limited development potential coupled with no additional availability for allocations, puts the country's water resources at high risk of overuse and degradation, and will require unprecedented management changes especially in the face of climate change. Given the expected population growth rates and socio-economic development, current patterns of water use and wastewater discharge are unsustainable (Oberholster & Ashton, 2008). These high levels of development and the intensity with which water is used for human activities is a direct threat to more than half of South Africa's riverine systems (DEA, 2012).

Water use in South Africa is predominantly agriculturally based (8.4 billion m^3), followed by urban requirements (3.5 billion m^3) and industrial use (1.5 billion m^3). These water supply allocations are expected to increase to 3.6 billion m^3 for urban consumption and 3.3 billion m^3 for industrial use by 2030 (WRG, 2009; du Plessis, 2019). In terms of domestic use, basins that supply water to the large urban populations such as Johannesburg, Tshwane, Durban, and Cape Town are expected to face severe gaps as demand grows. By 2030, it is projected that the Upper Vaal catchment will face a demand and supply gap of 31% and the Olifants River catchment a gap of 39%. Unconstrained growth of household demand, at 1.8% per annum coupled with economic development means that demand in South Africa is projected at 17.7 billion m^3 in 2030, with household demand accounting for 34% of that total (WRG, 2009; WWF, 2016). The country thus faces the challenge of bridging a supply gap of around 17% or 2.7 billion m^3 within the next decade. The increase in domestic demand is driven by growth in the proportion of the population that consumes the most water and increasing per capita consumption in the low and middle-income segments due to improved access to sanitation services, and increased landscaping in residential areas (WRG, 2009).

Agricultural water demand accounts for 62% of national water supply, yet the sector currently only has 10% of croplands under irrigation and only contributes 2.5% per annum to the country's GDP (WRG, 2009; DEA, 2012; DWS, 2018). The national water authorities have already capped agricultural allocation levels and therefore irrigation is unlikely to increase. However, the sustainability of the sector is highly vulnerable to the impacts of increased climate variability. Assuming no efficiency gains, a small change in rainfall yields could lead to a demand and supply gap of between 2.7 to 3.8 billion m^3 in 2030 (WRG, 2009; DWA, 2010a). Therefore, significant improvements in terms of water efficiency and agricultural productivity will be required in upcoming years, especially against the backdrop of strict withdrawal limitations as well as an increasing demand for food as the population's wealth and caloric intake increases (WRG, 2009).

Meeting the water demand for power generation is also one of South Africa's major water-related challenges. Generating electricity from coal-fired power stations, nuclear stations and even solar power stations requires a certain quantity of water (DEA, 2012). The country needs to make provision for increasing demands of up to 25 GW by 2025. South Africa's power generation is derived primarily from its dry-cooled, coal-fired power plants due to its natural abundance of coal reserves. Local supplies of water for both mining and power generation are usually insufficient to support both sectors on an ongoing basis, and water transfers from other regions are required to supplement the demand gap. While the demand for water specific to gold mining is set to decrease, the mining of coal will become the primary water user in the mining sector by 2030 (WRG, 2009). The mining sector currently accounts for 5% of water use in the country (DWS, 2016b). Concerns around the water requirements for the dilution of AMD are growing as it seems ever more likely that, as pollution increases, demand for dilution may exceed the amount currently required for other uses (WRG, 2009).

South Africa has well established standards and protocols for controlling pollution and flow requirements, however improvements in its demand management approach may assist in conserving both water quality and quantity further. Various technological, behavioural, economic, institutional, and regulatory incentives can be applied to promote the efficient and equitable allocation of water (SADC, 2008; DWS, 2018). Furthermore, the declining state of water resources in the country indicates the need to manage, use and allocate water differently to how it has been done in the past. This requires a willingness to change approaches and attitudes toward water management, and government responses in this regard are slowly beginning to reflect this. This change cannot come soon enough, with many of South Africa's large river systems in a state of stress and deterioration. Many of the country's major river basins are shared with neighbouring countries, making managing water a regional concern (DEA, 2012). A description of the primary water scarcity concerns in South Africa now follows.

3.3.2. Primary Water Scarcity Concerns in South Africa

The challenges associated with the scarcity of water resources in semi-arid to arid regions of the world, such as South Africa, have been highlighted for several decades. Despite much attention given to the subject, it is projected that future water use will likely exceed availability, with the situation exacerbated by droughts and the predicted long-term effects of climate change. South Africa is therefore fast approaching the point where it will no longer have freshwater reserves available to meet growing needs from various water use sectors (DWA, 2010a; DWA, 2010b; Turton, 2012; du Plessis, 2019).

Inadequate maintenance of existing infrastructure, slow response time to fix leaks and ruptures, weak technical competencies as well as a culture of water wastage has plagued South Africa for years and have contributed to the challenge of managing water security (DWA, 2010b; du Plessis, 2019). Water losses throughout the country are relatively high with 35 - 45% and 25.4% of losses occurring in the agricultural and domestic sectors, respectively. Losses in the agricultural sector are primarily due to runoff, inefficient irrigation techniques, wasteful application methods and the planting of crops that are water intensive. Losses in the domestic sector are mostly due to leakages. Alien invasive species also play a role and accounts for approximately three billion litres of water use per annum which comes directly from the country's main water supply systems (du Plessis, 2019).

Climate change is predicted to directly result in a further decline of surface water supply in South Africa. A 10% decrease in precipitation in Southern African regions receiving 500 mm or less per annum could result in a reduction of water draining from major basins by as much as 30 to 50% (de Wit & Stankiewicz, 2006; DWA, 2010a). The south-western parts of the country are expected to be more severely impacted (DWA, 2010a). Pressure to produce more food for a growing population will as a result increase both land use and water consumption for irrigation and therefore compound the effects of climate change (Saraiva-Okello et al., 2015; DWS, 2018). Increased abstraction for irrigation has also led to an array of consequences for the environment such as reduced surface and groundwater flows, shrinking wetlands and in some instances the extinction of species (du Plessis, 2019).

However, the future of water security in South Africa is not hopeless. Enough water can be made available to meet growing needs and overcome the impacts of climate change with informed IWRM (DWA, 2010a; DWA, 2010b; DWS, 2018). It is therefore essential that strategies be developed to reconcile the future requirements and availability of water at various locations, for various water use sectors in the country. Utilisation limitations, although already experienced in some regions, will not come into play uniformly across the country. Therefore, these strategies should be based on concrete assessments of the thresholds and remaining potential of water resources as well as the expected costs to bridge supply gaps at each local scale. Additionally, assessments should serve as the background for the most appropriate location and parameters for future developments as well as the decision on which sectors and levels to assign responsibility for the management of these resources (DWA, 2010a; DWS, 2018).

3.3.3. Climate Change and South Africa's Freshwater Resources

South Africa is the ninth largest emitter of sulphur in the world, contributing significantly to the overall level of GHGs in the atmosphere primarily through its industrial sector (DEA, 2012; Oberholster et al., 2017). Between 1990 and 2000, total GHG emissions in South Africa increased from 347.4 Mt carbon dioxide equivalents to 461.2 Mt carbon dioxide equivalents, with most of this growth in the energy and fuel sectors (WWF, 2016). Various climate change reports state that these types of anthropogenic emissions have unequivocally contributed to the changing of the earth's climate over several decades (DEA, 2012; IPCC, 2014; IPCC, 2022). Therefore, variations in the climate of a region, can be attributed at least in part to anthropogenic forcing (Nkhonjera, 2017). Climate and the hydrological cycle are inextricably linked, therefore changes to the one will cause changes to the other. These changes will have a unique set of impacts on surface freshwater in South Africa, and therefore need to be thoroughly understood, specifically in the context of water quality and availability (Mujere & Moyce, 2017; Nkhonjera, 2017).

The Southern African region has been identified as a climate change hot spot and is considered a critical area in terms of water stress. The region has an unstable rainfall regime, which, with global climate change, is predicted to become more erratic (de Wit & Stankiewicz, 2006). Due to water scarcity that results from high evaporation rates and low Mean Annual Precipitation (MAP), South Africa is the 30th driest country in the world (Enoch, 2018). The demand for water is increasing as South Africa becomes more developed and populated. Simultaneously, the availability and quality of the country’s freshwater resources are threatened by a variety of factors, of which, climate change is just one (WWF, 2016).

Extensive research indicates that climate change will result in temperature increases, increased evaporation, changes in spatio-temporal rainfall and runoff patterns, leading to increased frequency of flooding and drought as well as a reduction in groundwater recharge across the Southern African region (Turton, 2008; Turton, 2012; Petrie et al., 2015; Mosase & Ahiablame, 2018). A 2°C rise in temperature on a global scale could equal a 4°C rise for temperatures over Southern Africa (WWF, 2016). The region is thus warming at double the global average rate with shifting climatic patterns already affecting water resources and planning (van Vuuren, 2020). Increasing temperatures will cause rainfall to increase in some parts of the country, while other areas may experience decreases. In a scenario where the country experiences an overall decrease of 10% in its rainfall, surface runoff is expected to decrease to between 50 - 75% (Saraiva-Okello et al., 2015; Dallas et al., 2019; du Plessis, 2019). Less precipitation is predicted for the western region with high levels of confidence, with the eastern portion of the country possibly experiencing an increase in the occurrence of largescale floods (WWF, 2016).

Approximately 49 200 million m^3 of freshwater flows through South African rivers annually; a quantity that is considered relatively low by global standards (DEA, 2012, Enoch, 2018). Natural climate variability such as drought and human activities such as freshwater abstraction are jointly responsible for these low flows (Enoch, 2018). Due to such great variances in terms of climate and availability of water resources, large-scale water storage and transfer infrastructure have been developed. South Africa is one of the world’s top dam builders and has left very few of their water resources undeveloped. However, many of these water supplies are currently used beyond their sustainable supply rate (DWS, 2018; du Plessis, 2019). Climate change impacts are notoriously hard to quantify, however the impacts thereof are known to be a significant threat to biodiversity and ecosystem functioning (Petrie et al., 2015; Dallas et al., 2019). The following are some of the major impacts that may be expected. Firstly, South Africa’s water resources are not evenly distributed. As water availability decreases in some regions, there will be a corresponding migration of people away from water scarce areas to areas with higher levels of availability. Consequently, regions with better availability and accessibility will experience greater pressures on water resources. The more frequent occurrence of natural disasters and extreme weather events (droughts, floods, and cyclones) may also increase migration to urban areas. Destitute people seeking relief from climatic impacts will put additional pressure on natural resources and increase pollution in those areas (du Plessis, 2019).

Climate change and the associated water allocation reform indicates that South Africa's capacity to be self-sufficient in food production may decrease. Food security for the country therefore becomes a threat for the first time and will need to be viewed from a national security aspect (Turton, 2012). The energy production sector is inextricably linked with water use as well. Under the threat of climate change, efficiency when converting a unit of water into a unit of electricity becomes extremely relevant. Similarly, efficiency in the mining sector becomes even more important. The occurrence of AMD arising from gold and coal mines reduces the availability of water nationally and increases the costs of treating water for use in other sectors, contributing to water stress within a specific region such as Johannesburg (Turton, 2012).

The hydrological cycle and water availability are intimately linked with surface water flows and the dilution capacity of rivers. These factors are highly susceptible to the influences of climate change and therefore influence river water quality (Turton & Ashton, 2007; van der Merwe-Botha, 2009). Higher rainfall and intensifying precipitation will increase the suspended solids (turbidity) and pollutants that wash into rivers as a result of fluvial erosion. This will in turn contribute to the possible sedimentation of water bodies and contribute to water pollution within the specific catchment (Stolz, 2018). The occurrence of nutrient loading and eutrophication, which is already high in South African rivers is also set to increase. Additional nutrient loading as well as cyanobacteria blooms will lead to progressive outbreaks in health-associated risks which will negatively impact the human and animal populations. The rural communities will bear the brunt of the impacts because of their reliance on river water resources in terms of agricultural practices, consumption as well as other livelihood needs (Stolz, 2018; du Plessis, 2019). This in turn means that all pollutants and effluents will increasingly need to be treated to ever higher standards before being discharged into communal waters (van der Merwe-Botha, 2009).

As mentioned previously, climate change will also influence the region's biodiversity. Dallas et al. (2019) reported that preliminary data - from research which aimed to assess the effects of climate change on a certain freshwater fish - indicated that non-thermal variables such as flow, habitat complexity, DO concentration and conductivity could be important determinants of the distribution of native fish species. Low flows are also accompanied with a variety of consequences for water quality and the functioning of riverine ecosystems. South African freshwater resources used for fishing may experience a decrease in fish yields due to a disruption to their natural reproduction cycles due to effects of climate change. Benthic macroinvertebrate communities are also sensitive to the adverse effects of reduced river flow and subsequent water quality changes and can therefore be at increased risk in regions where a decrease in rainfall is predicted (Enoch, 2018).

Increased surface water temperatures accompanied with climate change may result in alterations to the water-gas equilibrium, increasing the speed at which microbial processes take place and accelerating nitrification, denitrification, respiration and methanogenesis (the production of methane by anaerobic bacteria) (Griffin et al., 2014). Changes in water temperature can therefore have significant effects on aquatic life in rivers (Ashton & Dabrowski, 2011). Changes in water temperatures and flows negatively affect aquatic life, increase waterborne and vector-borne diseases, cause the extinction of vulnerable species, shift species distribution and range, and change the biodiversity composition of an area. For instance, a 2°C increase in temperature may increase the occurrence of pest species such as the blackfly by more than twentyfold per annum. These pests thrive under certain flow and temperature conditions and attack livestock such as sheep. In this regard, they can cause major livestock losses currently calculated to exceed R500 million per annum (Dallas et al., 2019; van Vuuren, 2020).

Each aquatic organism has adapted to an optimal temperature range. Poikilothermic organisms (organisms whose internal body temperature varies considerably) are highly susceptible to variations in temperature and rely on these variations as behavioural cues (e.g.: feeding and reproduction). Other organisms are more tolerant to thermal fluctuations. Organisms living in freshwater with high temperatures and reduced DO contents often show adaptions to their respiratory systems (Baker & Greenfield, 2019). Baker and Greenfield (2019) found that the highly sensitive *Elassoneuria sp. (Oligoneuriidae)* sampled in the Mogalakwena and Limpopo rivers during high flow sampling season provides an example of such an adaptation. This particular species of mayfly has large gills which are ideal for the absorption of DO from the surrounding environment. Differences in temperature between the low flow and high flow seasons therefore influence the macroinvertebrate community assemblages present because each organism specifically adapts to an optimal temperature range. Therefore, depending on the level and length of the fluctuation in temperatures resulting from climate change, these changes could shift macroinvertebrate community assemblage composition more permanently (Baker & Greenfield, 2019).

In conclusion, South Africa has undergone significant reform in terms of how it manages its water reserves, yet its freshwater resources are prone to multiple water quality issues, over-utilisation, and high losses. The country is also one of those on the “wrong side” of the global annual average rainfall and experiences long, severe periods of drought. Due to most the country’s water resources already being allocated for use, it may result in the increased occurrence of widespread water use restrictions being enforced, despite significant transfers between basins and from Lesotho. By 2030, the major cities in South Africa are expected to face severe water supply gaps. This will be brought about in large part due to the predicted impacts of climate change.

South Africa has well established standards and pollution controls, however, climate change may become a determining factor when it comes to the future quality of the country’s water resources. Already, climate change is set to cause significant stress to freshwater ecosystems and aquatic biodiversity. Changes to water temperatures and the flow of rivers is likely to not only bring about the displacement of people and challenge food security; it will also contribute to more severe fluctuations in the dilution capacity of rivers, which help control pollution, and encourage the growth of harmful algal blooms through reduced DO content. Under these conditions, freshwater fish and macroinvertebrates may struggle to adapt, bringing about a higher extinction rate and a shift in the composition of these ecosystems and will be accompanied with an increase in water-related health issues for the affected population. Climate change is therefore an important aspect which requires more research so that suitable informed actions and adaptations are made to ensure water security within the already water stressed country. A discussion of the country’s primary water quality challenges now follows.

3.4. Water Quality in South Africa

Long-term data currently indicates that the water quality of South Africa’s surface waters has drastically declined over the past two decades (Donnenfeld et al., 2018). In some parts of the country, the health risks to humans, livestock and ecosystems are already being experienced (WWF, 2016). Only 16% of the country’s water sources are legally protected or managed in conservation areas, while the remaining 84% are subject to ongoing pollution and abstraction which is detrimental to the environment and human health (du Plessis, 2019).

Pathogens, minerals, and chemical contaminants are all significant emerging threats to freshwater quality. These threats are largely driven by the dilution capacity of water resources, poorly planned spatial development, historic socio-economic legacies and, in the longer term, climate change. There is further concern for the functioning of wastewater treatment and a lack of clarity surrounding water quality and infrastructure in the country (van der Merwe-Botha, 2009; Edokpayi et al., 2017).

Approximately 7.6 million m³ of wastewater is produced daily in South Africa. Most of this enters rivers through effluent discharge and runoff from mining, industry, agriculture and human settlements. To prevent further pollution and address current pollution levels, the country needs to reconsider how it manages its water resources (RSC, 2010; WWF, 2016; Enoch, 2018; du Plessis, 2019).

There are various chemical, biological, and physical parameters that can be used to describe the quality of water (Edokpayi et al., 2017). While measurements of these parameters do not provide continuous data, they do provide a "snapshot" of the water quality at a particular time and place which helps determine whether it is fit for a particular use. The various water quality issues arising in part from excessive concentrations of these constituents are discussed in the sections that follow. Some of the main water quality issues in South Africa include:

- Elevated concentrations of nutrients leading to excess algal growth and deoxygenation of water. This process is called eutrophication and is primarily caused by runoff from agricultural land and discharge from WWTWs;
- AMD which can be diffuse or point source from both active and abandoned mines;
- The continued discharge of micropollutants and heavy metals from industry;
- Increasing salinity due to saline intrusion into groundwater in coastal areas as well as excess salts due to the natural or anthropogenic addition of inorganic ions and;
- Sedimentation and siltation from deforestation, extreme rainfall events and engineering projects (RSC, 2010).

Such changes to the quality of freshwater in South Africa will necessitate costly investments in additional WWTWs and technologies (Turton, 2008; Donnenfeld et al., 2018). A description of the primary causes contributing to the continued degradation of the country's water resources as well as the main accompanied impacts or consequences thereof now follows.

3.4.1. Primary Causes of Water Quality Degradation in South Africa

Water quality can be impacted by contaminants from both point and non-point (diffuse) sources. Point sources are usually easy to identify and regulate, while non-point sources are more difficult to manage (Enoch, 2018). Examples of point source pollution include sewage effluent, industrial effluent, power generation, and mining decant (SADC, 2008; du Plessis, 2014; WWF, 2016; du Plessis, 2019). Examples of non-point or diffuse pollution include natural types of pollution, storm water runoff, agricultural activities, and leaching from landfills, soil erosion, and mining (SADC, 2008). Wastewater can contain various pollutants such as microorganisms, heavy metals, nutrients, radionuclides, and pharmaceuticals which all cause irreversible damage to aquatic ecosystems (Edokpayi et al., 2017). Various drivers including increasing urbanisation, population growth, and a growing industry and agricultural sector have led to an increase in the amount of discharge and type of pollutants in South Africa (SADC, 2008). According to the WWF (2016), water quality problems associated with non-point sources such as fertilisers and point sources such as mining and wastewater effluent, are the second largest threat to freshwater biodiversity in South Africa.

Rapid urbanisation is a major challenge for municipalities across the country. Migration to areas such as Johannesburg and Tshwane are still occurring at a faster rate than water and sanitation services can be developed and/ or upgraded or expanded (SADC, 2008; DWA, 2010b). According to Edokpayi et al. (2017), most cities in developing countries produce approximately 30 to 70 mm^3 of wastewater per person per annum, and less than half of all South African WWTWs treat wastewater to a safe and acceptable level. The resultant discharge of untreated sewage and industrial waste ultimately ends up in the country's water sources (SADC, 2008; DWA, 2010b). A large portion of South Africa's sewage, particularly in dense urban areas, is not treated properly prior to being discharged (Oberholster & Ashton, 2008; Donnenfeld et al., 2018). Untreated or inadequately treated human effluents contain pathogens, organic matter and chemicals that introduce excessive phosphates, nutrients, and coliforms into freshwater, negatively impacting both human and ecosystems' health. Many of these pollutants cause degradation processes that use up the available DO in water, reducing the amount of oxygen available for aquatic respiration, which can lead to anoxia (complete deoxygenation) and a reduction in aquatic biodiversity. Few organisms can survive in these conditions, and this water also becomes unsuitable for human consumption (UNEP, 2016). According to the DWS Green Drop Watch Report, many of the country's WWTWs are non-compliant with the set discharge standards (DWA, 2010b; DWS, 2023a; DWS, 2023b). DO levels below 5 mg/ℓ adversely affect aquatic ecosystems, and WWTW effluents in South Africa are usually lower than the required standard of 8 - 10 mg/ℓ (Edokpayi et al., 2017). Ongoing urban expansion as well as continued rural-urban migration will be accompanied by the further degradation of water resources because of increased municipal waste and will make the provision of water and sanitation an even greater challenge (du Plessis, 2019).

South Africa relies heavily on agriculture to ensure food security and support economic growth through exports. However, farming and forestry play one of the largest roles in terms of the burden placed on rivers through both pollution (water quality) and abstraction (water flow) (Oberholster & Ashton, 2008). Often the abstraction of water from rivers for irrigation substantially reduces the available surface water flows and contributes to declining water quality by returning contaminated water to rivers (UNEP, 2016; Enoch, 2018). This is largely the result of inefficient practices, however the excessive use of fertilisers and pesticides on croplands and plantations is a growing problem in various catchments, and as such there is a need to improve knowledge and technologies that can help to mitigate this. Agricultural runoff is especially concerning in areas where agricultural activities take place near and within river flood zones as fertilisers and pesticides contribute to nutrient enrichment in rivers and negatively impact aquatic life (de Villiers & Thiart, 2007; DWA, 2010b; van Vuuren, 2013; WWF, 2016; Enoch 2018; du Plessis, 2019). In most water bodies, nutrients such as phosphorus and nitrogen are low, arising mostly from the leaching of minerals. Higher levels of these nutrients indicate the impacts of human activities such as farming and cause eutrophication, the growth of nuisance plants and other changes in the structure of aquatic ecosystems (UNEP, 2016).

Agricultural activities also cause increased sedimentation and siltation of waterways by promoting soil erosion (du Plessis, 2019). Rivers in agricultural areas are often physically altered to regulate water supply and prevent damage from floods which compromises the vital riparian vegetation zone. This zone is necessary for riverbank stabilisation and nutrient cycling in the river, however, the dysfunction brought about by man-made alterations results in sedimentation which fills pools of water downstream impacting sensitive species such as the indigenous rock catfish (van Vuuren, 2013;

WWF, 2016). In 2007, the raising of the Massingir Dam wall caused the flooding of Olifants River Gorge inside the KNP, stimulating the deposition of large quantities of suspended sediments. Increased fish and Nile Crocodile deaths were noticed shortly after this occurrence. The crocodiles appeared to have contracted pansteatitis from eating fish which had contracted the disease. Although the cause-effect relationship has not yet been verified, it is thought that the accumulation of sediment deposits, containing high concentrations of adsorbed ionic and organic constituents, are the primary cause for the largescale Nile Crocodile deaths in the relevant catchment (Ashton & Dabrowski, 2011).

As long ago as the 1970s, it was acknowledged that aquatic environments worldwide are being negatively impacted upon primarily by the discharge of industrial waste products containing metals and chemical compounds (UNEP, 2016). A large amount of industrial development has taken place in South Africa over the past century, and since it is a developing country, this will continue to be the case. Some industrial activities have been found to be responsible for the discharge of hazardous chemicals and waste products into sewers, wetlands, and rivers (Oberholster & Ashton, 2008). As industries expand, the country can expect to experience an increase in contaminants that are typical of industrial output such as salts, endocrine disruptors, cyanobacteria, carcinogens, heavy metals, and radionuclides (Barker, 2006; Turton, 2008). The production and use of energy, interlinked with mining, adds another dimension to industrial pollution. Increasing emissions from power stations will result in higher sulphur and nitrogen oxide contents in the atmosphere which ultimately enter watercourses through acid rain (Marr et al., 2017b; du Plessis, 2019).

The main impacts of these pollutants have been observed in the aquatic food chain as well as predatory animals and birds (UNEP, 2016). A recent example of such impacts is the extensively studied Nile Crocodile deaths in the Olifants River Gorge circa 2007/2008. Over 170 Nile Crocodile fatalities were recorded inside the KNP, and populations throughout the catchment declined. The initial die-off of these keystone predator species is said to have been largely influenced by elevated heavy metal concentrations such as aluminium and iron deposited in the gorge through silts and clays. It has since been postulated by numerous studies that the die-offs were reflective of the overall degradation of the Olifants River catchment (Ashton & Dabrowski, 2011; Ferreira & Pienaar, 2011; Mirzabaev et al., 2019). Whilst the focus has mostly been on the environmental impacts, studies have also recorded significant human health risks mainly related to the consumption of fish in the Olifants River that have been affected by the bioaccumulation of heavy metals (Riddell et al., 2019a).

Mining, one of South Africa's oldest and most renowned economic sectors, has contributed to the foreign exchange earnings of the country for more than a century (Ashton et al., 2001). However, it is also a sector that comes with extensive environmental degradation due to the costs of addressing it and it being a persistent source of pollution even after mines have closed (Griffin et al., 2014). Mining activities disrupt the surface and subsoils, surface water, near-surface groundwater, fauna, flora and nearby land use practices (Ashton et al., 2001; DWA, 2010b; WWF, 2016). Decant from mine voids, mostly gold and coal, is highly contaminated containing high concentrations of sulphides, metals, and salts. Decant typically has low pH levels and high sulphate content as well as a mix of various heavy metals and radionuclides which pollute water resources particularly during the mine closure phase (du Plessis, 2019).

Approximately 10 000 km^2 of interconnected mines exist in Mpumalanga Province (Enoch, 2018). More than 50% of the Mpumalanga Province is currently being mined for coal or is under prospecting. This has caused widespread and significant damage to biodiversity in the province, and the implications are long lasting. The impacts of mining and industry on various catchments in South Africa have been investigated by Ashton et al. (2001) and Ashton and Dabrowski (2011) in detail. Their research indicated that mining operations in areas of the Limpopo and Olifants River catchments that experience low rainfall have relatively low and localised impacts on water quality, while those located in areas with higher rainfall have much more extensive impacts due to the continuous chemical reactions and the increased mobilisation of contaminants (Ashton et al., 2001). The data showed that water quality in these catchments had progressively worsened due to the entry of AMD into river systems (Ashton & Dabrowski, 2011). Polluting of nearby water sources can last for decades to centuries due to the chemical reaction that causes AMD. This source of pollution can be very persistent, causing some sites to possibly never fully be restored without costly restoration and treatment (WWF, 2016; Enoch, 2018; du Plessis, 2019).

3.4.2. Primary Impacts of Pollution

The quality of freshwater in many South African water courses has often been described as "too dirty". Water pollution causing this "dirty" water in South Africa stems from the aforementioned sources, which have differing impacts depending on the surrounding land uses, the pre-existing natural state of the local environment and the water body (van der Merwe-Botha, 2009). The continuous addition of pollutants renders the quality of the water poor enough that, against certain standards, it becomes unfit for use, causes a variety of health issues, and disrupts economic activity. The main threats to water quality country-wide relate to the following primary issues:

- Salinisation;
- Eutrophication;
- Sedimentation;
- Acidification and,
- Microbial contamination
  (van der Merwe-Botha, 2009; DWA, 2010b; DEA, 2012)

Marr et al. (2017a) states that reduced river flows, high sediment loads, regular discharges of raw sewage wastewater, elevated nutrient levels and the presence of heavy metals have also been reported in the Lowveld rivers that flow to the KNP, the study area of this research. These processes and pollutants give rise to the mentioned primary water quality problems within the country. A brief discussion of each now follows.

3.4.2.1. Salinisation

The DEA (2012) considers salinisation to be a persistent water quality problem in most freshwater resources in South Africa. Salinisation is the process whereby freshwater becomes extremely saline due to the addition of various types of inorganic salts. Salinity can refer to any inorganic ions, but usually it results from Na^+ (Sodium), Ca^{2+} (Calcium), Mg^{2+} (Magnesium), K^+ (Potassium), Cl^- (Chloride), SO_4^{2-} (Sulphate), CO_3^{2-} (Carbonate), and HCO_3^- (Bicarbonate), or combinations thereof depending on the source. Salinity can be determined by the amount of Total Dissolved Solids (TDS) found in a water body (du Plessis, 2019). Salinity levels are naturally low in rivers in areas underlain by granite, while in drainage basins with clay soils, where weathering is higher, water salinity tends to be proportionately higher (UNEP, 2016; Cañedo-Argüelles et al., 2019). Salinisation occurs naturally in coastal regions, as rivers acquire salts when mixing with tidal waters or from precipitation containing sea salt. Natural sources of salt in inland waters include mineral weathering from the underlying geology and rainfall. Therefore, even without anthropogenic inputs, some rivers are naturally more saline. When inland waters become saline however, it is usually the result of human activities. Anthropogenic changes to the salt content are thus usually a consequence of various land use practices, irrigation, effluent discharge, and brine water from mines (DEA, 2012; du Plessis, 2014).

Diffuse sources include urban settlements, municipal and mining waste, and pose the highest risk because their impacts are widespread (Griffin et al., 2014). High levels of TDS therefore cause significant limitations to the fitness of water for certain uses such as irrigation (du Plessis, 2019). When highly saline water is applied to some plants, such as the majority of food crops grown in South Africa, the salts interfere with the plants' uptake of water and often results in wilting (UNEP, 2016). High salinity levels also have negative impacts for aquatic ecosystems at various levels, generally because freshwater organisms have difficulty adapting to increased concentrations (specifically those that increase rapidly) and cause structural changes to aquatic biota communities (Griffin et al., 2014; UNEP, 2016).

Arid and semi-arid areas such as South Africa tend to experience more severe salinisation (UNEP, 2016). The recent Nile Crocodile deaths in the Olifants River may well be the result of such contaminated water released from mining areas in the Mpumalanga Province (van der Merwe-Botha, 2009; Cañedo-Argüelles et al., 2019; Riddell et al., 2019a). Mining and domestic effluents are also associated with elevated sulphate concentrations in rivers, which cause salinity. Several invertebrate species are sensitive to increased sulphate with their occurrences declining as sulphate levels rise (Kleynhans et al., 2015). The annual median sulphate concentration in the Olifants River has increased at a rate of as much as 2.76 mg/ℓ per annum in some parts of the river and is one of the growing concerns for human populations downstream as well as the KNP (de Villiers & Mkwelo, 2009; Marr et al., 2017a).

3.4.2.2. Eutrophication

In their natural state, most water bodies contain low levels of nutrients such as nitrogen and phosphorus that arise from the leaching of minerals and from decomposing matter. Higher levels of these nutrients are indicative of human impacts, particularly fertiliser from agricultural runoff and the discharge of sewage (van der Merwe-Botha, 2009; Paerl et al., 2011; UNEP, 2016). In South Africa, WWTWs have been designed to eliminate nitrogen from wastewater, however phosphates usually go largely untreated. Due to South African rivers being characterised by low levels of phosphorus in their natural states, this nutrient quickly alters the functioning of river systems. South African rivers are capable of assimilating and buffering elevated nitrogen levels to a certain degree, but phosphates are not assimilated in the same way (WWF, 2016). When water systems become enriched with nutrients, they can become eutrophied (de Villiers & Thiart, 2007; Paerl et al., 2011; DEA, 2012). This increases the primary productivity (consumption of oxygen) to excessive levels, encouraging the growth of vascular plants such as harmful algal blooms and water hyacinth, and leading to a depletion of DO. Eutrophication is the most widespread freshwater problem worldwide, as well as in South Africa where one third of water bodies are eutrophic (de Villiers & Thiart, 2007; Paerl et al., 2011; Turton, 2012).

The proliferation of harmful cyanobacterial algal blooms (CyanoHABs) resulting from nutrient enrichment are a serious threat to the sustainability of water resources worldwide because they alter food-webs and are hypoxia-generating. CyanoHABS are expanding internationally and now threaten some of the biggest and most important water resources across the globe (Paerl et al., 2011). Cyanobacterial blooms have also been recorded in most of the rivers and reservoirs in South Africa as a result of excessive additions of inadequately treated wastewater containing nutrients such as nitrogen and phosphorus. Where eutrophication occurs in these rivers, the dominant phytoplankton genera are mostly cyanobacteria *Microcystic spp* and *Anabaena spp* (DWAF, 1996a; Oberholster & Ashton, 2008). These Microcystins are a highly toxic range of chemicals (de Villiers & Thiart, 2007; Oberholster & Ashton, 2008; Oberholster et al., 2009; Turton, 2012; WWF, 2016; du Plessis, 2019). Under extreme conditions, Microcystins have been responsible for extensive kills of both invertebrates and fish (de Villiers & Thiart, 2007; WWF, 2016). Cyanobacterial poisoning resulting in fatalities in South Africa are widespread, but thus far have only affected livestock, domestic animals and wildlife (Oberholster & Ashton, 2008; Paerl et al., 2011). Wildlife deaths in the KNP, as well as cancer and other medical ailments have been linked with the presence of Microcystins. Toxins associated with eutrophic waters have recently been found in produce irrigated with such water (Oberholster et al., 2009; Turton, 2012).

The Olifants River, one of South Africa's key rivers, has a high level of eutrophication in its upper catchment. Elevated nutrients in the river and its dams result in downstream areas receiving polluted water that affects wildlife (WWF, 2016). The international implications of eutrophication arise when substandard water affects downstream riparian states, for instance in Mozambique (which is already receiving doses of eutrophic water from the Limpopo River) and Swaziland (Turton, 2012). Paerl et al. (2011) states that changing climatic conditions, such as temperature increases and altered rainfall patterns, will play a large role in nutrient enrichment issues such as eutrophication in the foreseeable future. CyanoHABs are likely to favour these changes; in particular, a rise in water temperature can create a positive feedback loop that perpetuates further CyanoHAB growth. Oberholster and Ashton (2008) note that high evaporation rates, which will increase with climate change, coupled with high nutrient loadings, which will increase with socio-economic development, lead to rapid rates of eutrophication due to the increased retention of nutrient loadings within the waterbody and its sediments.

Climatic changes, particularly warming, will play an interactive role in modulating the frequency, intensity, geographic distribution, and duration of CyanoHABS. The photosynthetic potential of CyanoHABS is furthermore determined by the amount of atmospheric CO_2. Therefore, increasing CO_2 emissions may result in the increased intensity of certain CyanoHABS. Consequently, understanding and managing the climatic drivers of CyanoHABS is a major challenge to ensuring the preservation and sustainability of all water bodies (Paerl et al., 2011). Lastly, the growth of algal blooms exacerbates other water quality and quantity issues. The turbidity of water, faunal and floral biomass and sedimentation usually increase, while species diversity decreases. Anoxic conditions may develop which promotes a favourable habitat for certain species, leading to a change in the dominant species of the aquatic biota (Edokpayi et al., 2017).

3.4.2.3. Sedimentation

The natural occurrence of soil erosion does not in itself threaten freshwater ecosystems (Enoch, 2018). However, sedimentation occurs mainly as a result of soil eroding into rivers due to poor land use practices, the majority of which occurs in the agricultural sector. Runoff carries excess soils into rivers, increasing their sediment load (du Plessis, 2014). The annual soil loss in South Africa is estimated at 300 to 400 million tonnes and is therefore a serious environmental concern. The main impacts of sedimentation include a reduction in dam storage capacity, increased water treatment costs, turbidity, and the disruption of aquatic biodiversity (du Plessis, 2014; du Plessis, 2019). For instance, the large dam feeding Bloemfontein is almost 90% full of silt, leaving only 10% for water storage. This has major implications for the economy and human livelihoods during times of drought (Turton, 2012).

Additionally, sediment loads carried by rivers negatively affect the functioning of aquatic ecosystems as is evident in the Olifants River. The Olifants River receives very high sediment loads due to poor land use practices and severe erosion just outside of the KNP boundaries. The resulting turbidity affects the growth of aquatic species and causes respiratory issues in fish and invertebrates (Gerber et al., 2015). Lastly, soils entering rivers carry with them various contaminants such as pesticides and fertilisers, which are released into the water body and compound the polluting effect of sedimentation (Enoch, 2018).

3.4.2.4. Acidification

The biological health of a water system is determined in part by its acidity or pH level. When pH levels decrease to between 3.5 and 5.6, a water system is acidic (Oberholster et al., 2017). Surface waters with calcium carbonate values of less than 10 mg/ℓ are acid sensitive (Oberholster et al., 2017). The acidification of waterways is a global water quality issue usually resulting from excessive nutrient loads and contamination by heavy metals and acid rain (UNEP, 2016; Oberholster et al., 2017).

Acidification has systemically degraded several rivers in South Africa such as the Olifants River and Limpopo River systems (Marr et al., 2017b). In the Olifants River catchment, AMD and acid precipitation were the two main causes of possible acidification that were noted during a four-year study period. In this catchment, abandoned and spontaneous combusting mines are contributing around 50 Mℓ/d of mostly untreated AMD into surface waters (Oberholster et al., 2017). Low pH levels adversely affect aquatic ecosystems in terms of their structure and ability to function naturally. Young organisms are less tolerant to heightened acidification and are affected more severely. The toxicity resulting from acidification poses serious health threats to both aquatic organisms and people consuming them as food (Barker, 2006; du Plessis, 2014; Oberholster et al., 2017).

3.4.2.5. Microbial Pollution

Microbial pollution occurs when human and animal faecal matter containing micro-organisms enters waterways. A very small amount of faecal matter contains millions of micro-organisms, some of which are pathogenic. This form of pollution has increased over the past decades, largely due to the expansion of sewage systems in the developing world (UNEP, 2016). Even though it is well known that pathogens can cause disease, untreated wastewaters are consistently discharged into South African rivers and water bodies. Increasing urbanisation and the lack of adequate sanitation services in both rural and urban areas is the major cause of microbial pollution (DEA, 2012; du Plessis, 2014).

Sewage can be discharged deliberately through sanitation infrastructure or open defecation, or inadvertently through runoff and combined sewage overflows during rainfall events. Various coliform indicators, such as *E. coli*, are used to detect the level of faecal contamination in water courses. Microbial pollution is increasing in South Africa due to expanding human settlements, inadequate sanitation provision, increasing runoff from impermeable surfaces and will be amplified by the inability of local municipalities to cope with larger sewage loads as migration to cities increases (du Plessis, 2014).

In summary, the quality of freshwater in many South African water courses is directly impacted by the continuous addition of multiple pollutants from surrounding land use. This results in serious challenges for these water resources including salinisation, eutrophication, sedimentation, acidification, and microbial contamination which render water unsuitable for certain uses without proper treatment. Furthermore, water resources contaminated in the aforementioned ways have negative impacts for aquatic ecosystems because freshwater organisms have difficulty adapting to increased concentrations, and often result in structural changes to aquatic biota communities. Ultimately these changes have downstream impacts for biodiversity, and severely affect conservation areas such as the KNP. The various water quality parameters which are used to indicate the types of pollutants present in a water course in South Africa are discussed in the following section.

3.4.3. Target Water Quality Ranges for Constituents as Indicators of Water Quality in South Africa

Various water quality constituents can be used to measure the water quality of a freshwater resource at a given point and time. When the concentration guideline is exceeded for any one or multiple constituents, it is possible that a potential environmental impact will occur, and therefore prompt a management response (van Dam et al., 2010).

Some of the typical water quality problems caused by the different land use sectors in a catchment include domestic, industrial, mining, forestry, and irrigation impacts (Table 3.1).

Table 3.1: Typical water quality problems and constituents associated with different types of land use (Adapted from: Ashton et al., 1995).

Land Use	Water quality problems caused / constituents elevated

Domestic	Ionised ammonia (NH_4^+); Chloride (Cl^-)
Industrial	Ionised ammonia (NH_4^+); Chloride (Cl^-); Manganese (Mn), Sulphate (SO_4)
Mining	Arsenic (As); Zinc (Zn); Sulphate (SO_4), TDS; pH
Forestry	pH; Aluminium (Al); Iron (Fe); Manganese (Mn), Potassium (K); Total Suspended Solids (TSS)
Irrigation	TDS; TSS; Chloride (Cl^-), Sodium (Na); Nitrate (NO_3)

The South African Water Quality Guidelines are the primary sources of information for determining the water quality requirements for Domestic Use (Volume 1), Recreational Use (Volume 2), Irrigation (Volume 4) and Aquatic Ecosystems (Volume 6) (DWAF, 1996a; DWAF, 1996b; DWAF, 1996c; DWAF, 1996d). These Target Water Quality Ranges (TWQRs) for each parameter are included in Appendix III. The parameters used for this research were chosen to cover a variety of physical, chemical and biological water quality issues that could be analysed spatially, temporally and in conjunction with other influencing factors such as the regional climate variability (rainfall and temperature), and river flow, and which would point to any possible causes of poor water quality in the study area (DWAF, 1996a; Edokpayi et al. 2017). The water quality parameters specifically selected for this research includes the following:

- **Physical Parameters:** EC and pH;
- **Chemical Parameters:** ammonia (NH_4), calcium (Ca), chloride (Cl), magnesium (Mg), nitrate (NO_3), phosphate (PO_4), sodium (Na), and sulphate (SO_4); and
- **Biological / Microbial Parameters:** *Escherichia coli* (*E. coli*).

These selected water quality parameters, and their primary effects on the quality of water resources, are briefly discussed.

3.4.3.1. Electrical Conductivity

Electrical Conductivity (EC) is described as the measurement used to determine the ability of water to conduct an electrical current due to the presence of various electrically charged ions (e.g.: carbonate, bicarbonate, chloride, sulphate, nitrate, sodium, potassium, calcium, and magnesium). Organic compounds dissolved in water do not usually affect EC as they do not ionise (DWAF, 1996a; DWAF, 1996c; DWAF, 1996d). The TDS of a water body is directly proportional to the EC; therefore EC is regularly used as an estimate of the TDS concentration (DWAF, 1996a). EC is therefore sensitive to variations in the concentration of various dissolved solids (du Plessis, 2014).

Mineral weathering rocks, leaching of soils and decomposition of plant material are natural sources of TDS (DWAF, 1996c). Changes to the TDS / EC, where EC is high, can affect the physiological functioning of aquatic organisms. These changes may affect the adaption of individual species, the structure of their communities and disrupt microbial and ecological processes (du Plessis, 2014; Singh et al., 2019). TDS tends to increase further downstream because of the addition of salts through natural and anthropogenic sources. Anthropogenic sources include domestic and industrial effluent and urban, industrial and cultivated surface area runoff (DWAF, 1996a).

Irrigation water with a high TDS will introduce salt into the soil profile, which may result in the accumulation of salts forming a saline soil. Crop yield is often reduced for crops grown in saline soils, because of their sensitivity to soil salinity. Under extremely saline conditions, crops cannot be grown successfully (DWAF, 1996c). It is essential to monitor EC as a water quality parameter, especially in water resources which supply conservation areas as high TDS levels result in increases in salinity which changes the ionic composition of water. The toxicity of individual ions may therefore also change, causing shifts in biotic communities and reducing more sensitive species, thereby reducing biodiversity (Weber-Scannell & Duffy, 2007; Singh et al., 2019).

3.4.3.2. pH

pH measures the hydrogen activity of a water sample (DWAF, 1996d). The complex acid-base equilibrium of various dissolved compounds (mainly the carbon dioxide-bicarbonate-carbonate equilibrium) determines the pH of natural waters. Where conditions create a favourable environment to produce hydrogen ions, a low pH occurs, whereas an environment favourable to the neutralisation of hydrogen ions results in an increase in pH levels. Most raw water sources have a pH of approximately 6.5 to 8.5 (DWAF 1996a). pH may be influenced by the geology and geochemistry of the underlying rocks and soils. Biological activities such as nutrient cycling and anthropogenic activities such as the discharge of industrial effluent may cause pH fluctuations. AMD is one of the biggest influences on pH (DWAF, 1996a).

The pH of surface water is particularly important for aquatic ecosystems. The presence of other compounds may also influence or be influenced by pH. For instance, at a high pH, ammonia is dissociated in its toxic un-ionized form. At low pH levels, the ability of fish to take up oxygen is compromised, and other deleterious effects on fish physiology occur. Exceptionally low or high pH in rivers usually result from the discharge of domestic or industrial wastewater containing acidic or alkaline compounds (UNEP, 2016). pH varies both diurnally due to variations in the relative photosynthesis and respiration rates; and seasonally as a result of the hydrological cycle (DWAF, 1996d).

Measuring the pH of a water body is critical for the health of freshwater fishes. While pH is predominantly determined by the surrounding geology, anthropogenic additions, for example AMD, can cause increased acidity which has negative physiological impacts on various fish species. Acidification can also increase the heavy metal content of a water body which has been found to reduce the survival and growth of larvae and lead to premature fish mortality (du Plessis, 2019).

3.4.3.3. Ammonia (NH_3)

Ammonia is naturally present in small amounts in the air, soil and water. Un-ionized ammonia is a gas produced naturally by the aerobic and anaerobic decomposition of organic material / nitrogenous matter. The un-ionized form of ammonia (NH_3) is toxic to aquatic biota, while the ionized form (NH_4^+) is not toxic but increases the risk of eutrophication. Both forms of ammonia are reduced forms of inorganic nitrogen. Ammonia is a common pollutant derived largely from commercial fertilizers containing ammonia and ammonium salts. Other sources of ammonia include sewage effluent discharge, discharge from industries that use ammonia in their cleaning operations, manufacturers of explosives, and atmospheric deposition from coal combustion (DWAF, 1996d).

pH and temperature are important determinants of the level of toxicity of ammonia (DWAF, 1996a; DWAF 1996d). Ammonia is more toxic under alkaline conditions than neutral conditions. Under more acidic conditions, ammonia toxicity is fairly low. Freshwater which is not contaminated with organic waste usually has a low ammonia concentration of less than 0.2 mg/ℓ, while untreated sewage may have concentrations exceeding 10 mg/ℓ due to organic decomposition under anaerobic conditions (DWAF, 1996a). Un-ionized ammonia is the most toxic form of inorganic nitrogen to aquatic biota (de Villiers & Thiart, 2007).

The monitoring of ammonia in freshwater is thus critical due to the aforementioned toxicity to aquatic biota. Ammonia is a toxicant which is not readily excreted by aquatic organisms and readily builds up in the internal tissues and blood, eventually causing death (EPA, 2013).

3.4.3.4. Calcium (Ca^{2+})

Calcium is a double positively charged ion and alkaline earth metal that occurs naturally in most waters. Mineral deposits of calcium are usually found as calcium carbonate, phosphate or sulphate. pH and temperature influence the carbonate/bicarbonate equilibrium of calcium which governs solubility. Typical calcium concentrations of approximately 15 mg/ℓ occur in freshwater. Calcium should usually be analysed in conjunction with its major associated anions of chloride, magnesium, sodium, and potassium. Water hardness is determined by the concentrations of calcium and magnesium present in freshwater (DWAF, 1996a).

Calcium occurs naturally in freshwater due to the weathering of rocks, and through soil seepage, leaching and other runoffs. The largest anthropogenic contributor of calcium is the industrial sector where calcium oxide is used in the production of building materials, in paper production and sugar and petroleum refinement (du Plessis, 2014).

Calcium has been indicated to be an essential mineral for the health of aquatic species. Critically low levels of calcium inhibit the growth, reproduction, and survival of calcium demanding organisms such as mussels, snails, crustacean zooplankton and crayfish. Changing calcium levels may thus affect the composition of freshwater communities. Furthermore, calcium is a carbonate which partially governs the pH of a water body and controls carbon cycling, thus when present in excessive amounts in freshwaters, calcium may contribute to acidity (Weyhenmeyer et al., 2019).

3.4.3.5. Chloride (Cl^-)

Chloride is the anion of the element chlorine, which does not occur naturally in the aquatic environment. Sodium, potassium, calcium, and magnesium chloride are soluble in water. Once in solution, it tends to accumulate. Although chloride itself is important for the functioning of freshwater habitats, high levels can have negative effects (University of Minnesota Morris, 2013). Agricultural return flows, sewage effluent discharge and various industrial processes are responsible for the accumulation of chloride in surface water (DWAF, 1996a).

Free forms of chlorine such as hypochlorous acid (HOCl) and hypochlorite (OCl-), or combined available chlorine (chloramines), occur in aquatic ecosystems due to a variety of reasons (DWAF, 1996d). Elevated chloride concentrations are primarily derived from a set of factors such as saline soils and groundwater, which have occurred due to both natural and anthropogenic factors. Irrigation and the removal of natural vegetation contribute to secondary salinisation in South Africa (Huizenga, 2011). Removing unwanted tastes and odours in drinking water through chlorination, bleaching of paper and textiles, sewage treatment, and the maintaining of swimming pools all produce wastewater containing chlorine (DWAF, 1996d).

Chlorine can react with a variety of organic substances to form compounds which may be harmful to aquatic biota (DWAF, 1996d). When the anion chloride is present in the freshwater ecosystem in high quantities it may interfere with osmoregulation (biological process which enables them to retain the correct salt concentrations in their bodily fluids) and is thus harmful to aquatic species as it can hinder survival, growth, and reproduction (Hunt et al., 2012). Chloride in freshwater ecosystems therefore should be monitored regularly.

3.4.3.6. Magnesium (Mg^{2+})

Magnesium is a common water constituent which occurs as a double positively charged magnesium ion and is an alkaline earth metal. Like calcium, the pH governs the carbonate/bicarbonate equilibrium, which is responsible for the solubility of magnesium in water. Magnesium is an essential nutritional element in a normal human diet and is also an essential element for plants. In freshwater, the concentration of magnesium is typically 4 - 10 mg/ℓ. Magnesium interacts with calcium and with various anions and organic acids, and therefore mean values should be interpreted with associated anions, calcium, sodium, and potassium concentrations (DWAF, 1996a).

While magnesium controls biological processes in freshwater organisms associated with protein synthesis, enzyme activation, energy transfer and cellular homeostasis, when present in high quantities in conjunction with calcium or sulphate it can approach levels which are toxic to these organisms. Additionally, magnesium is the central atom in the *Chlorophyll* molecule and therefore essential for primary production of algae which can lead to the eutrophication of a water body (van Dam et al., 2010; Kimambo et al., 2019; Salman et al., 2023).

3.4.3.7. Nitrate (NO_3)

Nitrate is derived from the oxidation of ammonia or nitrite. Nitrate and nitrite occur together in the environment and interconvert readily. Together they form the oxyanions of nitrogen. Nitrates are naturally present in soils and in the aquatic environment because of their association with the breakdown of organic matter to form eutrophic conditions. They also result from the oxidation of animal and plant debris and animal and human excrement. Sewage wastewaters, even those that have been treated, contain elevated nitrate concentrations (DWAF, 1996a). It is seldom present in high concentrations in surface waters that are free from anthropogenic pollutants because it is usually converted into proteins and other organic forms by aquatic plants (DWAF, 1996d).

Surface runoff, the discharge of various effluents containing human and animal excrement, fertilisers and organic industrial wastes are the primary inputs of inorganic nitrogen. Inorganic nitrogen has a stimulatory effect on aquatic plant and algal growth and is therefore of primary concern to water resource management. Inorganic nitrogen concentrations in unimpacted, aerobic surface waters are usually below 0.5 mg N/R. Inorganic nitrogen may increase to above 5 - 10 mg N/R in highly enriched waters (DWAF, 1996d). Despite its vital role within all ecosystems, in high concentrations, nitrogen becomes toxic to aquatic life and is one of the primary causes of eutrophication (Baker & Greenfield, 2019).

Assessments of inorganic nitrogen concentrations should always be completed in conjunction with an evaluation of the inorganic nitrogen to inorganic phosphorus ratio (N: P ratio). The nitrogen-phosphorus ratio in unimpacted systems is typically greater than 25 - 40 : 1. Eutrophic or hypereutrophic systems (i.e. those impacted by inorganic nitrogen and phosphorus) tend to have a nitrogen-phosphorus ratio of less than 10 : 1. Nitrogen fixation is likely to occur and this low ratio, which will provide additional inorganic nitrogen to the system (DWAF, 1996d).The importance of monitoring both nitrate/nitrite and phosphorus is highlighted by the increasing incidence of eutrophication in surface freshwaters around the globe.

3.4.3.8. Orthophosphate (PO_4)

Phosphorus is an essential macronutrient for the growth of plants and animals (DWAF, 1996d; du Plessis, 2014). It occurs in numerous organic and inorganic forms but does not occur in its elemental form in the natural environment. Orthophosphates, polyphosphates, metaphosphates, pyrophosphates, and organically bound phosphates are the forms of phosphorus found in natural waters. Orthophosphate can be transformed into an available and useable form through natural processes by aquatic biota (DWAF, 1996d).

Decomposition and synthesis between organically bound forms and oxidised inorganic forms of phosphorus result in phosphorus changing forms in water continuously. This interaction is influenced by the physical, chemical, and biological modifying factors of the water body such as the pH level. In balanced freshwater environments, plants convert phosphorus into cell structures through photosynthetic action. Phosphorus is also considered to be the most important nutrient influencing eutrophication (DWAF, 1996d).

Phosphorus concentrations are usually relatively low in South Africa because of its uptake by plants, with average concentrations of between 10 and 50 mg/ℓ in unimpacted waters. Impacted waters may contain up to 200 mg/ℓ of total phosphorus (DWAF, 1996d). Significant amounts of phosphates are found in sewage and various other wastewaters such as agricultural runoff due to the use of phosphate containing fertilisers. They are also deposited into freshwater through precipitation. Weathered deposits of phosphorus-bearing rocks and decomposed organic matter naturally elevate the phosphorus content of freshwater resources (DWAF, 1996d; du Plessis, 2014). Therefore, the spatial variation of naturally occurring phosphorus is high because it relates directly to the underlying geology of a region. Continually high concentrations of inorganic phosphorus are more important than the occasional increase, and any assessment should be coupled with the ratio of inorganic nitrogen to inorganic phosphorus (DWAF, 1996d).

Because phosphorus can have significant impacts on the balance of freshwater systems, this water quality indicator is one of the most essential to monitor. Phosphorus can cause excess plankton to grow, which in turn cycles large amounts of organic material into the water body resulting in lower DO. Lowered DO levels result in stress for aquatic biota that require oxygen for respiration. In anoxic (deoxygenised) condition, few organisms can survive (du Plessis, 2019).

3.4.3.9. Sodium (Na)

Sodium is a ubiquitous alkali metal usually present in the natural environment as sodium chloride, but sometimes as sodium sulphate or bicarbonate. Sodium levels in freshwaters are usually low in areas of high rainfall and high in areas of low rainfall.

Sodium does not precipitate when water evaporates therefore arid areas tend to have waters with elevated concentrations (DWAF, 1996a; DWAF, 1996c).

Processes that give rise the anthropogenically elevated levels of sodium in freshwater include industrial wastes that create brines, domestic wastewater due to the use of table salt, and the recycling of water such as when runoff or leachates occur from irrigated soils (DWAF, 1996a; DWAF, 1996c).

Increased sodium concentrations in freshwaters are one of the causes of salinity. As previously mentioned, increased salinity can affect the ability of aquatic organisms to maintain an osmatic balance. Thus, species richness declines in most freshwater ecosystems as salinity levels increase and toxicity tests indicate that most freshwater species may be completely eradicated from a water body once a certain threshold of salinity is exceeded (Cañedo-Argüelles et al., 2019). As such, it is essential that all major ions relating to the level of salinity in a freshwater system are monitored on a regular basis.

3.4.3.10. Sulphate (SO_4)

Sulphate is a common water constituent which arises from the dissolution of mineral sulphates present in soil and rock (du Plessis, 2014). Most sulphates are soluble in water and calcium sulphate is partially soluble. When added to water sulphates tend to accumulate, progressively becoming increasingly concentrated. In freshwater, sulphates tend to be approximately 5 mg/ℓ (DWAF, 1996a).

When high levels of sulphates are found in the natural environment, they can usually be ascribed to anthropogenic contamination. Examples of sources of sulphates include AMD associated with coal and gold mining, atmospheric sulphate deposition into waters, and the use of fertilisers that contains gypsum (DWAF, 1996a; Huizenga, 2011; Nosrati, 2015; Zak et al., 2021). Dissolved sulphate emanating from mining activities derives from metal sulphides such pyrite from coal rich and precious metal deposits (de Villiers & Mkwelo, 2009). With the location of most of the country’s coal power stations in the Mpumalanga Province or Olifants WMA, it can be expected that this contributes to increased atmospheric sulphur levels which increases the sulphate concentrations in surface waters as a result of precipitation and fog deposition (de Villiers & Mkwelo, 2009; Huizenga, 2011).

Sulphate pollution requires ongoing monitoring as it may have toxic effects on aquatic plants and organisms as well as on human health. Copper sulphate is also highly toxic to fish and invertebrates (de Villiers & Mkwelo, 2009). Increased sulphate levels have negative implications for the structure and functioning of freshwater ecosystems, due to the effects of lowering pH levels and enhancing the mobilisation of heavy metals and other nutrients. Additionally, elevated sulphate concentrations might also alter nitrogen and phosphorus cycling and cause an imbalance to the nitrogen-phosphorus ratio as well as lower the pH level (Zak et al., 2021).

3.4.3.11. Faecal coliform (FC) - Escherichia coli (E. coli)

*Faecal coliform*s such as *Escherichia coli* (*E. coli*) are the most common indicators of bacterial pollution. The presence of *E. coli* is used to determine the presence of faecal matter by warm blooded animals. *Faecal coliform*s are usually enumerated as counts (number of colonies) / 100ml or CFU/ 100ml of water and mean values should be used to interpret the TWQR criteria (DWAF, 1996a). Bacterial pathogens can be transmitted via the faecal/oral route by contaminated or poorly treated drinking water. They can cause diseases such as gastroenteritis, salmonellosis, dysentery, cholera, and typhoid fever (DWAF, 1996a).

Faecal coliforms are usually a function of sewage pollution and are therefore used as an indication of microbial pollution in waste and raw waters. Sources of faecal pollution include not only raw sewage, but also agricultural runoff containing the faecal matter of mammals, and animal wastes deposited onto land and washed into waterways in runoff (du Plessis, 2014).

Aquatic ecosystems are sensitive to the impacts of *Faecal coliforms* because it leads to the nutrient enrichment of water and therefore the growth of algae and other nuisance plants. These plants use up all the oxygen in the water, causing fish in the aquatic ecosystem to die. The parameter as an indication of water pollution can also be associated with eutrophication (du Plessis, 2014). Due to the multiple sensitives related to this parameter, it is an essential indicator of freshwater health for both humans (drinking and bathing in contaminated water may cause disease) and the environment.

In conclusion, given the continued scarcity of freshwater in South Africa, it has fast become a precious commodity. Water quality in South Africa has declined over the past two decades, already poses substantial risks to humans and ecosystems and has contributed to increased water stress and scarcity. The primary drivers include but are not limited to a growing urban population and a growing industrial and agricultural sector. Rural-urban migration is occurring at a faster rate than what municipalities can supply water and sanitation services, resulting in the inability of WWTWs to handle additional requirements. Therefore, partially treated wastewater is being loaded into water resources and poses a significant health risk to both humans and important ecosystems being preserved in conservation areas. AMD associated with coal and gold mining is expected to continue, alongside the salinisation and acidification of freshwater systems. Also linked to population dynamics is the capacity for South Africa to grow food for an expanding population. Agricultural return flows are one of the most widespread sources of pollution that threatens water security within its own industry. Ongoing pollution has led to several problems including salinisation, eutrophication, sedimentation, acidification and microbial contamination, of which eutrophication is the most widespread and concerning problem. Various constituents or water quality parameters can be used to determine the severity of water pollution in rivers as they can be linked to specific water quality problems and sources of pollution when present in high concentrations for extended periods.

All these processes significantly affect the health and ability of South African rivers to provide essential ecosystem services to both humans, as well as the environment in critical conservation areas such as the KNP. As a final important point, the importance of riverine habitats is briefly discussed.

3.5. Important Definitions and Characteristics of the Target Water Quality Ranges

The South African Water Quality Guidelines or TWQRs are a set of user specific guidelines which indicate the fitness of water for a particular use (DWAF, 1996a). The TWQRs are not water quality criteria, but rather water quality objectives for the appropriate management of water quality derived from both quantitative and qualitative criteria (DWAF, 1996d). The guidelines are an important source of information for water quality managers, however, are also of use to educators, researchers, and other interested parties (DWAF, 1996b).

The term "water quality" is used to describe the physical, chemical, biological, and aesthetic characteristics of a water body which indicates its suitability for various uses and protects the aquatic environment. These water quality characteristics are regulated or affected by water quality parameters in either dissolved or suspended water (DWAF, 1996c).

It is essential that water quality be maintained within a "no effect range" otherwise known as the TWQRs for each parameter. The "no effect range" is the concentration level at which the presence of a particular indicator of water quality would have no adverse consequences for the suitability of water for a particular use (DWAF, 1996a; DWAF, 1996c). The use of the “no effect range” as the set TWQR means that water quality must meet ideal standards, not just merely acceptable or tolerable standards (DWAF, 1996a).

3.6. The Importance of South African Riverine Habitats

Rivers are ecosystems that incorporate the characteristics and features of the catchments from which they drain, and as such are highly susceptible to an accumulation of common forms of pollutants (Baker & Greenfield, 2019). A river’s abiotic components such as geomorphology, hydrology, and physicochemical make-up, largely determine the diversity and abundance of the biotic components (Eze & Knight, 2018; Baker & Greenfield, 2019). The quality of surface water is thus largely shaped by the underlying factors of a drainage area, the prevailing climate, extreme weather events as well as the distribution of various land use types (Ashton & Dabrowski, 2011). Freshwater rivers are some of the most biodiverse ecosystems in the world (Berger et al., 2017). In South Africa alone, there are 223 types of river ecosystems which support a wealth of fauna and flora.

Due to unprecedented and continued anthropogenic pressures, riverine ecosystems experience higher extinction rates than terrestrial and marine ecosystems (Berger et al., 2017). In South Africa, 76% of river biodiversity was lost to habitat degradation, pollution, and abstraction of freshwater between 1970 and 2012, despite the increased protection of these freshwater resources through designated conservation areas (WWF, 2016).

Rivers’ responses to catchment disturbances are different for each river and depend on a range of anthropogenic and natural factors. Natural water quality characteristics reflect the impacts of environmental processes, while human activities exert a broad spectrum of additional impacts on rivers which affect the quality, quantity, and suitability of these freshwater resources for both humans and ecosystems (Ashton & Dabrowski, 2011). A good understanding of these interconnected factors is key to identifying reaches where environmental problems may occur because they strongly influence variables such as discharge, sediment supply, and riparian vegetation (Eze & Knight, 2018).

Furthermore, climate change that results in alterations to the hydrological characteristics and regime of the aquatic environment may trigger a chain reaction of changes within the ecosystem. These intrinsic changes may be observed in its overall functioning as well as via the various components of the ecosystem - water quality, in-stream and riparian habitat and in-stream biological communities. Thus, managing and meeting the Ecological Reserve is of utmost importance to ensure that the effects of climate change are well-mitigated and that long-term, sustainable management of these resources contains widespread degradation (Tanner et al., 2022).

Freshwater provision is a key ecosystem service to the KNP, as well as surrounding protected areas and communities (Biggs et al., 2017). However, several interests compete with the conservation of freshwater and its biodiversity (Berger et al., 2017) in the eastward flowing rivers that traverse the KNP (Riddell et al., 2019a). The decline in water quality and flow has been a key issue for the KNP in recent years, and may be increasing in severity due to agricultural, mining, industrial and urban activities upstream (Petersen et al., 2014).

In conclusion, rivers are living, evolving parts of the landscape with abiotic characteristics derived from the scrounging geology, the hydrology, and the physicochemical components. These factors determine the biotic diversity in any given river, and all collaborate to provide essential environmental services to humans and wildlife. However riverine systems are severely threatened in South Africa, resulting in high levels of biodiversity loss. Understanding these threats and the interrelations between water quality/pollution, flow/abstraction, and climatic factors, is key to ultimately protecting downstream users such as conservation areas like the KNP.

The state of global water resources, specifically in terms of water scarcity and water quality, has been discussed in this chapter. Both water scarcity and water quality issues affecting South African water resources were emphasised, and the specific water quality issues threatening South African waterways were discussed in detail. Lastly, the water quality guidelines and parameters used to measure water quality were highlighted, and the chapter concluded with a discussion of the importance of riverine habitats. A synthesis of this literature now follows.

3.7. Synthesis of the Literature

Water is essential for all forms of life, livelihoods and for socio-economic development. As has been widely documented for some time, an alarming number of countries are experiencing increasing limitations or stress to their water supply. The primary drivers include, but are not limited to, continued increasing populations, demographic changes, urbanisation, and climate change which are all responsible for impending water scarcity over the globe. Global water demand has been increasing at a rate of about 1% per year with requirements expected to grow by 2 400 m^3 by 2030, which means that water stress and insecurity is likely imminent for many Southern African countries in the near future.

If current trends in water management continue, many regions will face considerable challenges with potentially devastating consequences for all aspects of life. Aquatic ecosystems are indicating a downward trend in response to deteriorating water quality and an increasing number of water bodies and stretches of rivers are being rendered unsuitable for use across sectors. Currently, the majority of surface waters in South America, Africa, and Asia are still in fair condition and opportunities to curtail further negative consequences exist provided that water resource managers take the appropriate legislative and operational steps to avoid further impacts and minimise further degradation. The ongoing decline in water quality is accompanied by the decrease of water quantity and availability, presents multiple threats to sustainability through the negative impacts on human health, natural environments, and socio-economic development.

Climate change has stimulated an increased occurrence of droughts, floods, and other extreme weather events, all of which have the potential to reduce water availability and increase overall water stress. The implications for freshwater resources are concerning and will potentially leave millions of people exposed to large decreases in availability for every degree of warming experienced in each region.

South Africa is one of the countries on the “wrong side” of the global annual average rainfall. Despite a dense drainage network, its rivers are mainly small and shallow, yet they are the freshwater lifelines for human populations and ecosystems throughout the country. Climate change is predicted to become evident through increasing temperatures and an even larger variance in rainfall with surface runoff possibly decreasing by up to 50 - 75% as a result. Substantial water resource development and storage infrastructure as well as transfers between basins already form an essential part of South Africa’s water supply. Sedimentation in storage facilities has however already decreased storage capacity significantly, putting the country’s water security at high risk in times of drought. The country has already almost fully reached its capacity for further development of its surface water resources and will in the next decade need to bridge a supply gap of around 2.7 billion m^3. Significant improvements in terms of efficiency will therefore be required in upcoming years to try and meet requirements for food and energy production.

Primary drivers which include, but are not limited to, urbanisation, population growth, and a growing industrial and agricultural sector have led to an increase in surface water contamination in the country. Elevated concentrations of nutrients have led to nutrient enrichment, deoxygenation, and excess algal growth becoming one of the region's largest pollution problems. One third of rivers in the country are categorised as eutrophic and the presence of Microcystins in water is a growing concern, especially for the most downstream of users such as protected areas and rural populations who are directly dependant on river water. South Africa has well established standards and protocols for controlling pollution, however improvements in its demand management approach may assist in conserving both quality and availability further.

Rivers should therefore be regarded as ecologically, aesthetically, and recreationally important parts of the landscape. They are both a major water resource and a functional drain for the landscape, bringing together land, water, and biota. For these reasons, they are also a critical part of conservation lands. Any alterations to the concentration of chemical constituents and physical variables can exert a profound effect on the aquatic environment and its dependant ecosystems. It is evident that weather and climate patterns are shifting around the world, as well as in South Africa, where they are expected to largely decrease water availability. As water stress increases, the capacity of rivers to dilute contaminant loadings will decrease, thereby restricting the ability of rivers to provide essential ecosystem services. Changes in surface water temperatures are also known to have a strong influence on the increase of organic matter, nitrates, and phosphorus, which may proliferate to form mixed algal blooms that are poisonous to wildlife.

Many of the flow regime alterations and water quality impacts are occurring within kilometres of protected areas such as the KNP and pose a significant threat to the wellbeing of surrounding ecosystems and biodiversity. Only 16% of freshwater resources are protected in the country, resulting in flow requirements and quality standards currently not being met to maintain in-stream biota. In terms of the KNP, most studies focus on the Olifants River where poor water quality and persistent flow reductions have led to the deaths of wildlife for more than a few years and which has periodically dried up as a result of over-abstraction. This means that the KNP is currently unable to fulfil its mandate of serving as a refuge for freshwater species as well as the maintenance of biodiversity and ecosystems within the park. The effects of climate change, already at play in South Africa, will exacerbate these impacts further. The rivers being affected are the freshwater lifelines of the semi-arid region, and it is therefore imperative to protect them. It is critical that, in the face of the threats of climate change, we attempt to gain a better understanding of how river systems are changing to improve planning for those changes and accommodate them in management policies.

The methodology, describing the research design, data, collection, and statistical analysis thereof, for the research is described and discussed in depth in Chapter 4.

CHAPTER 4: RESEARCH DESIGN AND METHODOLOGY

4.1. Introduction

The broad aim of this research was to contribute to the existing knowledge regarding the response of rivers in terms of water quality to water flow and climate variability in a semi-arid region of South Africa, where climate change is expected to have some of the greatest impacts on the country's already limited water resources (UN Water, 2020). More specifically, this research aimed to analyse and evaluate, through a sequence of time series trends and correlation analyses, the spatio-temporal patterns of river water quality, as well as to determine the possible influence that water flow and climate variability has on water quality in selected perennial rivers. The focus of this research was on rivers which flow through the protected area of the KNP in the Lowveld of North-Eastern South Africa. Furthermore, the research aimed to identify significant historical pollution events and possible high risk areas for pollution.

The acquisition of water quality, water flow and climate datasets that span numerous decades was necessary to attain the primary aim and objectives of this research. The statistical analysis of spatio-temporal trends and the subsequent analysis of the aforementioned relationships allowed for the assessment of these aspects in relation to the environmental health of the KNP rivers.

Chapter 4 first outlines the research design by providing an overview of the research philosophy that was implemented and a summary of the research procedure. This is followed by an account of the procedures used to acquire the necessary data for the statistical analyses. The data analysis process and the techniques that were used in processing the acquired data are discussed in detail and are then followed by a consideration of the ethical components involved in conducting this research, as well as the research limitations. The chapter concludes with a short summary of the overall research design and methodology.

A discussion of the research design now follows.

4.2. Research Design

Creswell (2009) states that the research design is a plan for research that spans the decisions from broad assumptions to detailed methods of data collection and analysis. The research design is informed by the overarching research philosophy and research procedures and is based on the nature of the research problem (Creswell, 2009). A discussion of the research philosophy and the research procedures implemented during this research now follows.

4.2.1. Research Philosophy

The primary philosophy implemented in this research was a positivist research philosophy, which originated in the works of Francis Bacon, Auguste Comte, and the 20th-century 'Vienna Circle'. These groups of philosophers and scientists emphasised the use of a strictly scientific empirical research design to collect and analyse data and yield results that would then be unaffected by human subjectivism and bias (Creswell, 2009; Saunders et al., 2009). A positivist research philosophy therefore usually gives rise to empirical research methodologies and quantitative designs (Dan, 2017). Research that develops from a positivist philosophy is based on careful objective observations and measurements (Creswell, 2009). Positivist research philosophies are thus characterised by their highly structured nature, the large samples that are involved, and the quantitative measurements recorded (Dudovskiy, n.d).

This research made use of a collection of highly structured water quality, water flow and climate datasets containing large numbers of observations at specific locations and times, which were systematically processed and analysed using a set of pre-specified and strictly objective methods. The application of a positivist approach in the research design and methodology of this research allowed for the interpretation and reporting of unambiguous and accurate results, as presented in Chapter 5.

The research methodology utilised in this research was empirical and quantitative, as it attempted, through a systematic and rational process, to make planned observations of quantifiable phenomena, in this case, 11 water quality parameters, one water flow parameter, and three climatic parameters, namely rainfall, and maximum and minimum temperatures (Dan, 2017; Patten, 2017). Empirical methods typically involve the systematic collection and analysis of data and are, as such, most often used in quantitative research designs that collect primary data, as well as in those that analyse secondary data (Dan, 2017). Data collection for this research included the acquisition of secondary quantitative data from numerous sources, as well as the structuring and examination of the data through the application of a series of statistical analyses (Rockinson-Szapkiw, 2012). Since it made use of previously measured observations and described the relationships between the selected parameters, this research can be described as empirical and quantitative by nature.

Rockinson-Szapkiw (2012) states that a quantitative research design is most appropriate when the research requires the following:

- an explanation of the relationship/s between/among parameters;
- a prediction or determination of causal relationships; or
- the testing of a theory or model.

This research identified, examined, evaluated, and discussed the statistical relationship between a selection of water quality parameters, water flow, and climatic parameters over both time and space. The periods of time over which the data were accessed differed according to the sites selected for the monitoring of the river water. The spatial extent of the research covered the main rivers of the KNP at sites located near the park. Consequently, the research design for this research was classified as a quantitative correlational research design (Rockinson-Szapkiw, 2012; Asamoah, 2014).

Correlational research is a commonly used quantitative method within the positivist research philosophy (Asamoah, 2014). The term 'relationship' in quantitative correlational research refers to the status of one variable reflecting on another variable (i.e., there is an association between the two variables), but this does not imply causation between those variables (Rockinson-Szapkiw, 2012; Asamoah, 2014). This research design was therefore correlational by nature because it aimed to determine the strength of the relationship (the association) between multiple parameters and to explain the direction of the relationships between and among the respective parameters. Furthermore, correlational research designs are typically non-experimental, and variables are not manipulated or randomly assigned (Price et al., 2015). The variables used in this research were not manipulated in any way, except to calculate - where possible - average monthly aggregates for each of the datasets. This correlational research was retrospective as it made use of previously collected secondary data acquired from the DWS, SANParks and SAWS archives (Price et al., 2015).

In conclusion, the research methodology set out in this chapter was based on a positivist research philosophy. As with most positivist research philosophies, this research made use of empirical quantitative methodologies, giving rise to a highly structured and scientific design. A quantitative correlational design was selected as this is most appropriate when the relationship/s between/among variables is examined. The research performed planned observations and analyses of quantifiable phenomena, in this case, 11 water quality parameters, one water flow parameter, and three climatic parameters. Since correlational research designs are typically non-experimental, the data were not manipulated in any way prior to analysis.

A summary and illustration of the applied research procedure now follows.

4.2.2. Research Procedure

For this research to achieve the stipulated research aim and objectives, as presented in Chapter 1, the research design and procedures were differentiated into four primary phases, each with its own main steps and actions, as shown in Figure 4.1.

Phase 1 of the research design was firstly concerned with the identification of the primary literature themes of this research. The relevant literature was critically evaluated from a global, national (South Africa) and regional (KNP) perspective. A synthesis of the literature, provided as a conclusion, highlighted significant information related to the primary aim and objectives of this research. The identification and acquisition of the necessary data for the achievement of the primary aim and objectives of this research then followed. The collected data were reviewed and validated to ensure that the datasets were accurate. Unnecessary data columns were identified and removed to ensure that the datasets contained only relevant data. Null values, as well as extreme values or outliers, were identified and removed to ensure accuracy within the developed datasets.

Phase 2 of this research was undertaken to understand the nature of the datasets and to determine their basic attributes. A normality test for detecting outliers, and calculations involving descriptive statistics were then implemented for each of the primary parameters dealt with in this research. The completion of these steps allowed for the identification of the relevant analytical techniques pertaining to the data which were based on the aim and objectives of this research, and subsequently implemented in Phase 3.

Phase 1

Literature Review: Evaluate existing literature relating to water resources and climate change, from a global perspective, as well as on a national (South African) and regional (KNP) scale. Provide a suitable synthesis of critically evaluated literature.

Data Acquisition, Cleaning and Structuring

Step 1: Identify and acquire the necessary and relevant data from the DWS, SANParks and SAWS.

Step 2: Structure and clean the acquired data by identifying and removing null values, unnecessary data columns and extreme values.

Step 3: Structure data into water quality, water flow, rainfall, and temperature datasets, and calculate monthly averages for each parameter to prepare the data for analysis.

Phase 2

Initial Data Processing

Step 1: Test for normality using the Shapiro-Wilk normality test; also examine the generated P-P Plots and Q-Q Plots.

Step 2: Identify significant or problematic outliers. Remove the identified data without compromising the accuracy of the dataset.

Step 3: Complete the calculation of the basic descriptive statistics.

Phase 3

Main Data Processing and Analysis

PART A:

Step 1: Compile a time-series trend analysis for monthly water quality data to establish any significant variations in water quality over time and between monitoring sites. Compare the results to the selected DWS (DWAF) TWQRs.

Step 2: Establish and indicate by means of a time series trend analysis graph significant trends in water quality. Identify high risk areas for pollution, as well as pollution hotspots. Compile compliance graphs for each WMA.

PART B:

Compile datasets for correlation analysis and interpolate missing data where appropriate. Perform correlation analyses between water quality, water flow, rainfall, and temperature data to establish the possible relationships between these parameters. Present the results in correlation matrix tables.

Phase 4

Interpretation and Presentation of Results

Step 1: Evaluate spatio-temporal trends by identifying significant variations in the selected water quality parameters over time and between sites.
Step 2: Discuss the significance of the selected water quality parameters that occur outside of the TWQRs, and subsequently indicate substantial historical pollution events, possible high risk areas for pollution and existing pollution hotspots.
Step 3: Establish and evaluate the relationships between the water quality, water flow, and climate parameters. Determine the overall significance of these relationships with the aid of XLSTAT and QGIS.
Step 4: Critically evaluate the current state of water resources in the study area for the time period over which the data were analysed by evaluating the suitability of the water quality according to the selected DWS (DWAF) TWQRs.
Step 5: Suggest suitable recommendations for the identified areas of concern and provide future mitigation and management actions based on the findings of the research. Based on the conclusions of this research, provide possible avenues for future research.

Figure 4.1: Overall implemented research design, including primary research phases with the relevant principal steps and/ or actions.

Phase 3 of this research focused on the establishment of spatio-temporal trends between sites over the period for which each of the datasets was analysed and included a comparison of the actual water quality at each site with the selected South African TWQRs. During this phase, historical pollution events, high risk areas for pollution, and existing pollution hotspots were identified. Phase 3 was also concerned with the establishment of the nature and scope of the relationships between water quality, water flow, rainfall, and temperature, as well as the determination and evaluation of the relationships between these parameters and the significance thereof. The main data analyses conducted in this phase were primarily the time series trend and correlation analyses. A detailed description of the statistical analyses and methods used to process the data is provided in section 4.3 of this chapter.

Phase 4 of this research focused primarily on the examination and evaluation of the results obtained through the analysis of the respective datasets, and the interpretation and discussion of these results alongside their presentation in the form of tables, graphs, and maps. Suitable conclusions were established in this research phase and, based on the results obtained, recommendations and/ or strategies were formulated. The recommendations, strategies and interventions focused on the primary challenges established for water resources of the KNP during this research. Suitable interventions or actions were suggested for the mitigation and/ or reduction of future pollution events. Possible adverse effects of climate variability on water resources were identified as a major challenge and suitable interventions were also suggested. This phase was concluded by identifying opportunities for further research based on the obtained results.

A detailed description of the necessary data and the acquisition thereof, as well as illustrations of the relevant monitoring sites, now follow.

4.3. Data Acquisition

A review of the existing literature pertaining to water quality, water availability and flow, as well as climate change, was compiled and presented in Chapter 3. This chapter provided a brief discussion of the state of water resources from a global perspective, current water availability, demand, and impending scarcity. The world's primary water quality problems were also discussed in this chapter and informed the selection of the water quality parameters, as discussed under 4.3.2 of this section. Based on the available scientific literature, global climate change was considered in relation to its current and future impacts on water resources. Most of the literature review primarily focused on the state of water resources in South Africa, the intensification of the water scarcity and/ or stress challenges of the country and its primary water quality issues. The most recent research and/ or relevant information permitted a detailed evaluation of the possible impacts of climate change on water resources in South Africa, the effects of various pollutants on the aquatic environment, as well as on human health, and the importance of maintaining healthy aquatic ecosystems. The chapter concluded with a synthesis of critically evaluated literature, highlighting the most pertinent water challenges on a national and regional (KNP) scale.

Given that the aim of this research was to evaluate the trends in water quality, as well as the establishment of possible relationships between the selected water quality, water flow and climate parameters, the respective datasets for each monitoring site needed to be extensive and to span several decades, especially in terms of climatic data (Griffin et al., 2014; Lipsett, 2017). In view of the longitudinal nature of this research, primary data were not collected. Instead, long-term secondary data were acquired from the DWS, SANParks and SAWS. Meals et al. (2011) states that lengthy sequential datasets collected at a fixed location, and through consistent methods, with few intervals are essential for effective trend and correlation analyses. In their research of rainfall patterns in the KNP, MacFayden et al. (2018) defined long-term data as spanning more than 30 years; Odiyo et al. (2014) made use of climatic data spanning almost a decade to determine the long-term variability of rainfall and streamflow in the Luvuvhu River catchment; and de Villiers and Mkwelo (2009) made use of long-term datasets spanning at least two to three decades in their assessment of water quality monitoring practices on the Crocodile River in Mpumalanga Province. Thus, it was essential for this research that datasets for each of the selected water quality, water flow and climatic parameters spanned at least two decades. The only exceptions were for the microbial monitoring sites, where monitoring proved to be a more recent and infrequent practice.

As discussed in detail in section 4.2 of this chapter, the research design followed a quantitative methodological approach, making use of a variety of secondary quantitative data sources. The necessary data for this research included both physicochemical and microbial water quality datasets acquired from the DWS and SANParks for the seven selected KNP rivers. Monthly maximum water flow datasets were also obtained from the DWS Resource Quality Information Services (RQIS) (https://www.dws.gov.za/iwqs/report.aspx). Datasets containing climatic data (rainfall and temperature) were acquired for several climate sites from the SAWS. These spanned different time periods. Descriptions of these are provided in the subsections that follow and the respective dataset characteristics are detailed in the various appendices. Importantly, the time periods for which data were available at a given site proved to be a major factor which needed to be considered in the selection of each monitoring site as the selection of the sites was based on the high dimensionality of the data.

On consulting the available datasets, it was determined that physicochemical water quality datasets were for the most part long-term and continuous. A tabulated description of the physicochemical water quality dataset site numbers, site names, GPS coordinates and time periods for which data were available is included in Appendix IV. All 16 of the selected physicochemical water quality datasets spanned at least three decades, providing long-term data for the time series trend analyses and the correlation analyses with other relevant parameters. Griffin et al. (2014) highlights the value of continuous long-term records with consistent data collection, and in their research, rejected water quality monitoring sites based on whether the data collection had been terminated for the specific site, or when there were large intervals between observations. Physicochemical water quality datasets for many of the selected rivers were found to exist from as early as the 1960s, and usually spanned the period up to 2018. Other water quality datasets contained more recent samples up to the year 2021. Although there were some intervals, datasets with a larger overall quantity of observations were given preference. Where possible datasets that contained multiple samples per year as per the four-by-four rule (4x4) were also selected (Meals et al., 2011; Griffin et al., 2014; Lipsett, 2017; du Plessis, 2019).

Microbial water quality datasets were less extensive than the physicochemical datasets, with the shortest spanning only five years, and the longest spanning 16 years. Nine microbial water quality monitoring sites were selected for analysis. The lengthiest and most continuous datasets were predominantly located on the large perennial rivers, namely the Letaba, Sabie and Crocodile Rivers, of the selected study area. Owing to the lack of monitoring frequency by the DWS, microbial water quality monitoring sites did not meet the four-by-four rule. Water quality monitoring sites located within proximity of both physicochemical water monitoring sites and the KNP were consequently given preference. Further selection of these water quality monitoring sites involved the identification of those which had recorded the largest number of measurements in a year, as well as the longest number of years. For reference purposes, details regarding the water quality monitoring site numbers, site names, GPS coordinates and time periods for which the data applied are included in Appendix V.

In terms of water flow datasets, 32 monitoring sites in total were identified for possible inclusion in the correlation analysis. These water flow monitoring sites were carefully examined. For the sake of consistency and continuity in the datasets as well as proximity to the KNP only 18 water flow monitoring sites were selected for the final analysis. The datasets for these 18 water flow monitoring sites were downloaded from the DWS RQIS in the form of monthly maximum flow levels. The basis for the primary selection of the water flow monitoring sites was on their proximity to the selected water quality monitoring sites. Water flow datasets, spanning multiple decades up to 2021 were available for the selected rivers and contained data from as early as the 1930s. Although some intervals were present in the datasets, datasets were mostly lengthy and continuous. The water flow monitoring site numbers, site names, GPS coordinates and time period for which data were available are included in Appendix VI.

Using Google Earth, a total of 11 possible climate monitoring sites were identified in the initial spatial exploration of the study area. Subsequently, five rainfall and four temperature monitoring sites in and adjacent to the KNP were selected for inclusion in the data analyses. These datasets, spanning the years from 1950 to 2021, were found to be, for the most part, lengthy and continuous, with a minimum span of 31 years, and the most extensive datasets spanning 66 years. The details of the climate monitoring sites can be found in Appendix VII.

The selection criteria for climate monitoring sites included the distance of each site from the park, as well as the distance between the climate monitoring sites to be paired together for the analysis. The Geographical Information Systems (GIS) used for this part of the research included Google Earth for the preliminary screening of the climate monitoring site locations, and QGIS for the final screening and mapping of these sites. The proximity of the selected climate monitoring sites was found to be largely adequate, with the location of all sites being less than 100 km from the KNP border. Exceptions to the rule were those sites on the Limpopo River for monitoring water quality and water flow. In these instances, namely the monitoring sites on the Limpopo River, the selection of viable datasets based on the four-by-four rule and on the length and continuity of datasets, was determined by identifying the physicochemical and microbial water quality monitoring sites and water flow sites at two different locations, 306 km and 113 km from the KNP boundary respectively.

Water quality, water flow and climate monitoring sites located at the same approximate point were paired together (du Plessis, 2014). The locations of the various types of monitoring sites are indicated in the relevant sections below. Appendix VIII details which water quality, water flow and climate monitoring sites were paired together. Some limitations were experienced during this process. For instance, water flow site X3H021 on the Sabie River, is located downstream of the nearest physicochemical water quality monitoring site, X3H012. X3H021 water flow site is also located downstream from the nearest microbial water quality monitoring sites, namely "Sabie Microbial - Samora Camp" and "Sabie Microbial - Calcutta". The water flow data at this monitoring site was therefore only an approximate representation of the actual water flow data nearest to these water quality monitoring sites.

The water quality data were structured into Excel spreadsheets according to river and site name to give sound results for a spatial analysis of the water quality and to identify pollution hotspots for each river. Water flow data were downloaded according to the corresponding water quality sites, the former determined by mapping these points using GIS software and were already structured according to site number and name. The monthly SAWS climate data were structured according to the site name.

A detailed description of the data acquisition process and data characteristics, and illustrations of the selected monitoring site locations for water quality, water flow and climate data, now follow.

4.3.1. Water Quality Data

The DWS maintains a water quality database consisting of data collected as part of the National Water Quality Monitoring Programme (NWQMP). Sections of the rivers that fall within the KNP are sampled by Mr. H. Sithole from SANParks and the resultant sample data provided to the DWS for inclusion in the datasets (DWS, 2019). The historical water quality data for the selected KNP rivers were acquired from the DWS via email, as the online water quality database (https://www.dwa.gov.za/iwqs/wms/data/000key.asp) is no longer available. The correspondents for providing water quality data in this regard were Ms. T. Louw (LouwT2@dws.gov.za) and Ms. E. Vermaak (VermaakE@dws.gov.za).

The KNP conducts additional water quality monitoring on an ad-hoc basis and acquires regular water quality data from the Inkomati-Usuthu Catchment Management Agency (CMA) for the Inkomati Basin rivers (Crocodile and Sabie Rivers). To acquire the supplementary Inkomati-Usuthu CMA data, this research was therefore registered as a project with SANParks. The SANParks research agreement is provided in Appendix II.

The data required for an extensive understanding of water quality trends in rivers must primarily capture the temporal dynamics, as well as the spatial patterns of the selected water quality parameters. Water quality datasets must therefore contain data that are of a consistent quality on a local and catchment scale (Griffin et al., 2014; UNEP, 2016; Lipsett, 2017). The frequency and manner in which the water quality of the rivers of the KNP was monitored and data stored was therefore considered when the water quality monitoring sites were selected. The water quality data acquired from the monitoring sites were measured either monthly or weekly throughout each year but at no specified frequency, scheduled time, or on a fixed day or week. However, even with some missing data, the datasets were extensive and consistent enough to permit the structuring of monthly observations for multiple decades.

The DWS database consisted of a potential 38 physicochemical water quality monitoring sites and 26 microbial monitoring sites for the study area. The most suitable monitoring sites selected from this database were primarily based on the time span of the historical water quality datasets and resulted in 16 physicochemical and nine microbial sites for the final analysis. Furthermore, the monitoring sites were selected using the four-by-four rule, in so far as the data allowed, as recommended by the Canadian Council of Ministers for the Environment (du Plessis, 2019).

The four-by-four rule requires that there be compliance in terms of the following conditions:

- Monitoring sites are excluded when there are inadequate data records (i.e., when there are less than four measurements recorded within a year).
- Monitoring sites are excluded when measurements at the site cover less than four parameters and where there are less than four recorded measurements within a year.

This rule was implemented to ensure that only monitoring sites where samples were taken on a regular basis be included to ensure that the data and representation would be of a suitable standard. The proximity of water quality monitoring sites in relation to the water flow monitoring sites and SAWS climatic monitoring sites were also considered in the selection process.

The 16 resultant physicochemical water quality datasets consisted of extensive, long-term water quality data, spanning between 25 and 43 years. It should be noted that the microbiological datasets for the rivers were far less extensive, with the shortest dataset spanning five years (Luvuvhu River), and the longest spanning 16 years (Crocodile River).

The supplementary water quality data acquired from the KNP's Savanna Research Unit were assessed and most water quality monitoring sites were deemed to be incomplete and/ or too limited for the purpose of the correlation analysis phase of this research. Water quality monitoring sites were excluded on the basis that the datasets only spanned a nine-year period from 2012 to 2021 and contained multiple missing samples per year, especially in terms of the calcium, chloride, and magnesium water quality parameters. Longer time periods of at least a decade (Wijesiri et al., 2018), including consistent monitoring data of at least one measurement per month, are necessary for a significant correlation analysis between the selected water quality parameters and water flow, as well as the selected climate parameters (Lipsett, 2017). Furthermore, these monitoring sites were excluded on the basis that they did not meet the four-by-four rule (du Plessis, 2019). According to the four-by-four rule, the location of the sites within close proximity of the KNP and the continuity of the datasets (Griffin et al., 2014), only two monitoring sites provided by SANParks, one on the Crocodile River (X2H048) and one on the Sabie River (X3H012), were established to be suitable for inclusion in the analyses.

Importantly, most of the water quality monitoring sites do not monitor both physicochemical and microbial parameters. Separate monitoring sites were consequently selected to represent the physicochemical and microbial water quality on each of the rivers that were within close proximity of the KNP. As illustrated in Figure 4.2, the various selected water quality monitoring sites in the relevant WMAs, are mostly located within 100 km of the KNP borders. The water quality monitoring sites on the Limpopo River in the north are farthest from the KNP. These sites were selected based on the aforementioned research procedures and criteria and were established to be the only sites with viable water quality data for the Limpopo River.

The selection of the appropriate water quality monitoring sites for this research were thus subject to several selection criteria to assure the acquisition of long-term, consistent, and extensive datasets for the study area and their use as appropriate data in the data analysis phase of this research.

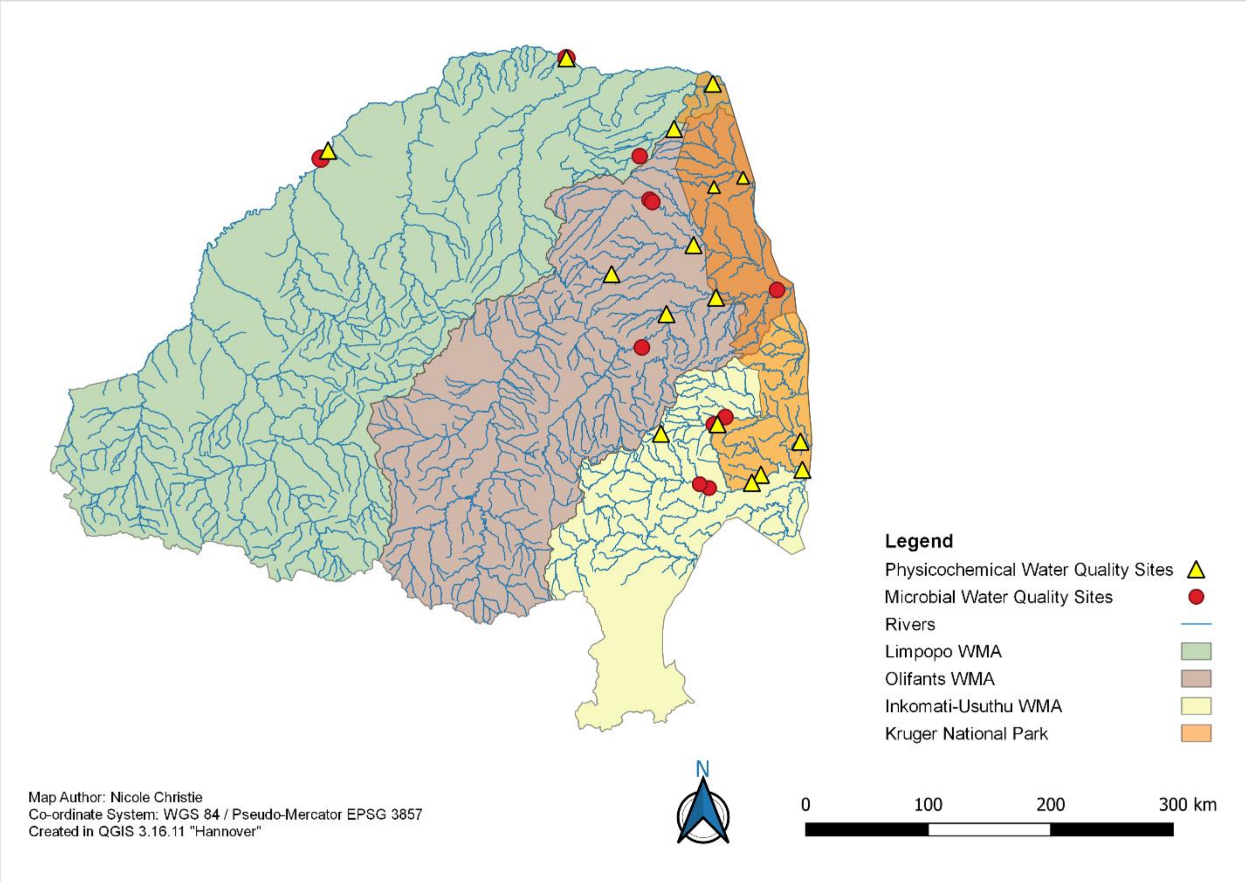

Figure 4.2: The location of the selected DWS and SANParks physicochemical and microbial water quality monitoring sites.

In addition to the selection of appropriate water quality monitoring sites, the selection of the most fundamental and informative water quality parameters was essential. A discussion regarding the selection of the water quality parameters used to establish the primary forms of pollution to determine the occurrence of historical pollution events, high risk areas and pollution hotspots, and to enable the researcher to conduct correlation analyses, now follows.

4.3.2. Selected Water Quality Parameters

UNEP (2016) states that water quality parameters should cover the major characteristics of the freshwater system, should consider, and include its physical characteristics, oxygen balance, nutrient status, mineral composition, and the presence of specific pollutants. The selection of water quality parameters should therefore provide a suitable reflection of the possible influence of anthropogenic pressures and impacts. Multiple water quality parameters are generally selected when conducting research into the vital resource, water. They may be indicative of various water quality problems (refer to Chapter 3). Thus, the water quality parameters that were selected for this research, were based on the main water quality problems facing South Africa, namely salinisation, acidification, eutrophication, sedimentation, and sewage and/ or microbial pollution as discussed in Chapter 3 under section 3.4.2.

According to Heath et al. (2010), the water quality parameters which give the best indication of the main types of anthropogenic pollution include the pH level, EC, and the nitrate, sulphate, and phosphate content. Sulphate and pH levels are useful indicators of mining-related impacts; the phosphate level is an indicator of farming-related impacts; nitrate is indicative of impacts from both farming and sewage; and an EC level generally indicates the presence of salts, usually from mining, farming or natural origins (Heath et al., 2010; Zak et al., 2021). It was thus imperative that these parameters be included in the research to represent the main forms of pollution which may affect the rivers of the KNP before they reach its western border.

There is thus no single water quality parameter that can be used to describe the overall quality of a given water resource. A wide variety of parameters are typically recommended for water quality analyses (Ashton & Dabrowski, 2011; Xai et al., 2014; Nosrati, 2015; Berger et al., 2017; Riddell et al., 2019a). The parameters selected and included in this research were based on the given selection criteria to obtain a comprehensive overview of the water quality in the selected KNP rivers in relation to the main water quality problems in South Africa, as well as to the South African TWQRs. The 11 selected water quality parameters were detailed and discussed extensively in Chapter 3 under section 3.4.3 and provide a broad perspective and cover a wide range of the water quality issues experienced in South Africa.

A detailed description of primary water quality issues and parameters was provided in Chapter 3, and a summary of the TWQRs used to determine the water quality status of the various selected rivers has been included in Appendix III for reference purposes.

A description of the acquisition process of water flow data now follows.

4.3.3. Water Flow Data

The DWS has water flow monitoring sites, both upstream of and in the KNP, which continuously monitor environmental flows into the park. The maximum monthly water flow data for at least two monitoring sites on each of the selected rivers were sourced from the DWS online database (http://www.dwa.gov.za/Hydrology/Default.aspx) and were paired with data from the nearest water quality monitoring site on the same river for the same time period, along with data from the nearest available climate monitoring site.

Each water flow monitoring site was selected according to the availability of corresponding water quality data, that was viable, and the proximity of the site to the KNP and to the SAWS climate monitoring sites. The length and continuity of each dataset was also considered in the selection of water flow monitoring sites. Maximum monthly flow measurements were used for the correlation analysis to ensure consistency in the structure of the data.

In all, 32 water flow monitoring sites were identified for possible inclusion, only 18 of which (Figure 4.3) were deemed to be suitable and selected for analysis (Appendix VI). Sixteen water flow monitoring sites provided datasets spanning between 30 and 50 years, and two water flow monitoring sites provided data spanning 20 to 30 years.

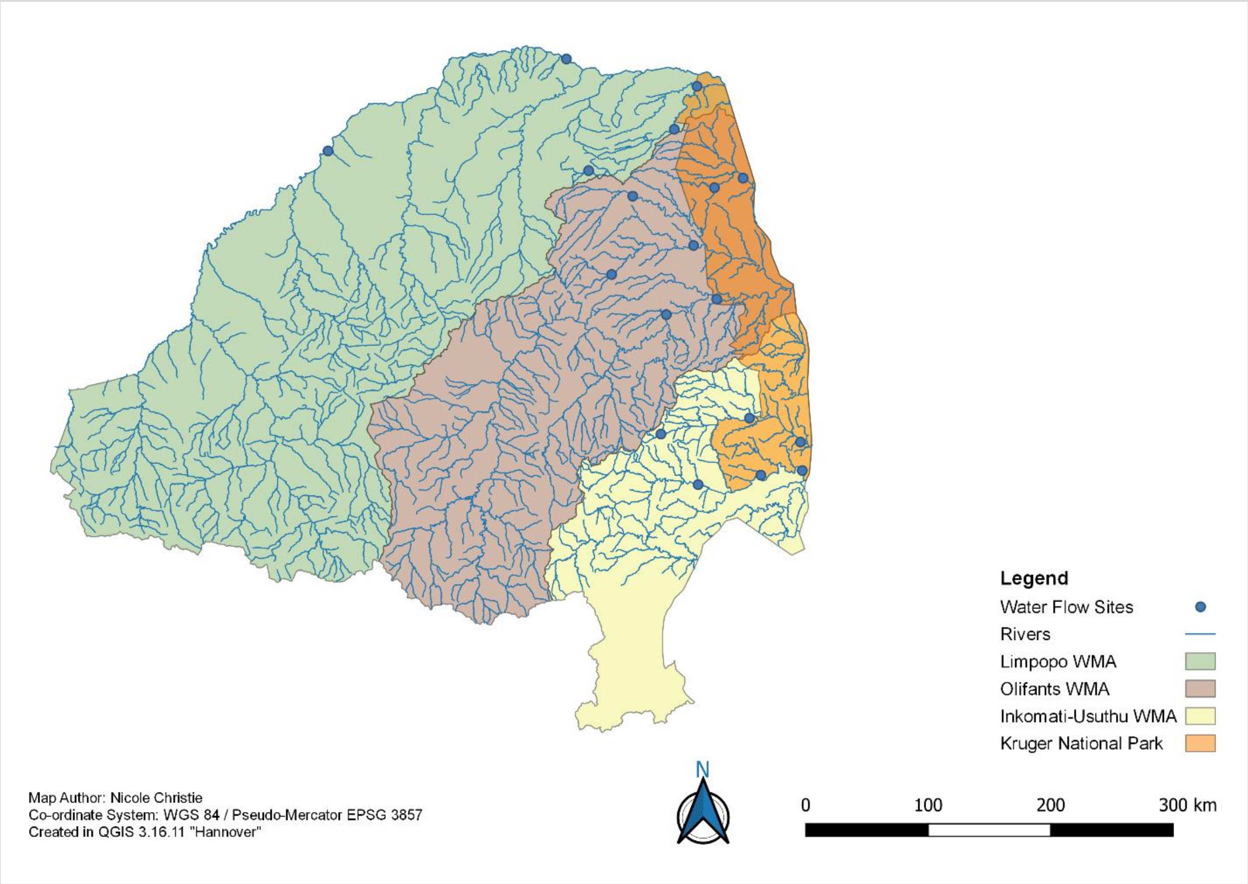

Figure 4.3: The location of the selected DWS water flow monitoring sites.

The water flow monitoring sites on the Luvuvhu, Shingwedzi, Letaba, Olifants, Sabie and Crocodile Rivers are all located within 100 km of the KNP border. Owing to the pairing of the water flow monitoring sites with the most viable water quality monitoring sites for the river, the water flow sites on the Limpopo River in the north are farthest from the KNP.

A description of the acquisition process of selected climatic data now follows.

4.3.4. Climate Data

As indicated previously in this chapter, this research required and made use of rainfall and minimum and maximum temperature data. Monthly average rainfall data and monthly average minimum and maximum temperature data were requested from the SAWS for the period 1955 - 2021, as long-term data were required to determine the temporal water quality trends related to climate variability. Rainfall and temperature data were acquired for 11 SAWS climate monitoring sites, which were identified as ones presenting with long-term monitoring data. These included Bourke's Luck, Graskop, Hoedspruit, Komatidraai, Letaba, Nelspruit, Punda Maria, Satara, Shingwedzi, and Skukuza. Rainfall data were also available for the Shingwedzi-Vlaketplaas climate monitoring site. Out of these climate monitoring sites, only five were determined as presenting with data of suitable quality and selected for inclusion in the analyses. These climate monitoring sites included Graskop, Nelspruit, Punda Maria, Skukuza, and Shingwedzi-Vlakteplaas. Climate monitoring sites that were excluded were done so on the grounds of the limited amount of data available or because the climate monitoring site was no longer being actively monitored.

The name of the climate monitoring site, the GPS coordinates and the type of climatic data measured at the site are detailed in Appendix VII. Climate data are recorded by SAWS at each site daily at 08:00 am, and average monthly values for each of the selected climatic parameters were calculated and entered into a Microsoft Excel spreadsheet.

The shortest dataset obtained from SAWS contained data spanning 25 years. The most extensive datasets contained data spanning 66 years. These depths of data are imperative in environmental and ecological studies as they provide a unique opportunity to investigate the impacts of change in climatic patterns, in this case in the selected rivers of the KNP over an extended time period. Climate monitoring sites located within the KNP river catchments proved to be invaluable as they provided ecological rather than logistical motivations for inclusion (Lipsett, 2017).

As shown in Figure 4.4, three of the five selected climate monitoring sites, namely, Punda Maria, Shingwedzi-Vlakteplaas, and Skukuza are located within the KNP borders. The remaining sites are located approximately 40 km outside the KNP.

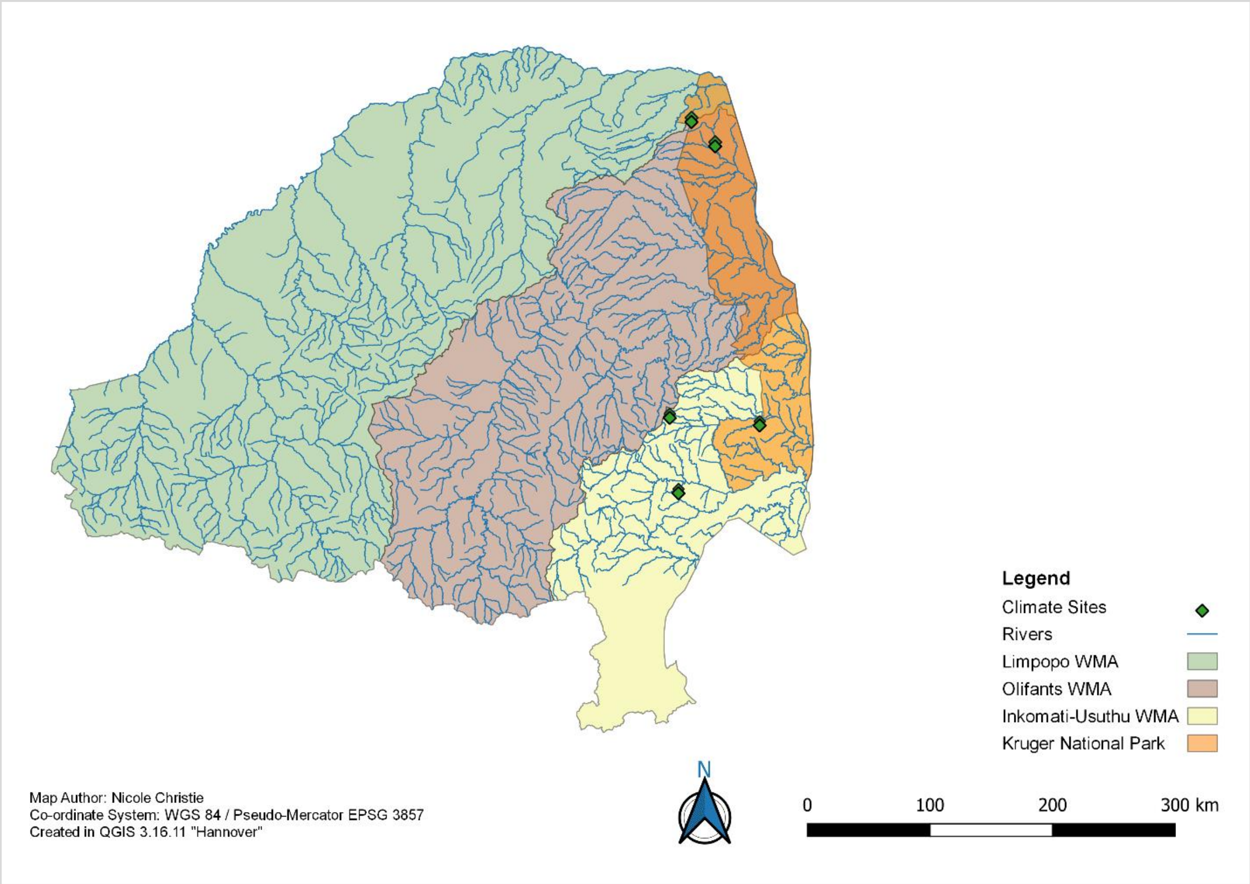

Figure 4.4: The location of the selected SAWS climate monitoring sites.

In conclusion, this section described the research procedures for the acquisition and selection of the various types of data required for the analyses of the possible impacts of climate variability on water quality and flow, as well as the spatio-temporal trends in water quality.

A detailed description of the processing of data and the various data analyses completed to establish spatio-temporal trends, possible correlations and/ or relationships, and the significance of these, now follows.

4.4. Data Processing and Analysis

This section provides a detailed description of the methods used to structure and process the data to achieve the desired outcomes, as stated in the research aim and objectives. Data processing and analysis were separated into phases, as stated in the Research Design (Section 4.1). A detailed description of the various data processing methodologies used and implemented for this research now follows.

4.4.1. Phase 1 and Phase 2

Phases 1 and 2 of this research were undertaken to understand the characteristics of the acquired data and to determine the most appropriate analytical techniques to attain the research aim and objectives.

All data cleaning, structuring, and statistical analyses were conducted using Microsoft Excel and XLStat Basic Plus software programmes. The GIS tools used for the screening and mapping of the respective monitoring sites included Google Earth and QGIS.

The initial processing of the data involved sorting, cleaning, and structuring the data, which were acquired in the form of Microsoft Excel spreadsheets from the various sources mentioned above. All data were sorted by date, and unnecessary columns and rows were removed. Null values and extreme values that were likely to have been caused through human error or malfunctioning of a sampling device were removed (e.g., pH units above 14). Monthly averages were calculated for each of the selected parameters.

Some common characteristics of water quality datasets may pose challenges in respect of their statistical analysis, namely, missing values, non-normal distributions, and the presence of outliers (Jesús et al., 2011; Fu & Wang, 2012; Tizro et al., 2014; da Silva Costa & Monteiro, 2015). In the case that datasets do not follow a normal distribution and are not free from outliers, the results obtained may be misleading when statistical inference is used. However, using certain non-parametric methods to conduct the analysis usually corrects this issue (Sinha & Kumar, 2015). The issues of missing values, normality of the data, and outliers were thus addressed prior to the analysis of the selected parameters.

The existence of missing data is a common feature of environmental data such as water quality, water flow, rainfall, and temperature. Two methods for dealing with missing data exist: deletion or imputation/interpolation. Deletion is considered the default method since it is straightforward, however deletion presents some limitations in that it reduces the dataset size and can result in the loss of critical information when many observations are deleted (Rodríguez et al., 2021). However, missing data in a water quality time series does not usually present a significant computational or theoretical problem for applying time series trend techniques (Hirsch et al., 1982; Lepot et al., 2017). Therefore, where datasets contained missing values, these missing values were not interpolated for the time series trend analysis. A further reason for not applying interpolation to the datasets is that interpolated values can easily be misleading in the analysis of a time series owing to the inter-annual variability within environmental data such as seasonal rainfall (Lipsett, 2017). The fact that missing data remained omitted from the analysis, allowed for the assurance that no misleading trends could be generated in the time series trend analysis. On the other hand, correlational research relies on the presence of at least two quantitative variables for each observation, and although these values need not follow a rigid timeline, correlation cannot be calculated with missing values (Asamoah, 2014). Therefore, data were only interpolated after the structuring of the datasets for the Spearman's Rank Correlation Analysis. Linear interpolation was applied to fill the missing data. Linear Interpolation is the simplest form of interpolation that connects two data points with a straight line (Noor et al., 2014; Rodríguez et al., 2021).

Owing to the temporal structure of most environmental data, such as water quality data, the analysis of outliers was an imperative consideration (da Silva Costa & Monteiro, 2015). Outliers can be described as unusual data points which do not fit the general pattern of the dataset (Enoch, 2018). Values in a timeline can be highly influenced by extreme events which could subsequently produce outliers in the data. The influence of outliers increases if the distribution of the dataset is non-normal, as is the case with most environmental data. Environmental parameters such as water flow are significantly influenced by extreme events, such as floods or droughts, and observations for these parameters are usually statistically highly skewed. Even one or two excessive events over a long period of time can bias the analysis of aggregated values (WRC, 2012).

However, in many instances, owing to the temporal correlation structure of these observations, which may provide insights into historical pollution events at specific locations, the analysis of outliers in a time series trend analysis is essential to a sound report on the state of water resources (da Silva Costa & Monteiro, 2015). Therefore, in this research, outliers were not usually removed, and the potential threat to the efficacy of the analyses posed by the presence of outliers in some of the acquired datasets was mitigated as follows. Firstly, the possible influence of outliers underlay the decision to use monthly data as opposed to annual data, as the process of aggregating observations into monthly intervals maintained a higher dimensionality in the datasets, and thus reduced the influence of outliers on the results of the final analysis. Secondly, the time series trend analyses applied in this research naturally indicated the presence of outliers in the time series plot, highlighting observations that were not consistent with the rest of the data (e.g.: Tizro et al., 2014). The non-parametric tests used provided greater statistical power in cases of non-normality and were robust against outliers and large data gaps (Meals et al., 2011).

Various statistical methods, such as correlation analysis, make assumptions about normality. However, environmental data, such as water quality data, do not usually follow convenient probability distributions such as normal and lognormal distributions, on which many classical statistical methods are based (Antonopoulos et al., 2001). The Shapiro-Wilk normality test was used to test for the distribution of the data. This normality test is used when the sample size is smaller than 50 ($n < 50$) but can also be used for larger sample sizes (Mishra et al., 2019). The Shapiro-Wilk normality test is commonly used in testing the normality of water quality data (Marr et al., 2017a; Marr et al., 2017b; Devane et al., 2019). If a sample distribution is normal, parametric statistical analyses, such as Pearson's Product Moment Correlation (PPMC), can be used. If the distribution is non-normal, or monotic, then statistical analyses such as Kendall's rank-order correlation test or Spearman's Rank Correlation Analysis must be applied (Puth et al., 2015; Valentini et al., 2021).

The null hypothesis states that data are taken from a normally distributed population. When $p > 0.05$, the null hypothesis is accepted and data are normally distributed (Mishra et al., 2019). The datasets were checked for normality using the Shapiro-Wilk normality test, and all datasets returned computed *p*-values, lower than the significance level, $a=0.05$. Therefore, the null hypothesis $H0$ was rejected, and the alternative hypothesis Ha was accepted. Partial regression plots (P-P plots) and Quantile-Quantile plots (Q-Q plots) were also generated for each parameter to visualise the distribution. Fu and Wang (2012) indicate that Q-Q plots provide an efficient means by which to determine how a sample distribution deviates from an expected distribution and are useful in detecting the presence of extreme values and outliers. P-P plots indicate how well a given set of data fit a specific distribution, providing an initial insight into the normality of the data (Ramachandran & Tsokos, 2021).

Basic descriptive statistical analyses (distribution, central tendency, and dispersion) were computed and tabulated for the selected water quality parameters, maximum annual water flow and climate data (rainfall and temperature). The minimum, maximum, mean, standard deviation, skewness and kurtosis were calculated for each of the parameters. The calculation of these descriptive statistics ensured that the original data had been sufficiently summarised and represented. Descriptive statistics aided in achieving the set objectives of assessing and describing spatio-temporal patterns between rivers and between the respective monitoring sites over the various time periods for which the data were available (Antonopoulos et al., 2001; da Silva Costa & Monteiro, 2015; Enoch, 2018).

In summary, Phase 1 and 2 focused on cleaning, structuring, and understanding the data as well as achieving the objective of identifying spatio-temporal trends in water quality for the monitoring sites. Descriptive statistics and normality were calculated for water quality parameters to summarise and describe the primary features of water quality datasets. Box plots, P-P plots, and Q-Q plots were generated for each parameter at each site which enabled the detection of significant outliers or extreme values that may be due to calibration and sampling errors, which were then removed. Box Plots indicated the distribution of the data and were useful in identifying how water quality differed between sites. Water quality was irregular between the various rivers for the observed time period. Skewness and kurtosis were calculated to determine whether the data came from a normal distribution. Values of skewness and kurtosis outside the range of -2 to +2 showed a significant departure from normality (Mustapha, 2013). Descriptive statistics showed that 47% of the data were highly skewed, and 39% were moderately skewed. Seventeen percent (17%) of the data had a moderate kurtosis, and 71% had a high kurtosis. This indicated that the distribution of most of the data were likely non-normal. A Shapiro-Wilk normality test was also conducted for each of the water quality parameters to confirm the distribution of the data. Ninety-eight percent (98%) of the water quality datasets were determined to be non-normally distributed, thus non-parametric data analysis methods could be applied.

4.4.2. Phase 3

Phase 3 of this research focused on the establishment of spatio-temporal trends between sites and the identification of historical pollution events, high risk areas for pollution and existing pollution hotspots. This research phase consequently established and evaluated the nature and closeness of the relationships between water quality, water flow, rainfall, and temperature. The main data analyses conducted in this phase were primarily the time series trend analyses (Part A) and the correlation analyses (Part B).

4.4.2.1. Part A: Time Series Trend Analysis

Part A of the main data analysis focused specifically on an evaluation of the spatio-temporal trends in water quality at selected monitoring sites in and adjacent to the KNP, the identification of the frequency of high pollution incidents, as well as consistently high pollution levels, above those as stipulated in the guidelines provided by the DWS (DWAF) TWQRs (Appendix III). More specifically, the analysis conducted needed to highlight any significant upward or downward trends in the variation of a given water quality parameter from the start date to the end date of the samples taken at each water quality monitoring site, as well as to indicate any significant differences in water quality between the respective monitoring sites.

To understand and illustrate the significant long-term temporal trends in the water quality of each of the seven rivers, a time series trend analysis of the monthly water quality data was compiled for the unique period for which the data for each monitoring site were available (Antonopoulos et al., 2001; Marr et al., 2017a; Marr et al., 2017b). A time series trend analysis was used to determine whether the measured values of a water quality parameter increased or decreased overall during a particular time period (Antonopoulos et al., 2001). A trend is the long-term systematic change in the mean value over time (Mudelsee, 2019). A time series trend analysis is thus used to assist in uncovering patterns and to estimate the rate of change in environmental data. These analyses are, however, unable to provide much insight into the attribution of a trend to a particular cause. Interpreting the cause of a trend requires knowledge of hydrologic processes, land use, and human activities in the watershed (Meals et al., 2011). The causes of significant water quality issues were spatially investigated using Google Earth and the TWQRs.

Meals et al. (2011) states that effective trend analysis requires long-term data collected at a fixed location through consistent methods, and with minimal missing values or intervals between the observations. Before proceeding with the time series trend analysis, as recommended by Meals et al. (2011), preliminary data reduction was performed by aggregating the observations into standard periods of monthly frequency intervals.

Classic parametric time series tests make assumptions about the characteristics of the dataset, which are not normally met by environmental data (especially surface water quality), including normality, linearity, and independence (Machiwal & Jha, 2006). An exploratory analysis of the water quality data in Phase 2 of this research showed that, in general, observations were non-normally distributed. When data are non-normally distributed, Machiwal and Jha (2006), Meals et al. (2011) and Mustapha (2013) propose the use of non-parametric tests to determine trends in a surface water quality time series. The non-parametric Mann-Kendall (MK) test was determined to be best suited for this research to detect possible monotonic and non-linear trends in environmental data, such as hydrology, rainfall, and water quality, and proved to be more robust against a non-normally distributed dataset (Lipsett, 2017; Marr et al., 2017a; Pohlert, 2020). It is possible to determine the existence of an increasing or decreasing trend using this MK analysis (Mustapha, 2013).

Long-term water quality data acquired from SANParks and the DWS were structured for the time series trend analysis, and a non-parametric MK time series trend analysis was applied to each of the 11 selected water quality parameters on each of the seven rivers. The test, performed in XLStat, calculated Kendall's Tau, the *p*-value at *a=0.05* and a 95% confidence level on both sides (e.g.: Park et al., 2021), the Sen's slope, and generated visual representations of each time series.

The MK method tests the null hypothesis (*H0*) that the data are uniformly distributed, and that each observation is independent or free of trends. The alternate hypothesis (*Ha*) states that the data follow a monotic trend (Pohlert, 2020). The MK method calculates a positive or negative *S* variable (sum of the difference between data points) which, when a trend is present, indicates the direction and magnitude of the trend (Lipsett, 2017; Pohlert, 2020).

The *S* variable is calculated by means of the following equation:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\ (X_j - X_i)$$

Where n is the number of values in the dataset and sgn is sign. *S* is normally distributed when n is greater than or equal to 8 (Lipsett, 2017; Pohlert, 2020). *S* is initially assumed to be 0 (i.e., no trend), and is incremented or decremented if the value from a later time period is found to be higher or lower than data from an earlier time period. The final value of *S* is the net result of all such increments and decrements (Khambhammettu, 2005). Owing to the use of the sign differences and not the actual values of the variables, the test is expected to be less affected by the outliers (Mustapha, 2013).

South Africa has a set of eight water quality guidelines that act as criteria for specific water quality parameters and in so doing, dictate water quality management in the country. These guidelines also include background information about the effect of these parameters on the user (e.g., domestic, agriculture, etc.) in certain concentration ranges. As such, the user can assess for which uses and/ or consumption purposes the water is suitable (DWAF, 1996d; Stolz, 2018). The obtained time series trend analysis results for the water quality data were compared to the TWQRs for aquatic ecosystems (DWAF, 1996c) to determine the suitability of the quality of the water for aquatic ecosystems in the KNP. Because there are often no TWQRs in terms of aquatic ecosystems for some water quality parameters, the TWQRs for domestic use and irrigation were also included to determine suitability. The primary land use activities in the study area were predetermined in Chapter 2 to be a mixture of both urban and rural settlements and agricultural activities, thus leading to the selection of TWQRs for domestic use and irrigation purposes. A comparison of the temporal trends using the time series trend analysis and the TWQRs was completed for each of the selected water quality monitoring sites.

To further understand the state of and assess the spatial characteristics of water quality, and ultimately determine the water quality parameters that present the highest risk, a compliance graph was compiled indicating the percentage of observations that were of an ideal, acceptable, tolerable, and unacceptable standards for each parameter in each WMA. The TWQRs for aquatic use were utilised where possible, and domestic TWQRs were used if there were no aquatic guidelines (apart from chloride). The domestic guideline for chloride was utilised as the aquatic guidelines are stringent, as observed in

Chapter 5, and almost all parameters occurred within unacceptable levels. The following legend (Table 4.1) was used to illustrate this for each WMA, as well as for the full study area.

Table 4.1: Compliance graph legend indicating the percentage of observations falling within ideal to unacceptable TWQRs for each of the physicochemical and microbial water quality parameters in the three WMAs.

Ideal	
Acceptable	
Tolerable	
Unacceptable	

4.4.2.2. Part B: Correlation Analysis

Part B of this research focused on meeting the research objective of determining the impacts of climate variability on river water resources in the study area. Recently, several studies have been conducted using statistical analyses that assess the strength of a correlation between environmental parameters. For instance, numerous studies such as Valentini et al. (2021) and da Silveira et al. (2021) used statistical techniques such as principal component analysis (PCA), correlation analysis, and variance analysis to examine water quality in the Mirim Lagoon Hydrographic Basin, Brazil. Moreover, studies such as Cassalho et al. (2019) made use of a correlation analysis to investigate which geomorphological and/ or climatic parameters most significantly influenced stream flows in Rio Grande do Sul, Brazil. Meanwhile, research conducted by Shamsudin et al. (2016) explored the relationship between *Escherichia Coli* and physical water quality parameters by means of a Pearson's Correlation Analysis (PCA).

Water quality sites were paired with the nearest corresponding water flow and climate monitoring sites. A correlation analysis was completed for each water quality parameter in relation to water flow, rainfall, and temperature to establish the presence and direction of a relationship between the parameters. Correlation analyses allowed for an investigation into whether observations in a parameter (either a water quality, water flow or climate parameter) increased or decreased alongside another observation or showed a negative or positive change in relation to the other parameter.

There are several methods which can be applied to measure correlation (Asamoah, 2014). Where datasets are non-linear or non-normally distributed and therefore require the use of non-parametric analytical methods, two rank-order correlation coefficients (Spearman's rho (ρ stated as R_s) or Kendall's tau (τ)) can be used to determine the strength of association between two continuously measured observations. These two methods measure a broader class of association in comparison to linear parametric methods such as PPMC. A high absolute value for Spearman's or Kendall's correlation coefficient indicates that there is a monotonic (but not necessarily linear) relationship between the two observations being examined (Puth et al., 2015).

Spearman’s Rank Correlation Analysis is based on ranks and produces robust results when observations in the dataset do not satisfy a normal distribution (Gitau, 2010; Valentini et al., 2021). The method quantifies the strength and direction of the association between two observations using the coefficient ρ (degree of association), which returns a value ranging from -1.0 to 1.0. Zero indicates no trend, while decreasing and increasing trends are represented by a negative or positive ρ value, respectively (Asamoah, 2014; Enoch, 2018). By calculating the coefficient of correlation, an indication could be obtained as to whether two parameters (e.g., pH and rainfall) had a weak or strong association. The direction of the relationship between the two parameters could also be determined. The higher the absolute value of ρ, the stronger the association between the two parameters. Positive values suggest that higher values of one parameter are associated with higher values of the other parameter, whereas negative values suggest that higher values of the one parameter are associated with lower values of the other (Gitau, 2010; Puth et al., 2015; Masupha, 2017; Samsudin et al., 2017). The use of ranks rather than actual values in Spearman’s Rank Correlation Analysis makes it robust against outliers and missing values (Gitau, 2010).

A Spearman’s Rank Correlation Analysis was conducted at $a=0.05$ significance level. The degree of dependence between the X and Y variables was estimated with the Spearman’s Rank Correlation coefficient ρ (Gitau, 2010).

The equation used for the coefficients of correlation is as follows:

$$\rho\ (\mathrm{R_S}) = 1 - \frac{6 \sum d_i^2}{n\ (n^2 - 1)}$$

where:

di = difference between each rank of x and y values

And n = number of data pairs

The coefficients of correlation (ρ) for each of the selected water quality monitoring sites are displayed in the relevant correlation matrix tables, and significant high and low correlation values are also highlighted and discussed in detail in Chapter 5. Significant R_S were colour coded as indicated in Table 4.2.

Table 4.2: Spearman's correlation matrix legend indicating the degree of correlation between water quality, water flow and climate parameters.

Strong positive correlation (> 5.0)	
Moderate positive correlation (3.0 to 5.0)	
Moderate negative correlation (-3.0 to -5.0)	
Strong negative correlation (< -5.0)	

In summary, data processing for this research was undertaken in three phases. The first phase was an exploratory phase in which data were acquired from various sources, the relevant datasets were identified, cleaned, and structured for analysis. Phase 2 examined the selected datasets more closely, but determined the distribution of the observations, missing values, and significant outliers. Basic descriptive statistics were calculated. The data were determined to be non-normally distributed and non-linear, and therefore non-parametric analytical methods were applied in the next phase. Phase 3 investigated the spatio-temporal trends in water quality data on the seven rivers through an MK time series trend analysis. Historical pollution events and potential pollution hotspots were identified by comparing the results of the time series trend analysis to the DWS TWQRs. A Spearman's Rank Correlation Analysis was undertaken to determine the strength of the relationship between the water quality, water flow, and climate parameters. The strength and direction of the respective relationships were indicated by the coefficient in the correlation matrices that were produced. The final phase concerned the interpretation and presentation of results, which are included in Chapter 5.

The physicochemical and microbial water quality parameters were compared with water flow at the corresponding water flow monitoring site and climate parameters at the nearest corresponding climate site to determine whether a relationship exists between water quality, water flow and climate variability within the study area. The monthly water quality datasets were paired and compiled with a water flow dataset and climate datasets that followed the same timeline. The data were previously determined to be non-normally distributed, therefore a Spearman's correlation analysis was selected (Valentini et al., 2021). A Spearman's correlation matrix was generated for each of the river sites indicating the value of the coefficient (Rs written as "R" or "r") for each correlation. When Rs is greater than 0.5 or less than -0.5 a correlation between parameters is strong. Correlations closest to 1.0 and -1.0 are strongest (Levine et al., 2013). A high absolute value for Spearman's correlation coefficient indicates that there is a monotonic (but not necessarily linear) relationship between the two parameters being examined (Puth et al., 2015). A monotic relationship can indicate one of two relationships: when two parameters have a strong positive correlation, their concentrations vary in the same direction, while parameters with a strong negative correlation vary in opposite directions (Valentini et al., 2021). Compliance graphs, together with the time series trend analysis, furthered the understanding of the temporal change in water quality for the river sites as well as each WMA. Compliance graphs also indicated the severity of water pollution at each site.

The research also required that several ethical considerations to be made. A discussion of these ethical considerations and an account of how any concerns were addressed now follows.

4.5. Ethical Considerations

Several ethical considerations were considered with regards to the acquisition and analysis of the data required for this research.

Water quality data were primarily acquired from the DWS. These are made available, upon request by email to the public and are, therefore, not censored; nor is access restricted. The acquisition and use of water quality data therefore presented no ethical issues as no physical sampling was conducted by the researcher and the existing data were used. Water flow data were acquired from the DWS online repository, which is freely accessible to the public for downloading. The acquisition and use of data therefore presented no ethical issues.

The supplementary water quality data acquired from SANParks required this research to be registered as a research project with SANParks through Ms S. Mabuza (Science Liaison Officer) and a SANParks supervisor was assigned. Registration of the research project involved the submission of a research proposal outlining the research questions, methods, the anticipated research period, as well as an indication of the requirements for support from SANParks. Furthermore, the registration of the research project with SANParks required the signing of the “SANParks Scientific Services Spatial Data User Agreement”, which is listed in Appendix II. Clause 2 of the data-user agreement applied to this research, as the data were used for the purpose of conducting research only and not for commercial gain. The data-user agreement required that researchers with registered SANParks projects provide reports on the outcomes of the project, as well as copies of data and publications upon completion of the research. A copy of the final examined dissertation was therefore provided to SANParks. A SANParks research permit, reference SS519, was granted on 12 July 2021.

Climate data acquired from SAWS required the completion and signing of a non-disclosure statement, indicating what data were required. The agreement is included in Appendix I, and binds the researcher to the following:

- To acknowledge SAWS in the resulting thesis/project or when published, for the data it provided.
- To provide SAWS with a copy of the results in printed or electronic format; and
- To provide no third party with the data in question.

Ethical approval for the research was also required and obtained from the University of South Africa (UNISA) for the period, 12 February 2021 to 31 January 2024 (Appendix IX). The ethical approval application was declared as posing “a negligible risk” and was expedited by the UNISA-CAES Health Research Ethics Committee on 12 February 2021, in compliance with the UNISA Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment. The ethical approval reference number is 2021/CAES_HREC/014. Ethical approval was granted for three years, subject to submission of the relevant permission letter to SANParks and SAWS, as well as the submission of yearly progress reports.

The ethical considerations for this research were therefore mostly limited to the acquisition of various data. The main ethical considerations included the registration of the research as a project with SANParks, the signing of a non-disclosure agreement for SAWS, and ethical approval from UNISA.

A consideration of the limitations of the data and analyses now follows.

4.6. Data Limitations

It should be noted that some shortcomings were identified in the data which consequently presented limitations for this research. While data were sourced from credible national departments, thus allowing for confidence in the integrity of the data, limitations were present in all datasets as there were in some instances gaps and/ or missing data. Explanations which could account for missing data include site malfunction, calibration errors, mismanagement, or natural disasters. For example, on account of severe flooding in 2000, several water flow gauging sites were damaged, thus resulting in concurrent data gaps (Lipsett, 2017).

The issue of missing data frequently occurs when dealing with environmental data, mainly due to challenges such as instrument failures, inconsistent or inaccurate monitoring or capturing of data, changes to data collectors and changes or issues with systems. The issue of missing data is much more prevalent in developing countries such as South Africa due to budget constraints, lack of skilled water management personnel and the lack of capacity to carry out frequent monitoring (Rodríguez et al., 2021). The datasets obtained which contained missing data in their records were examined and were included in this research only if no more than four consecutive years were missing. For example, given its proximity to the water quality and water flow gauging sites along the Letaba River, the Letaba climate-monitoring site was in a prime location for this research. However, climate data was available only up to the year 2010/2011 and if used for the correlation analysis, would have required the exclusion of up to eight years of the most recent water quality data, and up to ten years of the most recent water flow data. Such values were not interpolated as, on account of the inter-annual variability within the environmental data, they could have been misleading (Lipsett, 2017). The implementation of non-parametric analytical methods in this research ensured that there were no misleading trends generated through the inclusion of multiple interpolated values.

The distance between the climate monitoring sites and the associated water quality and water flow monitoring sites presented a limitation in the analysis of the relationships between these parameters. In most cases, the climate monitoring sites were selected based on their location, within close proximity of the water monitoring sites. However, in some cases, this proved to be impractical owing to differences in the length of the datasets. As such, on account of the length and continuity of their data, some monitoring sites were paired together.

The methods used for the initial collection and chemical analysis of the water quality samples at sources can also be regarded as a limitation. Although the type of analysis used provides accurate measurements in terms of the quantity of a given contaminant present in the river, it only takes the water that flows past a specific point at the time of collection into account. Since concentrations of the selected water quality parameter may fluctuate considerably over the period of a month, infrequent readings may be subject to some degree of inaccuracy (Oberholster et al., 2017). Water quality samples are in fact only representative of conditions at the instant of sampling. They do not provide much insight into the historical conditions or information about the effects of changes on the riverine ecosystems beyond the scope of the given research (Fouché & Vlok, 2012). It is important to note that land use and changes in land cover may also influence the water resources of a region (du Plessis, 2014; Stolz, 2018). Therefore, the effects of climate variability on a water body cannot be regarded in isolation. However, it should be noted that a detailed exploration of the relationship between land use and land change and the changes in water quality was beyond the scope of this research.

Some limitations regarding the use of the TWQRs as standards for determining the pollutant levels were also identified. In certain instances, TWQRs were not available for some or all the selected water quality parameters. The DWS indicates that the following could apply where such conditions prevail:

- The parameter is not perceived to be of primary concern to that particular water use sector.
- The parameter is not considered to be a widespread problem in South Africa; and
- The parameter is a matter for concern to the water use sector in question and is a problem in South Africa, but information concerning its effects on water use still needs to be developed and/ or modified for conditions in South Africa.

In particular, the list of water quality parameters addressed in Volume 7 of the TWQRs which provides guidelines for water quality in aquatic ecosystems, is by no means comprehensive, especially not in the case of organic compounds. Therefore, the research included the TWQRs for both domestic use and irrigation as well, as these represent the primary forms of land use in the relevant WMAs. The results of several MK time series trend analyses were compared to the South African TWQRs for domestic use, irrigation, and aquatic ecosystems to determine historic as well as persistent pollution. There are no domestic use TWQRs for phosphate. There are no TWQRs for EC, pH, calcium, magnesium, sodium, and sulphate for aquatic ecosystems. There are also no TWQRs for calcium, magnesium, phosphate, and sulphate for irrigation in South Africa.

Thus, the primary limitations of this research included shortcomings in the data such as missing values and incomplete datasets; the sampling methods used; the exclusion of some water quality parameters in certain TWQRs; and the locations of some of the monitoring sites in relation to the study area. The research design attempted to minimize the impacts of these limitations by ensuring that datasets with the highest dimensionality of data were used, and that these datasets were for the most part long-term, consistent, and had few missing or null values.

4.7. Conclusion

The ultimate goal of this research was to investigate and evaluate the historical and current state of water resources in the seven major rivers that feed the KNP, and to determine the possible effects of climate variability on the quality and flow of water received by the KNP via these major river systems. The drying up and pollution of these major rivers have been two of the main conservation focus areas for decades, and multiple concerted research efforts have thus helped significantly in maintaining water quality and flow at better standards than would have been the case without intervention (Petersen et al., 2015).

A positivist research philosophy was applied within this research and gave rise to an empirical, quantitative research design. Therefore, large amounts of long-term secondary data were acquired and analysed using quantitative techniques which included a time-series trend analysis and correlation analyses.

One of the crucial aspects of this research was the examination of the possible impact of climate variability on the water quality and flow of the rivers originating outside the

KNP. These major rivers have their headwaters some few hundred kilometres outside the KNP, on the escarpment of South Africa, and are subject to multiple anthropogenic influences across different types of land use before finally entering the KNP, which could be exacerbated by the impacts of a changing local climate (Lipsett, 2017; Riddell et al., 2019a). Therefore, the relationships between several factors such as water quality, maximum monthly water flow, rainfall and temperature needed to be considered to determine the possible impacts of climate variability on the KNP rivers and by extension, on the KNP landscape and environment, and its biodiversity.

All water quality, water flow and climatic parameters were considered in conjunction with the selected South African TWQRs and the possible commercial and domestic impacts that these rivers would experience as they approach the KNP such as agricultural abstraction and pollution, mining pollution, sewage disposal and industrial wastewater addition.

The intention of applying the selected data analysis procedures and statistical methods in this research was to prescribe a process by which the research aim, and objectives could be achieved. The main analysis was therefore divided into two major parts. Part A of this research was concerned with establishing the spatio-temporal trends of water quality in the seven selected rivers at each of the 16 physicochemical monitoring sites and 11 microbial monitoring sites. The results of the time-series trend analysis were compared with the selected South African TWQRs to determine the suitability of the water, to identify pollution hotspots over time and to provide an account of the current state of these water resources. Part B of this research was concerned with establishing whether there were relationships or associations between the water quality, water flow and climatic parameters, and if so, the direction and strength of these relationships. A Spearman's Rank Order Correlation Analysis was selected to meet these objectives (refer to these statistical analyses in Chapter 5).

Various ethical considerations and data limitations were considered. Ethical approval was obtained from UNISA for the research to be conducted within a particular time period. This research was registered as a project and required the signing of a user data agreement for the researcher to obtain data from SANParks. A disclosure agreement was also completed and signed with SAWS prior to the receipt by the researcher of climatic data from their database. No ethical issues were identified in respect of the acquisition of data from the DWS since such data are made available to the public and in the public domain.

Some limitations were identified during this research. The most notable limitation in the data was the frequency of missing values which could be accounted for in terms of site malfunctions, calibration errors, mismanagement, or natural disasters. These values were usually not interpolated, and limitations were accounted for in the choice of non-parametric analytical methods, which proved to be robust against outliers, missing values and non-normal distributions.

In summary, there is a current need to frequently and continuously investigate spatio-temporal patterns pertaining to the quality and flow of river water for conservation areas such as the KNP. This would enable them to fulfil their mandates of supporting some of South Africa's most sensitive ecosystems, which are the building blocks of biological diversity and sustainable tourism. Vulnerabilities to climate change are known to be magnified in a country such as South Africa, where water resources are naturally scarce. Therefore, the long-term impacts of climate variability on water resources need to be studied on a local scale, such as in the KNP, to determine significant impacts specific to the environment of the selected study area. The methods presented here enabled the researcher to compile a body of additional knowledge regarding climate-related impacts on certain freshwater rivers in the KNP environs, which could be useful to various water resource managers, as well as to conservationists in the KNP.

A detailed discussion and evaluation of the obtained results now follows.

CHAPTER 5: DISCUSSION OF RESULTS

5.1. Introduction

Changes to hydro-climatic conditions have increased pressure on freshwater resources (Veldkamp et al., 2016). Through changes to temperature and evaporation, rainfall, and runoff, as well as to groundwater recharge, the mobilisation and distribution of pollutants may vary and can compromise the overall functioning of freshwater ecosystems by creating chemical and biological imbalances (UN Water, 2020; UN Water, 2021). The rivers of the KNP are no exception to this, and concern for the state of these rivers in the context of an ever-changing climate is increasing (Pollard et al., 2011; Biggs et al., 2017; Riddell et al., 2019a).

This research thus focussed upon understanding and critically evaluating the state of the freshwater rivers flowing into the KNP, the impacts of anthropogenic pollution and the unintended consequences of potential climatic influences on these rivers. This chapter provides a discussion and critical evaluation of the research's key findings, is organised according to each WMA and discusses the results of the time series trend and correlation analyses for each river sequentially. Each section provides a background to the selected WMA and is followed by a map of the water quality, water flow, and climate monitoring sites used in the analyses of the rivers in each of the WMAs. Time series trend analysis graphs and correlation matrix tables are provided and discussed for each monitoring site. Lastly, compliance graphs for each of the WMAs were compiled as an additional measure to examine the temporal trends in depth.

A discussion of the results of the various analyses for each of the monitoring sites and parameters within each WMA now follows.

5.2. Analyses for the Limpopo Water Management Area

As described in Chapter 2, the Limpopo River WMA (Figure 5.1) includes the Limpopo and Luvuvhu Rivers. The Limpopo River was once a strong flowing perennial river but now dries up periodically as a result of the intensifying effects of the El Niño-Southern Oscillation (ENSO) influences on drought in the river basin (Ashton et al., 2001; Jury, 2016; Mosase & Ahiablame, 2018). The Luvuvhu River is a perennial river largely affected by soil erosion and sedimentation, both of which have altered the river's flow regimes and resulted in changes to the riparian habitat (DWS, 2019).

Natural water quality in the Limpopo WMA is controlled by chemical weathering and the contribution of mostly sulphates and chloride to the water (Huizenga, 2011). The WMA is characterised by ever-increasing quantities of effluent emanating from urban and industrial activities. The WMA is also substantially altered by urban development, extensive irrigation systems, and livestock farming enterprises. In terms of aquatic health, the WMA has historically been regarded as largely degraded (du Plessis, 2019).

The locations of the selected water quality, water flow and climate monitoring sites of the Limpopo and Luvuvhu Rivers included in the data analyses are presented in Figure 5.1. A discussion of the water quality trends, pollution hot spots, high risk areas and the relationships between water quality and climate variability now follows.

5.2.1. The Limpopo River

The physicochemical quality of the water in the Limpopo River was analysed at two sites, namely, A5H006 (for the period 1980 - 2018) and A7H008 (for the period 1993 - 2018) (Figure 5.1). The microbial quality of the water in the Limpopo River was also analysed at these two sites, while data recorded at the A5H006 site were analysed between 2008 and 2017, and at the A7H008 site, between 2010 and 2017. The water quality data for the Limpopo River were all non-normally distributed.

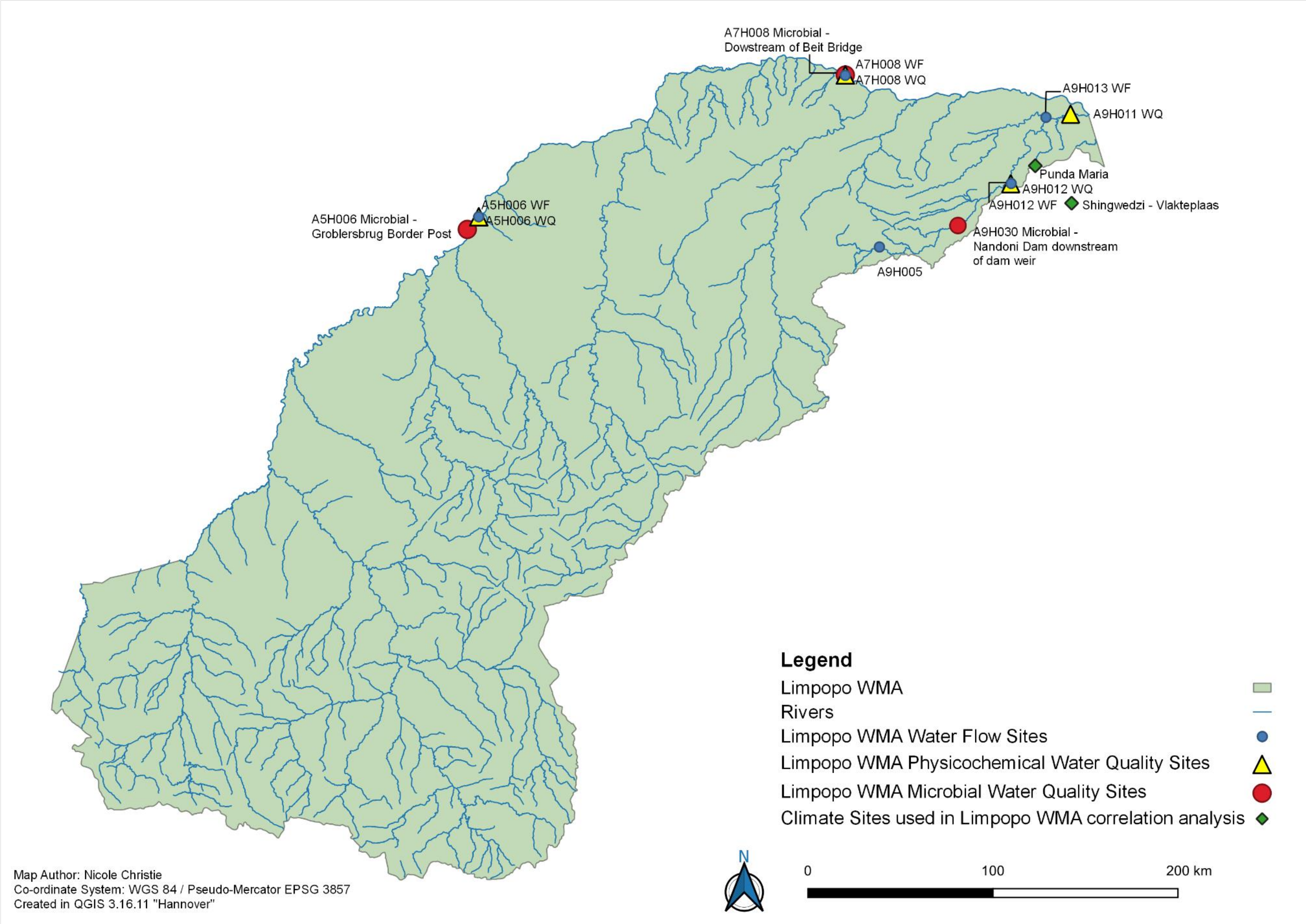

Figure 5.1: Map of the Limpopo WMA - water quality, water flow and climate monitoring sites.

The distribution of the data for each of the selected physicochemical water quality parameters was similar for sites A5H006 and A7H008; however, the overall quality of the water differed in terms of the mean concentrations of the various parameters. Box plots indicated that the mean values for all water quality parameters were generally higher at site A7H008, located downstream from site A5H006, thus water quality deteriorated further downstream, closer to the KNP. This is most likely due to the addition of pollutants from several sources along the river as a result of the intensive mining and agricultural activities in the region (Riddell et al., 2019a) as the river flows towards and into the KNP.

Box plots indicated that mean *E. coli* counts differed largely between the sites. The microbial quality of the water was better upstream, at site A5H006, than downstream, at site A7H008. Numerous outliers were present within the A7H008 dataset, indicating more frequent high pollution incidents. Increased pollution at site A7H008 may in part be due to the WWTWs located just two kilometres (2 km) upstream in Zimbabwe. The results obtained from the time series trend and correlation analyses now follow.

5.2.1.1. Time Series Trend Analysis for Sites on the Limpopo River

The results of the MK analyses for the physicochemical water quality parameters at site A5H006 showed varying trends (Figure 5.2). The computed *p*-values of EC, pH, calcium, chloride, magnesium, sodium, sulphate, and ammonia were lower than the significance level of $a=0.05$. Thus, the null hypothesis (*H0*) was rejected, and the alternative hypothesis (*Ha*) was accepted. Large *S* values revealed a strong upward trend for these parameters, indicating that the concentration of these water quality parameters increased over time. No significant long-term trends were observed for phosphate and nitrate.

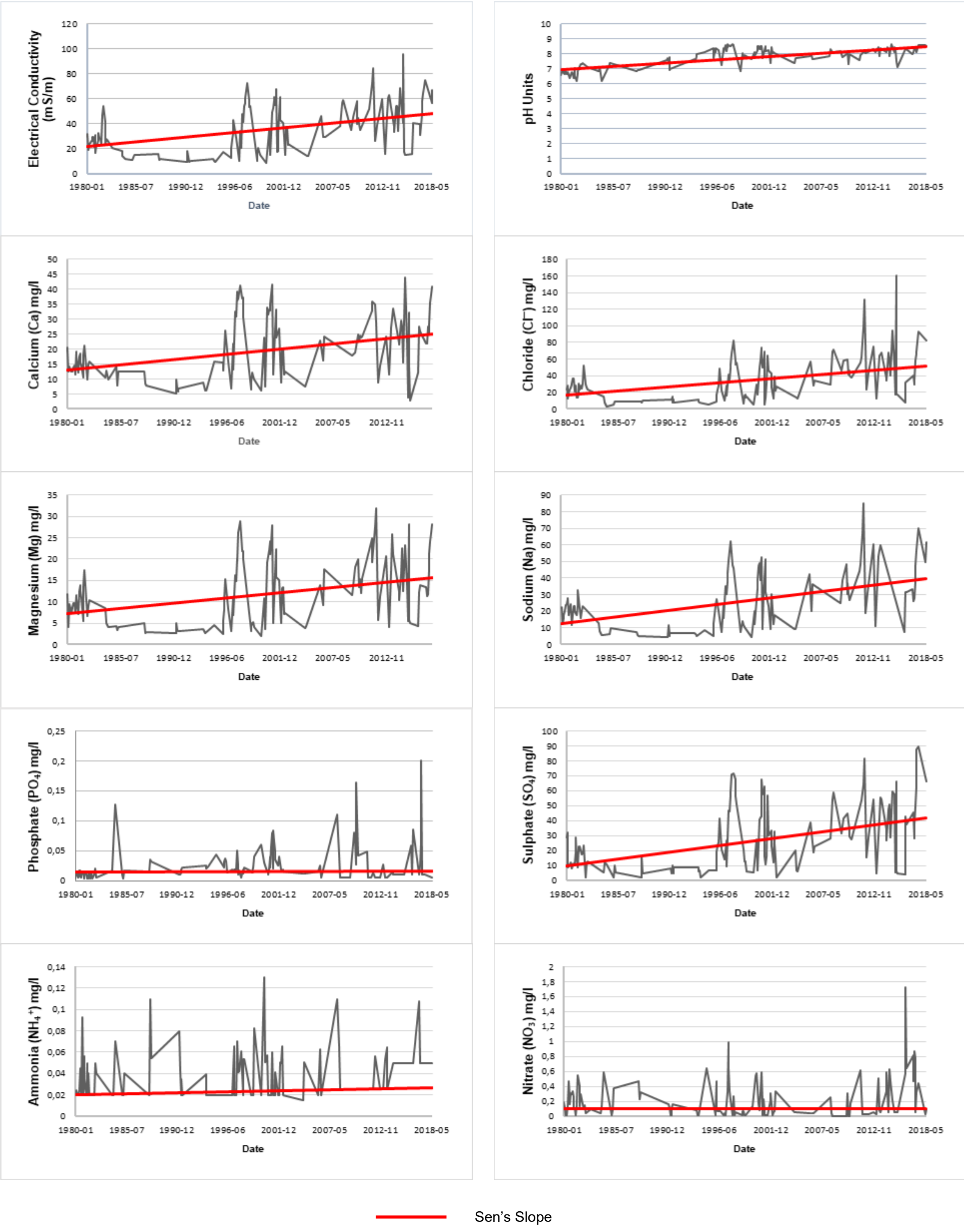

Figure 5.2: MK analyses for physicochemical water quality at site A5H006 on the Limpopo River for the analysed time period.

Despite an increasing trend, EC and the calcium, chloride, and magnesium concentrations fluctuated between ideal and acceptable levels for domestic use TWQRs. pH also fluctuated between ideal and acceptable levels for domestic use, while the sodium, sulphate, ammonia, and nitrate concentrations were of an ideal standard.

The chloride concentrations at this site for the aquatic ecosystem TWQRs consistently reached unacceptable standards. Although chloride is important for the functioning of freshwater habitats, excessive or consistently high levels may have negative impacts on freshwater ecosystems (University of Minnesota Morris, 2013; Hong et al., 2023). The pollutants responsible for the accumulation of chloride in freshwater include agricultural return flows, sewage effluent, and effluents arising from various industrial processes (DWAF, 1996a). Chlorine can react with a variety of organic substances to form compounds, which may be harmful to aquatic biota (DWAF, 1996d). When large quantities of the anion chloride are observed in a freshwater ecosystem, the substance may interfere with osmoregulation, which can hinder the survival, growth, and reproduction of aquatic species (Hunt et al., 2012). Chloride may also increase species mortality and the long-term alteration of the entire local ecosystem (University of Minnesota Morris, 2013). For the aquatic systems, the phosphate concentrations at this site remained within the ideal range, while the ammonia and nitrate concentrations fluctuated between ideal and acceptable ranges.

EC, chloride, and sodium fluctuated between ideal and acceptable ranges for irrigation use over the observed time period, with only a single observation showing an increase to a tolerable level. The pH ranges fluctuated between ideal and tolerable for irrigation use, while the respective ranges for the ammonia and nitrate concentrations remained ideal for irrigation.

At site A7H008, downstream, the MK analyses for all the physicochemical water quality parameters, apart from ammonia, determined *p*-values greater than the significance level of $a=0.05$; thus, *H0* was accepted (Figure 5.3). No significant trends were present for these parameters, although, EC, pH, chloride, sodium, phosphate, sulphate, and nitrate presented with weak positive *S* values. Calcium and magnesium had weak negative *S* values. Since ammonia was the only parameter that displayed an increasing trend over the long-term, this indicates that water quality at this specific site was dominated primarily by domestic and industrial influences over the observed time period (Table 3.1).

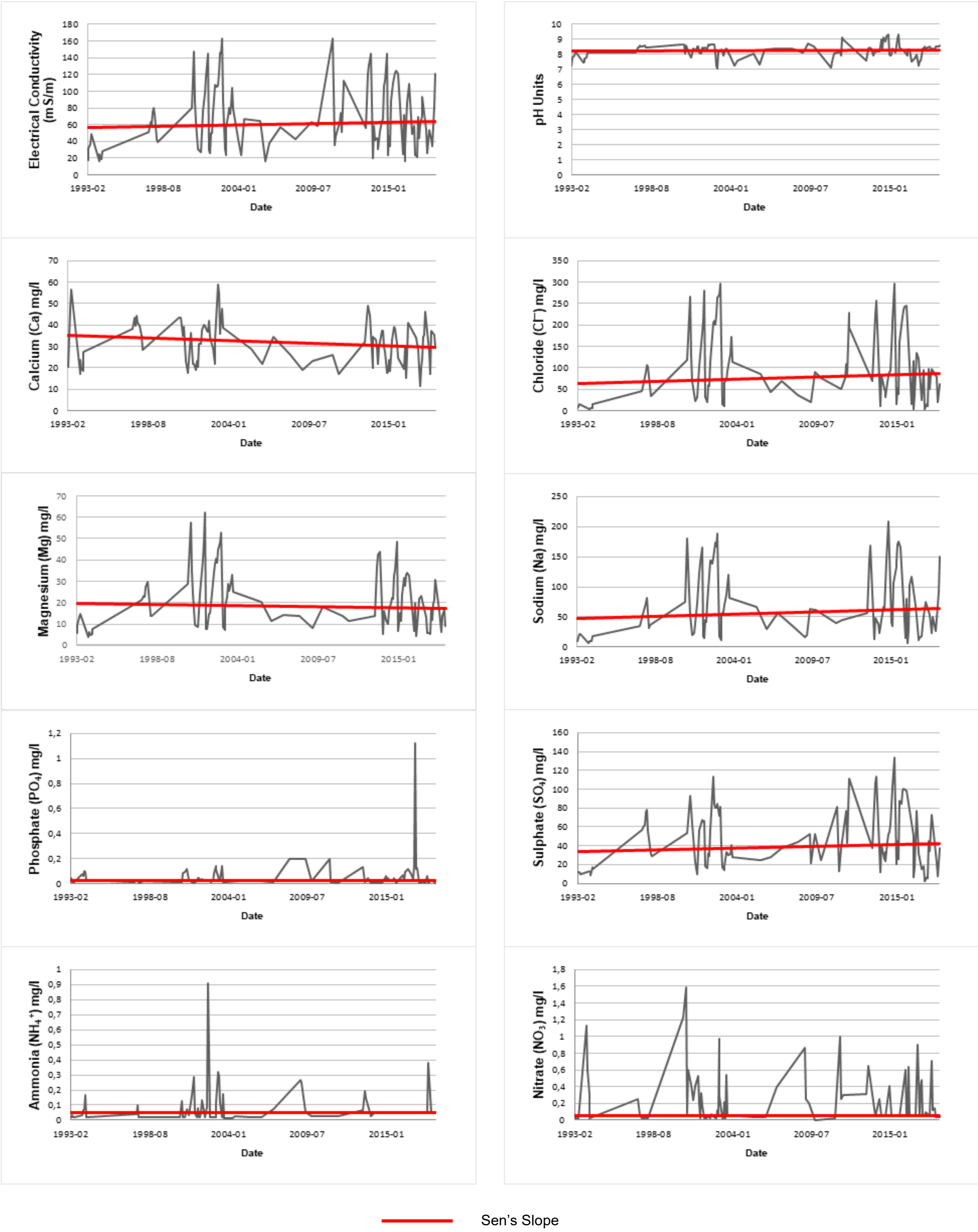

Figure 5.3: MK analyses for physicochemical water quality at site A7H008 on the Limpopo River for the analysed time period.

The pH level as well as the calcium and sodium concentrations fluctuated between ideal and acceptable levels for domestic use. EC, chloride and magnesium fluctuated between ideal and tolerable levels for domestic use. It should be noted that a large proportion of the recorded chloride concentrations consistently met the TWQRs for tolerable levels, and although no trend was observed, this may suggest that the site is at high risk for future pollution. Before 2002, the magnesium concentrations were within tolerable levels for domestic use, whereafter they fluctuated between ideal and acceptable levels. Even though there was no significant trend for magnesium, a slight decrease in its concentration was evident at the site when the overall trend was considered. Sulphate, ammonia and nitrate concentrations remained within ideal levels for domestic use over the observed time period.

EC and pH levels as well as chloride and sodium concentrations fluctuated between ideal and tolerable standards for irrigation use. Both chloride and sodium concentrations were predominantly within tolerable levels over the observed time period. Those parameters which met the ideal TWQR standards for irrigation use included ammonia and nitrate concentrations.

Chloride concentrations were within unacceptable levels for aquatic ecosystems. As mentioned, the consequences of consistently high concentrations of chloride could have severe consequences for aquatic life and ecosystems as a whole and should be flagged as a potential water quality risk (Hong et al., 2023). Other parameters, including phosphate, ammonia and nitrate concentrations fell within ideal to acceptable levels for aquatic ecosystems.

The results of the MK analysis for microbial water quality at site A5H006 indicated no significant trends (Figure 5.4). The analysis determined a computed *p*-value greater than the significance level of $a=0.05$; thus, $H0$ was accepted. A weak positive S value was calculated for *E. coli*.

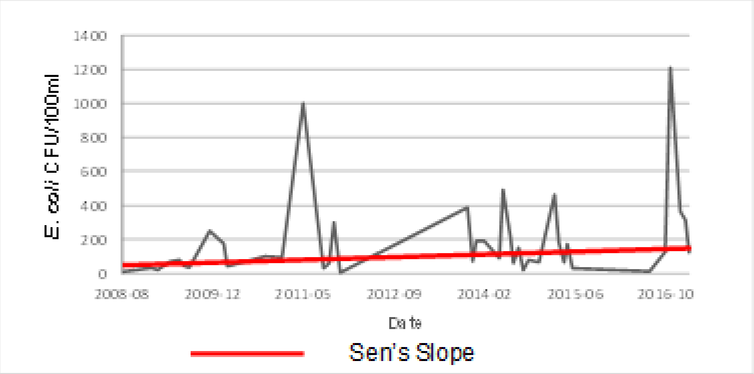

Figure 5.4: MK analysis for microbial water quality at site A5H006 on the Limpopo River for the analysed time period.

Although there was no significant trend present, most observations indicated that, since 2008, *E. coli* pollution has primarily been of an unacceptable standard for domestic use, while its counts for irrigation use have ranged from tolerable to unacceptable.[1]

Owing to the consistently high *E. coli* counts at this site, where the Limpopo River forms the border between Botswana and South Africa, site A5H006 should be considered a microbial pollution hotspot. Possible sources of microbial pollution that could be identified at this site include sewage facilities at a fuel station and guest lodge located on the Botswanan side of the river, and a truck repair service facility on the South African side. The Groblersbrug border post between Botswana and South Africa is also located at this site and could be considered as a possibility for discharging untreated wastewater into the river. The surrounding area is dedicated to agriculture; thus, animal and human waste from the farms may enter the river via runoff. It is unlikely that the nearest WWTWs, 118 km away, is solely responsible for *E. coli* pollution at the site. However, it should also be noted that the small sample size (40 observations) for this site presents a limitation. The small dataset can be attributed to infrequent and inconsistent monitoring. More comprehensive data and consistent monitoring are necessary to fully determine the quality of the water and the consistent level of pollution at this site.

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[1] There are currently no TWQRs for aquatic ecosystems; however, it is widely understood that aquatic ecosystems are sensitive to the impacts of *Faecal coliforms.* High *E. coli* counts may disrupt the nutrient content of an aquatic ecosystem, leading to nutrient enrichment and the growth of algae and other nuisance plants. These plants prohibit the flow of oxygen in water, thus leading to the mortality of aquatic species (du Plessis, 2014).

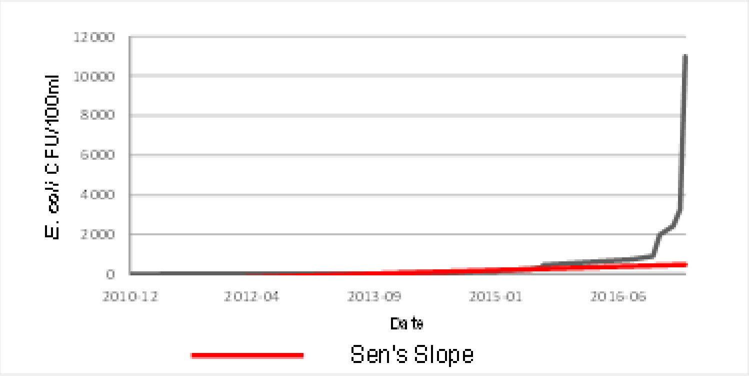

Figure 5.5: MK analysis for microbial water quality at site A7H008 on the Limpopo River for the analysed time period.

Varying trends were established from the results of the MK analysis for the microbial quality of the water at site A7H008 (Figure 5.5). *Ha* was accepted since a *p*-value lower than the significance level of *a=0.05* was computed. The *S* value was positive, indicating a strong increasing trend in *E. coli* CFU/100 ml over the observed time period. As shown in Figure 5.5, the *E. coli* count increased significantly over a short period of time from just over 700 CFU/100 ml in 2016 to 11 000 CFU/100 ml in 2017. The sudden increase in *E. coli* could be considered as an outlier in the dataset; however, the decision was made to include this value in the analysis owing to the clearly increasing concentrations over the six months prior to this significant increase. It is recommended that this site be investigated further to determine whether the recorded data are outliers or whether there is in fact an ongoing *E. coli* pollution problem.

E. coli counts at this site were established to be of an unacceptable standard for domestic and irrigation use. Owing to nutrient enrichment and eutrophication, high concentrations will have adverse effects on aquatic species. Furthermore, site A7H008 is located near a border post between South Africa and Zimbabwe, namely, Beit Bridge border post, where sanitation infrastructure may be discharging human wastewater directly into the river. There also appears to be a WWTWs in Zimbabwe less than two kilometres (2 km) upstream from the site, which may explain the increasing *E. coli* counts at this site. Additionally, two WWTWs are located approximately 20 kilometres upstream from the site on the South African side. Whether untreated or partially treated wastewater is released into the river upstream or near the site cannot, however, be determined. Thus, further investigation and increased monitoring at this site are required.

5.2.1.2. *Correlation Analysis Results for Sites on the Limpopo River*

Table 5.1 provides the coefficients of correlation for the Spearman's correlation analysis completed for water quality at site A5H006 in conjunction with the selected water flow and climate sites. The results of the correlation matrix established that correlations between water quality, water flow, and climate parameters were negative and weak. As indicated in Chapter 4 and Figure 5.1, the large distance between the various monitoring sites presented a limitation, possibly influencing the obtained results.

The results of the Spearman's correlation analysis completed for water quality at site A7H008, and the selected water flow and climate sites of the Limpopo River indicated significant positive and negative correlations between some of the parameters (Table 5.2).

The correlation matrix indicated that various water quality parameters had strong positive correlations with one another. Also, pH, chloride, magnesium, sodium, and sulphate had strong positive correlations with EC; thus, as concentrations of these parameters increased at this site, so did EC.

A strong negative correlation was established between water flow variations and EC. This suggests that as water flow decreased, so EC increased. As the flows returned to their "normal" levels, EC levels in the river declined. This observation was supported by the strong negative correlations of water flow with chloride, magnesium, and sodium which are all ions responsible for conductivity of freshwater (DWAF, 1996a; Karmakar & Singh, 2021). Correlation coefficients with negative values indicate an inverse relationship, which Antonopoulos et al. (2001) states is due to the diluting effects of surface water. The dilution factor is the ratio between the volume of freshwater and the quantity of the physicochemical or microbial parameter being measured. Because of their lower average rainfall, more arid regions present with lower dilution factors (Keller et al., 2014). A reduction in water flow impacts the dilution factor of rivers, often resulting in higher concentrations of pollutants (Enoch, 2018). Thus, the observed inverse relationship between water flow and EC at this site on the Limpopo River exists as a result of variations in the dilution factor.

Table 5.1: Spearman's correlation matrix for site A5H006 on the Limpopo River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp	Average Min. Temp
EC	**1**													
pH	0,630	**1**												
Calcium	0,911	0,653	**1**											
Chloride	0,962	0,587	0,869	**1**										
Magnesium	0,957	0,560	0,940	0,940	**1**									
Sodium	0,938	0,578	0,885	0,940	0,933	**1**								
Phosphate	-0,221	0,142	-0,102	-0,283	-0,224	-0,274	**1**							
Sulphate	0,892	0,631	0,897	0,875	0,899	0,865	-0,145	**1**						
Ammonia	0,172	0,185	0,164	0,171	0,156	0,182	-0,005	0,184	**1**					
Nitrate	0,096	-0,011	0,180	0,055	0,107	0,108	0,093	0,096	0,199	**1**				
Water flow	-0,266	-0,122	-0,124	-0,313	-0,260	-0,258	0,297	-0,123	-0,063	0,148	**1**			
Average Rainfall	-0,202	-0,141	-0,163	-0,235	-0,224	-0,217	0,139	-0,179	-0,238	0,019	0,501	**1**		
Average Max. Temp	-0,144	-0,203	-0,166	-0,164	-0,122	-0,136	0,050	-0,125	-0,026	-0,144	0,251	0,326	**1**	
Average Min. Temp	-0,270	-0,237	-0,219	-0,309	-0,269	-0,272	0,174	-0,211	-0,133	-0,085	0,416	0,583	0,772	**1**

Table 5.2: Spearman's correlation matrix for site A7H008 on the Limpopo River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp	Average Min. Temp
EC	**1**													
pH	0,616	**1**												
Calcium	0,477	0,313	**1**											
Chloride	0,906	0,580	0,429	**1**										
Magnesium	0,845	0,536	0,609	0,886	**1**									
Sodium	0,864	0,558	0,486	0,892	0,877	**1**								
Phosphate	-0,213	-0,387	-0,264	-0,262	-0,267	-0,265	**1**							
Sulphate	0,828	0,662	0,356	0,822	0,739	0,731	-0,281	**1**						
Ammonia	0,104	0,117	0,038	0,029	-0,004	0,043	0,172	0,104	**1**					
Nitrate	-0,165	-0,181	-0,260	-0,128	-0,240	-0,240	0,152	-0,061	0,354	**1**				
Water flow	-0,697	-0,500	-0,488	-0,643	-0,644	-0,673	0,311	-0,493	0,014	0,377	**1**			
Average Rainfall	-0,436	-0,326	-0,378	-0,360	-0,374	-0,377	0,264	-0,392	-0,068	0,151	0,486	**1**		
Average Max. Temp	-0,312	-0,149	-0,282	-0,333	-0,300	-0,321	0,276	-0,256	-0,114	-0,039	0,359	0,442	**1**	
Average Min. Temp	-0,527	-0,399	-0,391	-0,504	-0,483	-0,484	0,346	-0,432	-0,112	0,009	0,579	0,622	0,866	**1**

At site A7H008 (Table 5.2) average minimum temperature was also found to have a strong negative correlation with EC and chloride. Research has shown that low temperatures inhibit EC; thus, as the temperature decreased, so the water at this site became less conductive (Hayashi, 2005). Furthermore, a similar relationship was established between chloride and average minimum temperature. Additionally, the correlation between EC and chloride was very strong, thus indicating that chloride was the primary ion responsible for influencing EC at this site. Therefore, activities that contributed to increased chloride concentrations had the greatest impact on EC which were consequently influenced my temperature variations. As mentioned in the time series trend results for this site and in terms of the aquatic ecosystem TWQRs, chloride was the leading cause of water quality degradation in the river.

Changes in temperature and water flow were thus highly impactful on EC and would be more likely to have negative consequences for the functioning of the aquatic ecosystems near this site. High levels of EC result in increased salinity, which changes the ionic composition of the water. The individual ions responsible for EC may also change in terms of toxicity, thus causing disturbances in biotic communities and negatively affecting the more sensitive species. As a result, biodiversity tends to decrease (Weber-Scannell & Duffy, 2007; Singh et al., 2019).

Table 5.3 provides the coefficients of correlation for the Spearman's correlation analysis completed for microbial monitoring site A5H006. The results indicated no significant correlations between *E. coli* and the climate parameters over the observed time period.

Table 5.3: Spearman's correlation matrix for microbial water quality at site A5H006 on the Limpopo River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	0,171	**1**			
Average Rainfall	0,283	0,274	**1**		
Average Max. Temp	0,099	0,047	0,575	**1**	
Average Min. Temp	0,307	0,242	0,767	0,750	**1**

The correlation matrix indicated that *E. coli* had a weak positive correlation with average minimum temperature (R = 0,307), and no significant correlation with water flow (R = 0,171), average daily rainfall (R = 0,283) and average maximum temperature (R = 0,009). Shamsudin et al. (2016) state that there is a moderate association between parameters when R = 0,30 - 0,49. The correlation analysis for the Rhode River estuary conducted by Shamsudin et al. (2016) indicated a strong positive correlation specifically between temperature and *E. coli* (R = 0,763). This supports the observation that the average minimum temperature at this microbial site may have had an impact on *E. coli*. However, it is worth noting that these authors made use of a Pearson's correlation analysis, which indicates a linear relationship and as discussed in Chapter 4 and does not account for the monotic relationships typically observed between environmental data.

The results obtained for the Spearman's correlation analysis for microbial water quality, water flow, and the climate parameters at site A7h008 again indicated no significant relationships with *E. coli* (Table 5.4). Therefore, no climatic influences on microbial water quality could be determined for this site.

Table 5.4: Spearman's correlation matrix for microbial water quality at site A7H008 on the Limpopo River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp	Average Min. Temp
E. coli	**1**				
Water flow	-0,161	**1**			
Average Rainfall	0,005	0,488	**1**		
Average Max. Temp	-0,032	0,159	0,424	**1**	
Average Min. Temp	0,036	0,557	0,565	0,831	**1**

5.2.1.3. Synthesis: Water Quality and Climate Impacts for the Limpopo River

The physicochemical quality of water in the Limpopo River for the observed time period can generally be described as acceptable. Although some water quality parameters tended to fluctuate to tolerable and/ or unacceptable standards, most parameters were established to be of an ideal to acceptable standard for domestic use, irrigation, and aquatic ecosystems. Overall, the microbial water quality in the Limpopo River can be described as substantially degraded. The *E. coli* at both sites reached unacceptable counts for all uses over the observed time period which could be attributed to several factors, including dysfunctional WWTWs and agricultural activities and livestock farming along the river.

There was a high level of spatial variability, including an upward trend, in terms of the water quality between the sites on the Limpopo River. The mean values for the water quality parameters increased between sites A5H006 and A7H008 (e.g.: the mean EC almost doubled from site A5H006 to site A7H008), thus indicating that the physicochemical quality of the water became more degraded closer to the KNP. The mean values of *E. coli* also increased between the microbial water quality sites, A5H006 and A7H008, thus indicating that the microbial quality of the water in the Limpopo River became more degraded closer to the KNP.

The MK trends in water quality also varied between the sites. Overall, the water quality at site A5H006 became more degraded over time, while no indication of such a trend was evident at site A7H008, except that there were increasing concentrations of ammonia. The microbial water quality sites also varied greatly in terms of their trends. No clear trend was present for site A5H006, while site A7H008 became more degraded over time (i.e., there was an observable increase in *E. coli*). According to the obtained results, the main water quality parameters for the Limpopo River that are cause for concern are therefore EC, chloride, and *E. coli*.

The correlation analyses conducted for sites on the Limpopo River indicated that climate variability has had no significant impact on the physicochemical water quality of the river. Site A5H006 exhibited no relationship between the parameters, while some water quality parameters at site A7H008 exhibited negative relationships with water flow and average minimum temperature. Changes in the *E. coli* counts could not be attributed to climate variability as there was little to no relationship between parameters at both sites.

In conclusion, the water quality of the Limpopo River has a high spatio-temporal variability, and some sites are more at risk of increased pollution than others. However, according to the established results, water quality changes could not be attributed to variations in the local climate.

A discussion of the water quality trends, pollution hot spots, high risk areas and the relationships between water quality and climate variability on the Luvuvhu River now follows.

5.2.2. The Luvuvhu River

The physicochemical quality of the water in the Luvuvhu River was analysed at two sites, namely A9H011 (for the period 1983 - 2017) and A9H012 (1988 - 2018) (Figure 5.1). The microbial quality of the water in the Luvuvhu River was analysed at one site, namely “A9H030 Microbial - Nandoni Dam, downstream of dam weir” (herein after referred to as A9H030), between 2009 and 2015. Water quality data were found to have a predominantly non-normal distribution, with only nine percent (9%) of the data following a normal distribution.

The distribution of data around the mean concentrations for each water quality parameter was similar for sites A9H011 and A9H012. Overall, the water quality differed in terms of the number of outliers in the datasets which suggests that site A9H011 experienced a greater number of extreme pollution events than site A9H012, located further downstream. Thus, the physicochemical quality of the water improved between the sites, as it flowed downstream, becoming more suitable for conservation purposes in the KNP.

The box plot for *E. coli* at site A9H030 on the Luvuvhu River indicated that, owing to the high number of large outliers in the dataset, the dataset mean occurred outside the upper quartile. This resulted in a highly skewed distribution of data. The microbial water quality at site A9H030 exhibited a similar distribution to that at site A7H008 on the Limpopo River. However, the water quality for site A9H030 was established to be of a poorer quality than that for both microbial sites on the Limpopo River. In terms of the microbial quality of the water, this site on the Luvuvhu River was established to be the most degraded in the Limpopo WMA. The results obtained by the time series trend and correlation analyses now follow.

5.2.2.1. Time Series Trend Analysis for Sites on the Luvuvhu River

The results of the MK analyses for the physicochemical water quality parameters at site A9H11 showed varying trends (Figure 5.6). The computed *p*-values for EC, pH, calcium, magnesium, phosphate, sulphate, ammonia, and nitrate indicated that significant trends could be established, including the following. Large positive *S* values revealed strong upward trends for EC and pH, and in calcium and magnesium concentrations over time, thus indicating an overall increase. Large negative *S* values were also established and revealed a strong downward trend for the phosphate, sulphate, ammonia, and nitrate concentrations, thus indicating an overall decline in concentrations.

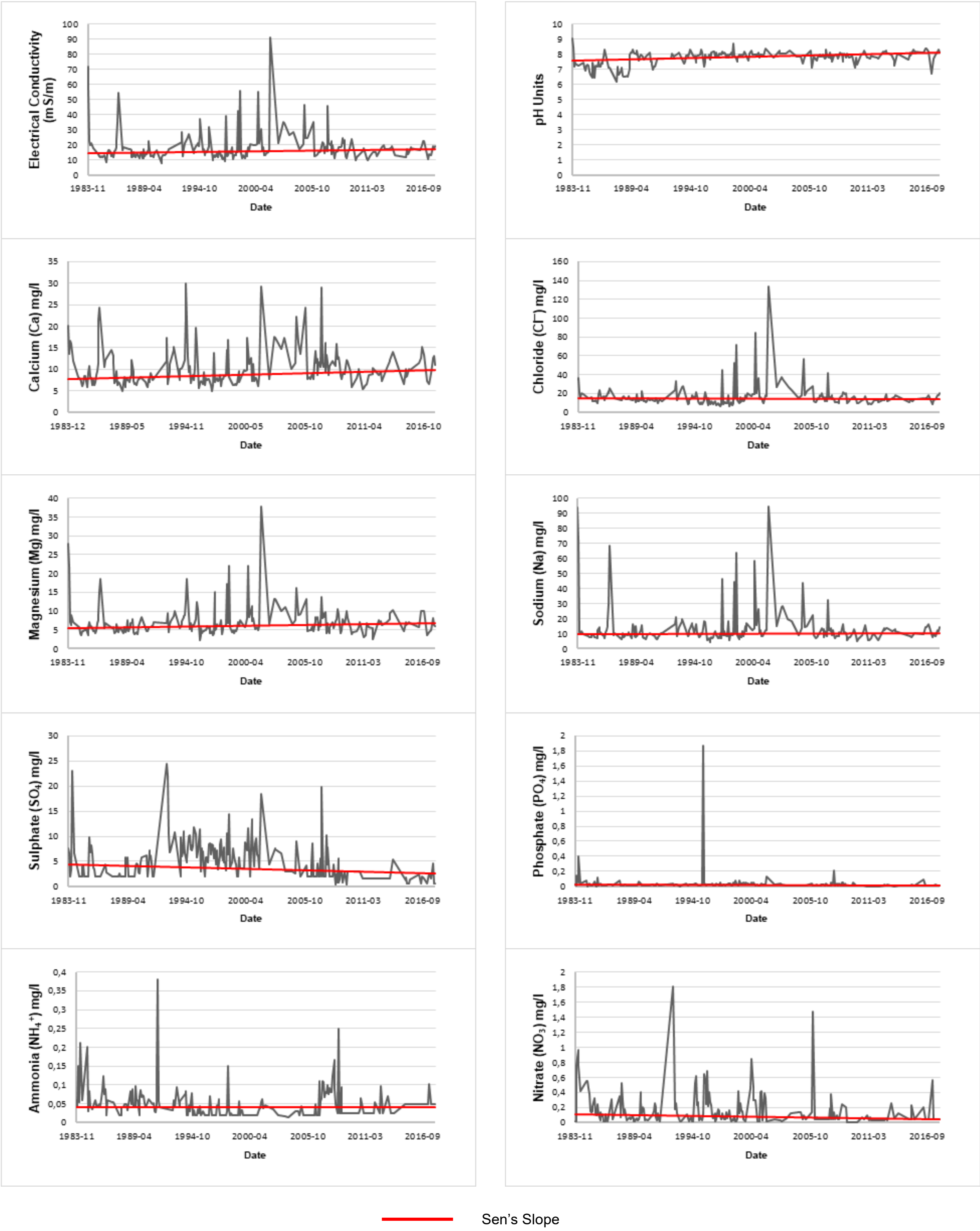

Figure 5.6: MK analyses for physicochemical water quality at site A9H011 on the Luvuvhu River for the analysed time period.

Based on the obtained results, the overall physicochemical quality of the water at site A9H11 appeared to be good. However, the chloride concentrations were established to be of an unacceptable standard in terms of the aquatic ecosystem TWQRs. The phosphate and ammonia concentrations were established to be of an ideal standard, while the nitrate concentrations were within ideal to acceptable ranges for the observed time period.

The concentrations of pH, calcium, sodium, sulphate, ammonia, and nitrate complied with ideal standards for domestic use, while EC, chloride, and magnesium concentrations fluctuated between ideal and acceptable ranges for domestic use. In terms of the TWQRs for irrigation use, the ammonia and nitrate concentrations were within the ideal range, while the chloride and sodium concentrations fluctuated between ideal and acceptable range. EC and pH fluctuated between ideal and tolerable ranges for irrigation use.

The completed MK time series trend analyses for the physicochemical water quality parameters at site A9H012 also provided for observable trends (Figure 5.7). The MK analyses for all parameters, except for nitrate, indicated significant trends. Large positive *S* values revealed strong upward trends for EC and pH, and the calcium, chloride, magnesium, sodium, and ammonia concentrations over the observed time period, thus indicating that overall, the levels of these parameters increased. Large negative *S* values were also established and revealed strong downward trends for the phosphate and sulphate concentrations, thus indicating an overall decline in concentration over the observed time period.

The overall physicochemical quality of the water at this site appeared to be of an ideal standard. Only chloride fell within the unacceptable range for aquatic ecosystems. All other parameters complied with ideal standards for domestic use, irrigation use and aquatic ecosystems.

While the physicochemical quality of the water at this site was determined to be largely of an ideal standard over the 30-year time period, it must be noted that the MK analyses indicated an increasing trend for six out of the 10 water quality parameters. This site should therefore be highlighted as a possible high risk area. As such, there is a need to improve monitoring to ensure that further increases, which may shift the parameters into tolerable levels, be identified in a timeous manner to avoid deterioration in the quality of the water.

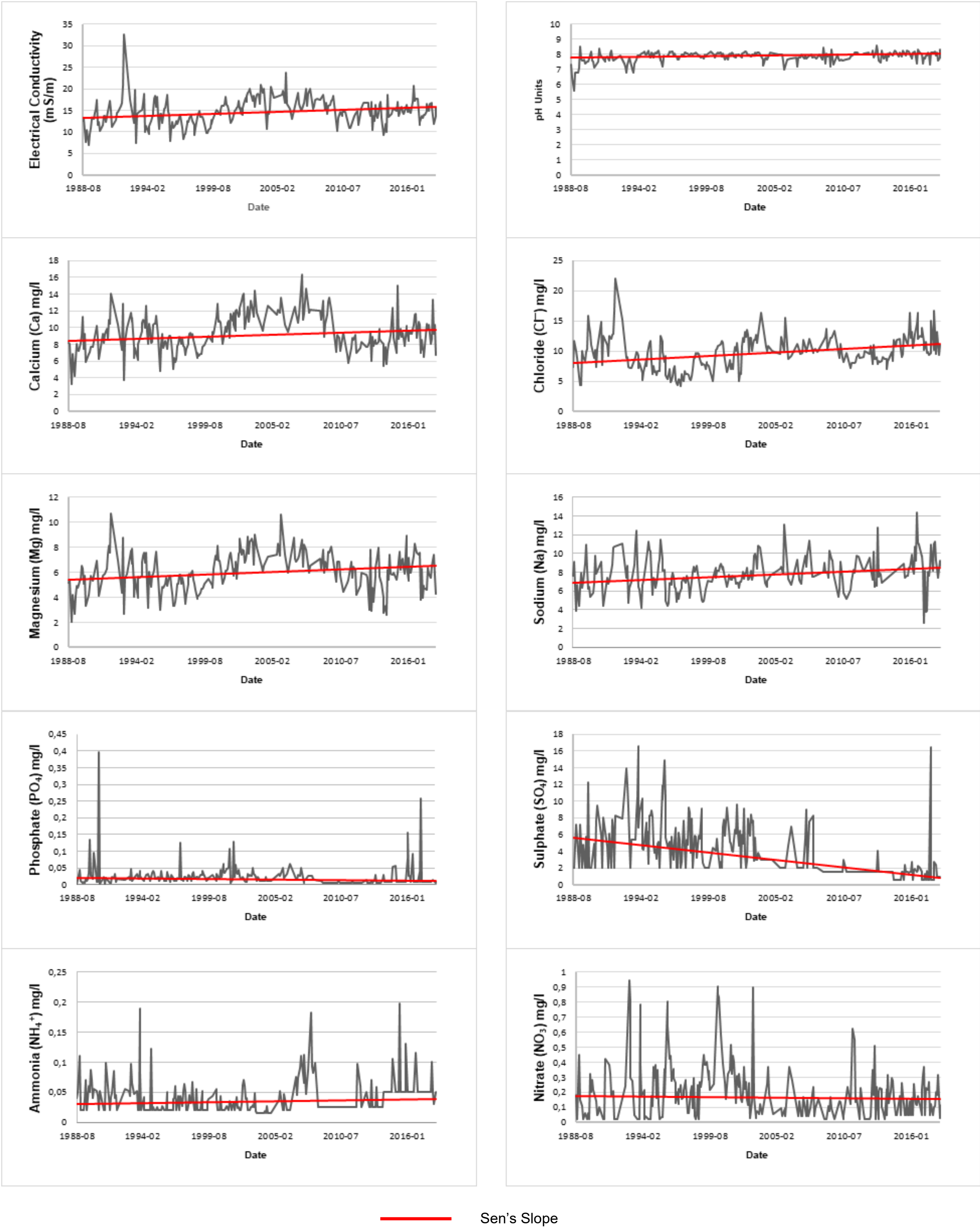

Figure 5.7: MK analyses for physicochemical water quality at site A9H012 on the Luvuvhu River for the analysed time period.

The MK analysis for monitoring the microbial quality of the water at site A9H030 (Figure 5.8) indicated no significant trend for *E. coli* counts. In fact, counts fluctuated widely from 0 CFU/100 ml in 2011 to 30 000 CFU/100 ml in 2011. While a count of 30 000 CFU/100 ml may be considered an outlier, the decision to include this value in the analysis was due to the multiple incidences of high pollution events between 2009 and 2015. The *E. coli* counts did not appear to coincide with the wet and dry seasons; thus, episodes of excessive *E. coli* counts at this site could more likely be associated with anthropogenic activities. Several observations for *E. coli* fell within the unacceptable range for domestic and irrigation use. Less than 50% of the observations complied with the tolerable range prescribed for domestic use, while 75% complied with the tolerable range prescribed for irrigation.

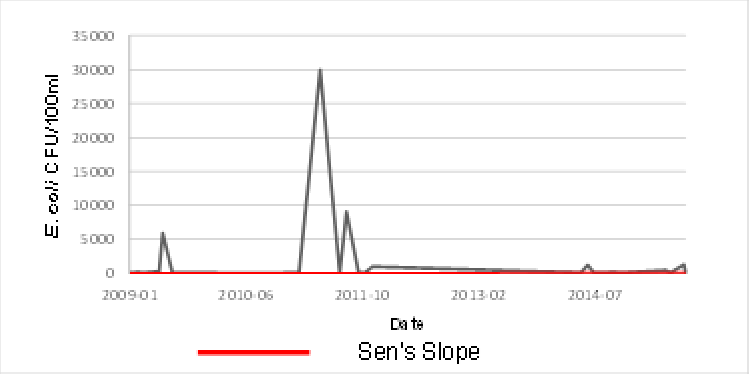

Figure 5.8: MK analysis for microbial water quality at site A9H030 on the Luvuvhu River for the analysed time period.

5.2.2.2. Correlation Analysis Results for Sites on the Luvuvhu River

The coefficients of correlation for the Spearman's correlation analysis completed for water quality at site A9H011 and the selected water flow and climate sites on the Luvuvhu River indicated both significant and moderate positive and negative relationships between some of the parameters (Table 5.5). Overall, it was established that variations in water flow, and not climatic parameters, had the greatest impact on water quality.

The correlation matrix indicated that various water quality parameters (EC, pH, calcium, chloride, magnesium, and sodium) had moderate to strong positive correlations with one another. These ions all contributed to the conductivity of the river at this site, as well as to its acidity or alkalinity (DWAF, 1996a).

Table 5.5: Spearman's correlation matrix for site A9H011 on the Luvuvhu River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,430	**1**												
Calcium	0,864	0,386	**1**											
Chloride	0,832	0,306	0,688	**1**										
Magnesium	0,898	0,478	0,819	0,714	**1**									
Sodium	0,867	0,466	0,692	0,794	0,821	**1**								
Phosphate	0,142	0,120	0,094	0,096	0,058	0,169	**1**							
Sulphate	0,065	-0,001	0,015	0,030	0,070	0,163	0,382	**1**						
Ammonia	-0,035	-0,083	0,057	-0,007	-0,041	-0,069	-0,019	-0,219	**1**					
Nitrate	-0,177	-0,143	-0,154	-0,056	-0,275	-0,156	0,235	0,156	0,038	**1**				
Water flow	-0,424	-0,267	-0,362	-0,248	-0,533	-0,396	0,191	0,140	-0,072	0,293	**1**			
Average Rainfall	-0,125	-0,130	-0,052	-0,061	-0,201	-0,159	0,151	0,095	-0,141	0,210	0,580	**1**		
Average Max. Temp.	0,069	0,035	0,146	0,076	0,047	0,068	-0,052	-0,103	-0,026	-0,102	0,199	0,409	**1**	
Average Min. Temp.	-0,116	-0,104	-0,007	-0,059	-0,155	-0,109	0,015	-0,033	-0,065	0,101	0,426	0,646	0,869	**1**

A moderate positive correlation was established between phosphate and sulphate. This may be attributed to the use of fertilisers along the farms bordering on the river. The use of fertilisers that contain gypsum contribute to increased sulphate concentrations, while most fertilisers primarily contribute to increased phosphate concentrations (Nosrati, 2015; Zak et al., 2021). However, both sulphates and phosphates are also naturally occurring substances that arise from minerals present in soil and rock (DWAF, 1996a; DWAF, 1996d; Huizenga, 2011; du Plessis, 2014). Thus, increases in both water quality parameters could be attributed to both anthropogenic and natural sources.

Variations in water flow could be associated with conductivity at site A9H011. A moderate negative correlation was established. This observation was further supported by the strong negative correlation between water flow and magnesium, as well as the moderate negative correlations between water flow and calcium and sodium. These ions were thus responsible for the conductivity of the water (DWAF, 1996a), with the correlation between EC and magnesium being strongest and indicating that magnesium was the main ion responsible for variations in EC at site A9H011. As previously mentioned, the inverse relationship between water flow and EC can be problematic for aquatic ecosystem health as water flow impacts the dilution factor of surface water, which could result in higher levels of EC. Furthermore, increased salinity, indicated by the aforementioned parameters, is toxic to the aquatic environment (Weber-Scannell & Duffy, 2007; Keller et al., 2014; Enoch, 2018; Singh et al., 2019).

The established coefficients of correlation derived from the completed Spearman's correlation analysis for site A9H012 (Table 5.6) show significant positive correlations between some of the parameters, and moderate positive and negative correlations between others.

The general conclusion reached was that variations in climate parameters had little association with changes in water quality. As observed at the previously mentioned sites, the correlation matrix indicated strong positive correlations between all major ions. A moderate positive correlation was also established between phosphate and sulphate.

Table 5.6: Spearman's correlation matrix for site A9H012 on the Luvuvhu River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,244	**1**												
Calcium	0,818	0,206	**1**											
Chloride	0,635	0,058	0,496	**1**										
Magnesium	0,845	0,170	0,810	0,589	**1**									
Sodium	0,659	0,182	0,521	0,569	0,626	**1**								
Phosphate	-0,027	-0,107	0,076	-0,069	-0,013	-0,060	**1**							
Sulphate	-0,053	-0,171	0,087	-0,214	-0,022	-0,132	0,482	**1**						
Ammonia	-0,002	-0,038	-0,092	0,216	-0,044	0,100	-0,017	-0,183	**1**					
Nitrate	-0,369	-0,133	-0,235	-0,196	-0,309	-0,400	0,203	0,228	0,058	**1**				
Water flow	-0,390	-0,194	-0,276	-0,173	-0,359	-0,441	0,172	0,098	-0,006	0,571	**1**			
Average Rainfall	-0,186	-0,180	-0,157	0,056	-0,198	-0,174	0,140	0,128	-0,022	0,260	0,540	**1**		
Average Max. Temp.	0,060	0,007	0,034	0,148	-0,006	0,030	0,085	0,056	0,060	-0,122	0,227	0,445	**1**	
Average Min. Temp.	-0,135	-0,111	-0,129	0,064	-0,177	-0,098	0,130	0,077	0,056	0,067	0,462	0,669	0,872	**1**

Like site A9H011, this may be attributed to the use of fertilisers on the farmlands along the river, or to natural sources, such as the minerals present in the soil and rock (DWAF, 1996a; DWAF, 1996d; Huizenga, 2011; du Plessis, 2014).

As with site A9H011, a moderate negative correlation was established between water flow and EC, and a similar relationship observed. This observation was further supported by the strong negative correlation established between water flow and magnesium, as well as between water flow and sodium, with the ions contributing to the increased conductivity of the water source (DWAF, 1996a). Potentially higher levels of salinity would then be caused in the waterway, thereby affecting the functioning of the biotic community and by extension, aquatic biodiversity (Weber-Scannell & Duffy, 2007; Keller et al., 2014; Enoch, 2018; Singh et al., 2019). Petersen et al. (2014) observed this relationship in 2013 after the river experienced a major flood, causing water quality to deteriorate in the river temporarily. This furthermore caused a negative response in both macroinvertebrate and fish communities in the river.

Table 5.7 provides the coefficients of correlation obtained from the completed Spearman's correlation analysis for the microbial quality of the water at site A9H030, water flow and the selected climate sites on the Luvuvhu River. The results indicated no significant correlations for *E. coli*. No relationships were established between *E coli* and water flow (R = -0,201), average daily rainfall (R = -0,194), average maximum temperature (R = -0,251), or average minimum temperature (R = -0,172).

Table 5.7: Spearman's correlation matrix for microbial water quality at site A9H030 on the Luvuvhu River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	-0,201	**1**			
Average Rainfall	-0,194	0,105	**1**		
Average Max. Temp.	-0,251	0,150	0,556	**1**	
Average Min. Temp.	-0,172	0,194	0,667	0,923	**1**

5.2.2.3. Synthesis: Water Quality and Climate Impacts for the Luvuvhu River

Overall, the physicochemical quality of the water in the Luvuvhu River can be classified as being of an acceptable standard. Although some water quality parameters fluctuated to tolerable levels, most parameters remained within ideal to acceptable standards for domestic use, irrigation, and aquatic ecosystems. Overall, the microbial water quality of the Luvuvhu River can be classified as substantially degraded. The *E. coli* counts at the site were mostly of an unacceptable standard for all water uses.

Minimal spatial variability was found between the relevant sites on the Luvuvhu River. The mean values for the water quality parameters were similar for sites A9H011 and A9H012, thus indicating that the physicochemical quality of the water remained similar for both. The spatial variance in *E. coli* could not be established as only one microbial site was available and analysed. However, this site, A9H030, can be considered an *E. coli* pollution hotspot and should be closely monitored since its recorded tolerable and unacceptable levels could result in water-related illnesses and thus pose a risk to human and environmental health.

The established trends in the physicochemical quality of the water were similar for the two sites. The physicochemical water quality parameters at both sites indicated a largely increasing trend, meaning that the quality of water became more degraded over time. There was little variation between the two sites, thus indicating that the entire lower portion of the river closest to the KNP was under duress, with polluted water flowing into the KNP. Furthermore, the microbial quality of the water exhibited no significant trend; however, the *E. coli* counts varied greatly over time with some counts as high as 30 000 CFU/100 ml. The main water quality parameters of concern for the Luvuvhu River are those presenting with an increasing trend, specifically chloride and *E. coli*.

The correlation analyses conducted for sites on the Luvuvhu River indicated only weak relationships, namely, that the river was not largely influenced by climate variability. However, the correlation analyses showed that some of the parameters at the physicochemical water quality monitoring sites could be associated with variations in the river's water flow. These parameters, revealed monotic relationships, increasing in concentration as water flow reduced. There were also strong positive relationships between all major ions. However, no relationship between *E. coli* and climate variability was established.

In conclusion, it can be stated that the water quality of the Luvuvhu River is gradually becoming more degraded, with the entire lower portion of the river and the KNP at risk of degradation. However, it was also established that changes to the quality of its water are unlikely due to variations in the local climate, with anthropogenic factors, such as poor agricultural practices, urbanisation and polluted urban runoff, and the inappropriate management of land use, being the strongest influences (Gumbo et al., 2016).

5.2.3. Water Quality Compliance for the Limpopo WMA

To further investigate temporal trends in water quality compliance, compliance graphs were compiled for the Limpopo WMA (Figure 5.9). They provide the percentages of ideal, acceptable, tolerable, or unacceptable measurements taken for domestic use or aquatic ecosystems for the observed time period. A comparison between the full study period and the most recent past five years was made to determine whether water resource planning and management had improved the water quality of the Limpopo WMA over time or had contributed to its deterioration.

As was established by the time series trend analyses, the physicochemical quality of the water was mostly, except for chloride, of an ideal to acceptable standard. On the other hand, the microbial water quality was mostly of an unacceptable standard. Historically, the water quality trends for the selected sites in the Limpopo WMA were therefore primarily characterised by microbial contamination, followed by salinity (sodium, magnesium, chloride, and calcium).

Compared to the full study period, overall, water quality over the last five years of the study period showed, to some extent, an overall deterioration. Unacceptable *E. coli* counts presented with the largest shift, rising from 76% to 89%. Sodium, calcium, and EC also shifted significantly from ideal to acceptable levels in that they increased by eight percent (8%), 12% and nine percent (9%), respectively. Compared to the full study period, chloride saw a four percent (4%) shift from ideal/acceptable to tolerable standards over the last five years of the study period. Only ammonia and phosphate remained unchanged.

WWTWs and other diffuse forms of pollution, such as runoff from farms and from animal/livestock waste products, as well as waste from informal settlements, are thus a leading concern for these sites. Owing to mismanagement and inadequate maintenance, most WWTWs do not comply with the minimum standards; this needs to be addressed to avoid ongoing environmental and human health problems (du Plessis, 2019; DWS, 2023a; DWS, 2023b).

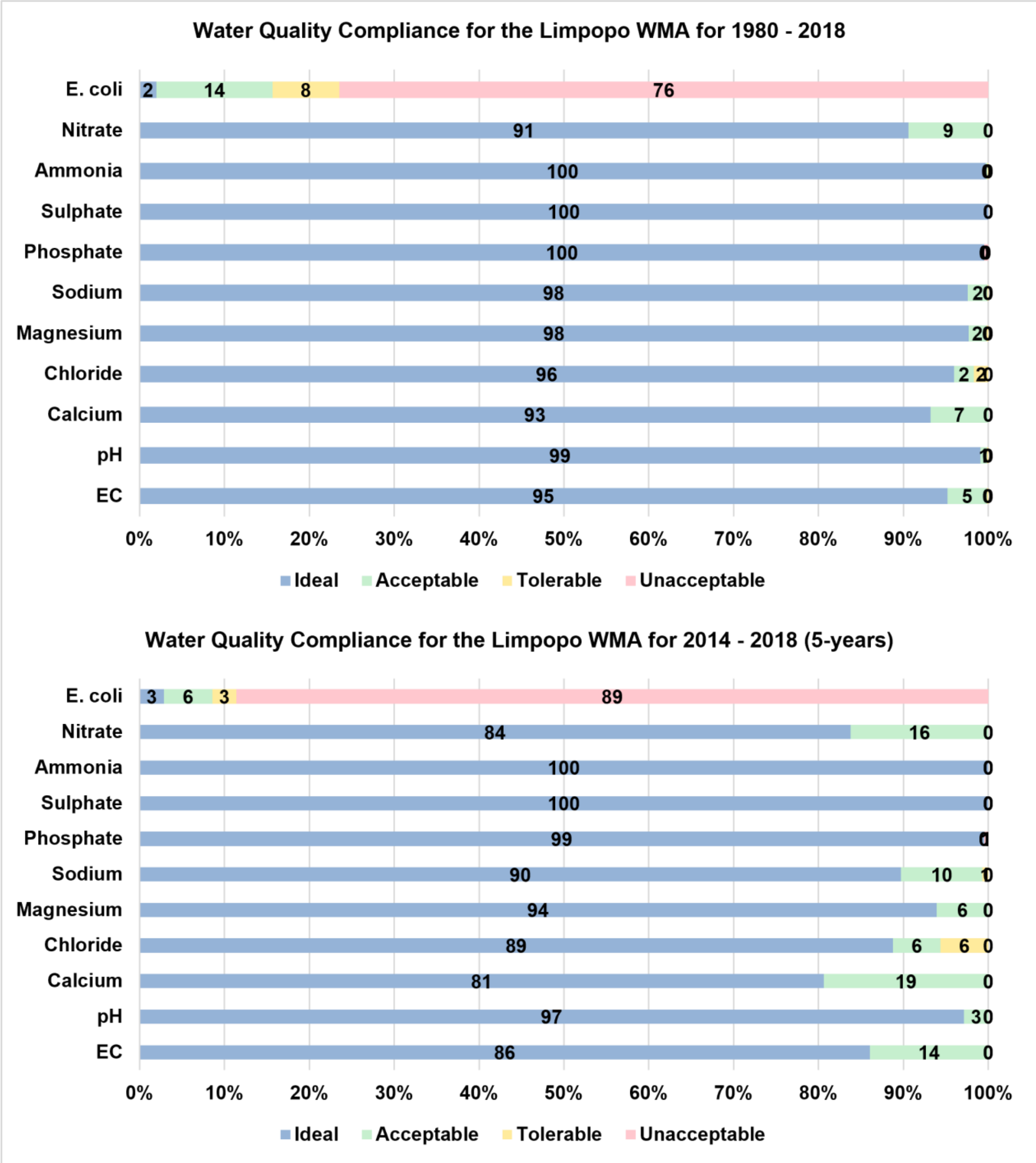

Figure 5.9: Percentage of compliance of national in-stream water quality guidelines at selected monitoring sites in the Limpopo WMA with a five-year to full study period comparison.

A discussion of the established water quality trends of the Olifants WMA now follows. It specifically identifies the relationships between water quality and climate variability for sites in the Olifants WMA and focuses on the pollution hot spots and high risk areas in this WMA.

5.3. Analyses for the Olifants Water Management Area

As described in Chapter 2, the rivers examined in the Olifants WMA for this research include the Shingwedzi, Letaba and Olifants Rivers. Over the years, the declining state of water resources in the Olifants WMA has received a great deal of attention. Increased mining activity and poor waste and wastewater management have resulted in the deaths of fish and crocodiles, making the WMA an area of concern (Ferreira & Pienaar, 2011; Pollard & du Toit, 2011).

The Shingwedzi River is the largest of the seasonal rivers in the KNP, flowing only after sufficient rain has fallen (van Vuuren, 2017b). The Shingwedzi riverbanks are afforested areas, with tourism being the particular focus area. Furthermore, the river is also used for irrigation to support the commercial and subsistence farms along its banks (Fouché & Vlok, 2012).

The Letaba River is highly impacted by anthropogenic influences including, but not limited to, commercial plantations, agriculture, and sand mining, and is, therefore, prone to human-induced erosion (DWS, 2019). Historically, there has been a noticeable decline in the quality of its water near the KNP. This has been due to salinisation and nutrient enrichment emanating from untreated and partially treated wastewater and agricultural runoff (Pollard & du Toit, 2011).

In terms of the Olifants River, a large part of the eastern portion of the river's catchment is under conservation. However, the land use types/ activities outside the KNP borders that are the main factors affecting water quality include irrigated commercial agriculture, afforestation, livestock and game farming, mining, and small-scale rain-fed agricultural initiatives (Ashton and Dabrowski, 2011; Biggs et al., 2017).

Figure 5.10 indicates the selected sites for collecting research data regarding water quality, water flow and climate for the data analysis of rivers in the Olifants WMA. A discussion of the water quality trends, pollution hot spots, high risk areas and the relationships between water quality, water flow and climate variability for sites on the Shingwedzi River now follows.

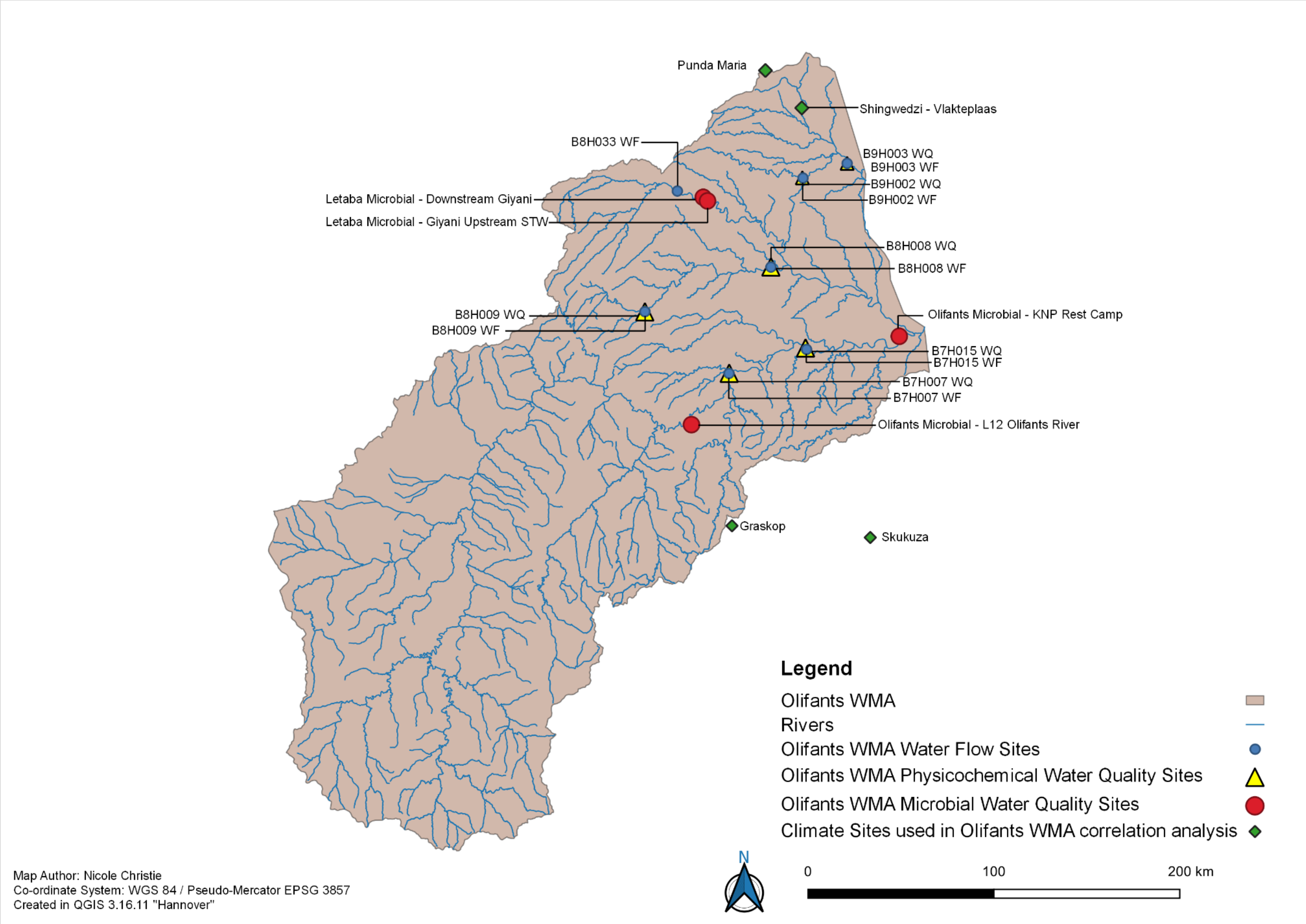

Figure 5.10: Map of the Olifants WMA - water quality, water flow and climate monitoring sites.

5.3.1. The Shingwedzi River

The physicochemical quality of the water in the Shingwedzi River was analysed at two sites, namely B9H002 and B9H003 (Figure 5.10) between 1984 and 2018. No microbial water quality sites met the criteria for inclusion in the analysis as none of the datasets complied with the minimum data requirements as set out in Chapter 4. With less than four measurements per annum and, therefore, numerous gaps in the content, the datasets for microbial water quality on the Shingwedzi River were incomplete.

The physicochemical water quality data for the Shingwedzi River were all non-normally distributed. The distribution of data around the mean, as indicated by the box plots, as well as the mean for each water quality parameter, was similar for the two sites. This observation was consistent with the results obtained from the completed MK analyses, which indicated virtually identical trends in the physicochemical quality of the water at both sites. A discussion of the results obtained through the time series trend and correlation analyses now follows.

5.3.1.1. Time Series Trend Analysis for Sites on the Shingwedzi River

The MK analyses for physicochemical water quality parameters at site B9H002 detected a trend for all parameters, except phosphate (Figure 5.11). Large positive *S* values revealed strong upward trends for EC, pH, calcium, chloride, magnesium, sodium, and sulphate, thus indicating that the overall concentrations of these parameters increased over the observed time period. Large negative *S* values revealed strong downward trends for ammonia and nitrate, indicating an overall decrease in the concentrations.

EC and the chloride and sodium concentrations were within ideal to tolerable levels for domestic use and irrigation. However, some of these values were consistently of a tolerable level; thus this site should be classified as a potentially high risk area for future pollution. The pH levels and the sulphate and nitrate concentrations were predominantly of an ideal standard for domestic use and irrigation.

For domestic use, magnesium concentrations ranged from ideal to tolerable levels, while ammonia concentrations were within ideal to acceptable levels. However, since the calcium concentrations fluctuated to unacceptable levels for domestic use in the years 1998 - 2001, this site should be highlighted as high risk for future pollution. Fluctuating calcium concentrations are of concern and could have negative impacts on the components of freshwater ecosystems. Calcium is a carbonate, which partially

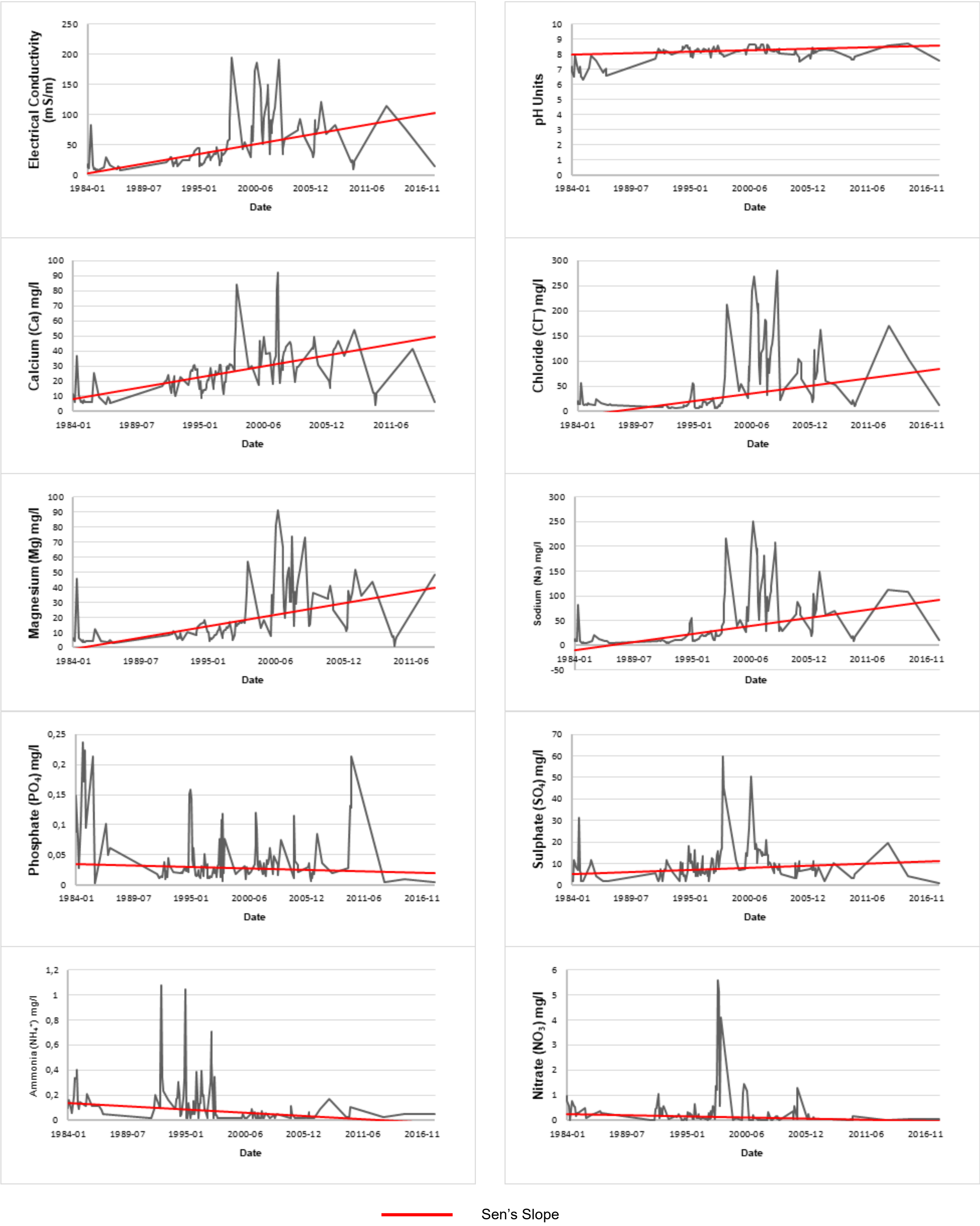

Figure 5.11: MK analyses for physicochemical water quality at site B9H002 on the Shingwedzi River for the analysed time period.

governs the pH of a waterbody which in its turn controls carbon cycling. Thus, when present in excessive amounts in freshwater bodies, calcium may contribute to acidity (Weyhenmeyer et al., 2019).

The phosphate concentrations were within the ideal range for aquatic ecosystems, the ammonia concentrations were within ideal to acceptable levels, and the nitrate concentrations were within ideal to tolerable levels. However, the chloride concentrations proved to be of an unacceptable standard for aquatic ecosystems.

The MK analyses for the physicochemical quality of the water at site B9H003 returned the same results (Figure 5.12) as those for site B9H002 (Figure 5.11). All parameters, except for phosphate, presented with computed *p*-values lower than the significance level of $a=0.05$, thus indicating a trend. Large positive *S* values revealed strong upward trends for EC, pH, calcium, chloride, magnesium, sodium, and sulphate, indicating that the overall concentrations of these parameters increased over the observed time period. Large negative *S* values revealed strong downward trends for ammonia and nitrate, indicating an overall decrease in concentrations.

In terms of its suitability for domestic use, the EC and pH levels, and the calcium and ammonia concentrations fluctuated between ideal to acceptable levels over the observed time period. The chloride, magnesium, and sodium concentrations were within ideal to tolerable levels stipulated for domestic use. However, it should be highlighted that between 1998 and 2000, the chloride concentrations reached levels of almost 300 mg/ℓ. While this does not present problems for human consumption, the TWQRs for aquatic ecosystems are stringent, and such high concentrations may rapidly exceed the tolerance levels of some sensitive aquatic species, thus disrupting the process of osmoregulation. Chloride can lead to the acidification of waterways and mobilise various metals found in soils which are toxic to the aquatic environment (Enoch, 2018).

Between 1998 and 2005, sodium concentrations also rose to 250 mg/ℓ. As discussed in Chapter 3, increased sodium is a leading cause of increased salinity in freshwater bodies. In fact, saline water can affect the ability of freshwater aquatic organisms to maintain an osmatic balance. As salinity increases, so the abundance of freshwater species may decline (Cañedo-Argüelles et al., 2019). It should be noted that elevated sulphate concentrations can alter the cycling of nitrate and phosphate, thus causing an imbalance that leads to eutrophication (Zak et al., 2021). It was established that the sulphate and nitrate concentrations were at an ideal level, thus indicating a very low to negligible risk of eutrophication.

For irrigation use, EC and pH, and the chloride, sodium, and nitrate concentrations fluctuated between ideal and tolerable levels. Importantly, the completed MK analysis showed that most parameters followed an increasing trend. This site should therefore be flagged as a high risk area for increased future pollution.

The ammonia concentrations were of an ideal standard for the observed time period in terms of irrigation use, as were the phosphate concentrations for aquatic ecosystems. Furthermore, the ammonia concentrations fluctuated between ideal and acceptable levels for aquatic ecosystems, while those for nitrate fluctuated between ideal and tolerable levels and rose to levels between 3 mg/ℓ and 6 mg/ℓ in 1997/1998 and 2005, respectively.

Since nitrate exhibited an overall decreasing trend over the observed time period, it is unlikely that it would pose a eutrophication risk to the river. On the other hand, however, once again, the chloride concentrations were within the unacceptable range for aquatic ecosystems and, owing to the potential negative effects of chloride on the environment, should, as previously described in this chapter, be highlighted as a concern.

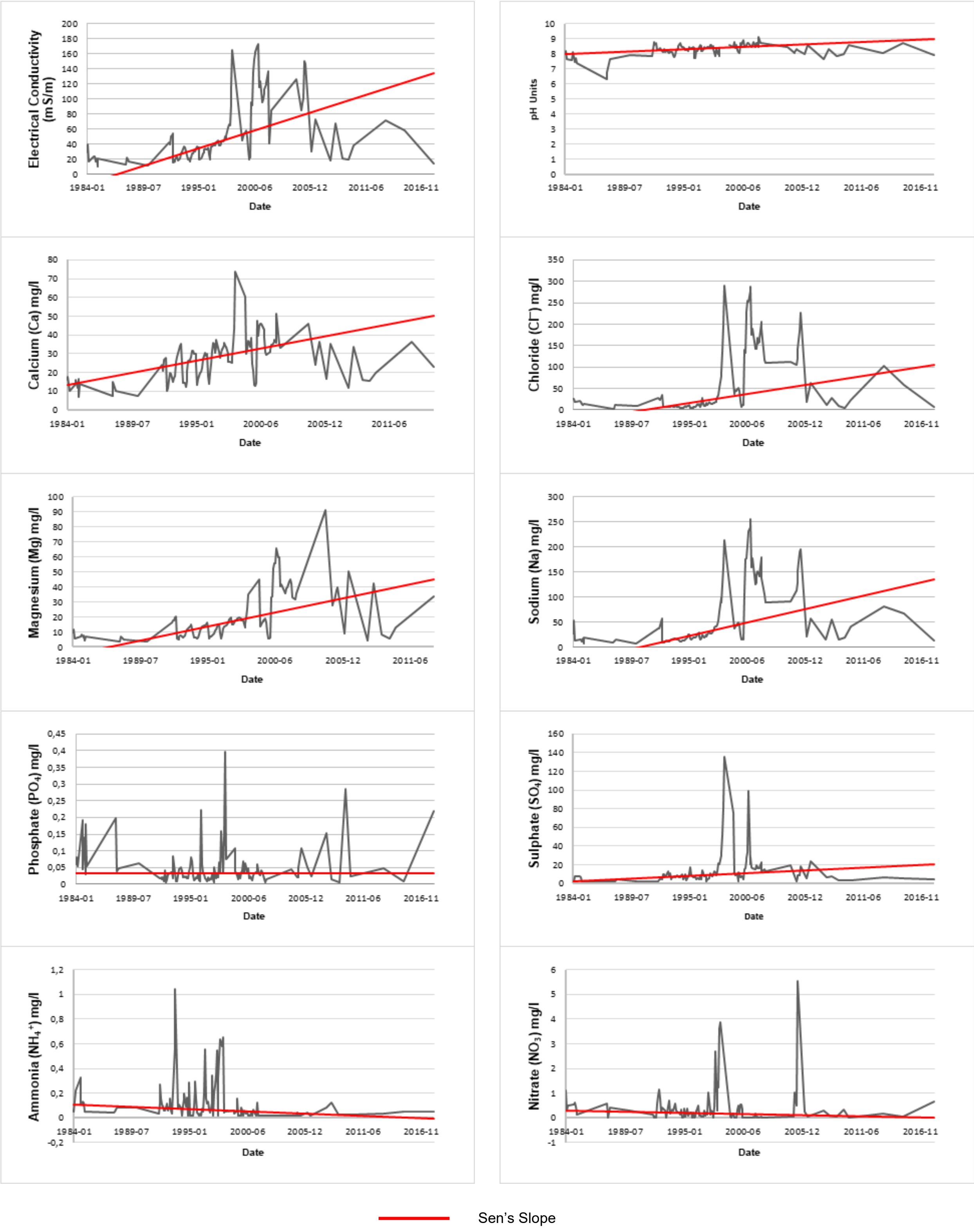

Figure 5.12: MK analyses for physicochemical water quality at site B9H003 on the Shingwedzi River for the analysed time period.

5.3.1.2. Correlation Analysis Results for Sites on the Shingwedzi River

The established coefficients of correlation for the Spearman's correlation analysis completed for site B9H002 returned significant to moderate positive and negative correlations between water quality and the climate parameters (Table 5.8). Overall, it could be determined that variations in the climate parameters may be associated with changes in water quality, and that site B9H002 appears to be more susceptible to variations in the local climate when compared to the previously analysed sites in the Limpopo WMA.

The correlation matrix indicated strong positive correlations between EC and all major ions (calcium, chloride, magnesium, and sodium). Ammonia had a strong negative correlation with chloride, which indicates that the quality of the water at the site was influenced by domestic and industrial pollutant sources such as untreated or partially treated wastewater effluent (Table 3.1). Moderate negative correlations were also established between ammonia and EC, calcium, and magnesium. Since EC had strong positive correlations with calcium and magnesium, this may suggest that these are the primary influencing factors for conductivity. Nitrate had moderate negative correlations with pH and sodium. Since the correlation between pH and sodium was a strong and positive one, this may indicate that nitrate and sodium were the primary regulators of acidity and alkalinity at this site.

Water flow had a strong negative correlation with calcium and moderate negative correlations with EC, pH, magnesium, and sodium, respectively. Water flow also had a moderate positive correlation with phosphate. In terms of possible correlations between water quality and the respective climate parameters, the matrix showed moderate associations. Average rainfall had a moderate positive correlation with water flow; thus, it can be deduced that in terms of these parameters average rainfall also affected water quality specifically. This deduction is supported by correlation results indicating moderate inverse relationships between average rainfall and EC, pH, calcium, and magnesium, respectively, as well as a moderate positive correlation between average rainfall and phosphate.

The average maximum temperatures were only moderately associated with variations in pH, while the average maximum temperatures were moderately associated with variations in pH, calcium, and magnesium.

Table 5.8: Spearman's correlation matrix for site B9H002 on the Shingwedzi River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,563	**1**												
Calcium	0,911	0,499	**1**											
Chloride	0,863	0,298	0,704	**1**										
Magnesium	0,946	0,532	0,881	0,797	**1**									
Sodium	0,967	0,503	0,830	0,909	0,913	**1**								
Phosphate	-0,189	-0,256	-0,267	0,045	-0,258	-0,131	**1**							
Sulphate	0,505	0,337	0,426	0,417	0,413	0,498	-0,010	**1**						
Ammonia	-0,441	-0,041	-0,331	-0,522	-0,402	-0,522	0,169	-0,268	**1**					
Nitrate	-0,288	-0,328	-0,193	-0,250	-0,298	-0,334	0,158	-0,008	0,311	**1**				
Water flow	-0,428	-0,416	-0,545	-0,105	-0,422	-0,327	0,320	-0,073	-0,015	0,188	**1**			
Average Rainfall	-0,327	-0,395	-0,446	-0,085	-0,356	-0,223	0,377	-0,077	0,081	0,184	0,481	**1**		
Average Max. Temp.	-0,139	-0,312	-0,162	-0,072	-0,181	-0,126	0,086	-0,077	-0,046	0,022	0,055	0,336	**1**	
Average Min. Temp.	-0,291	-0,383	-0,365	-0,161	-0,338	-0,231	0,148	-0,071	-0,046	0,077	0,297	0,600	0,845	**1**

As indicated by the coefficients of correlation in the Spearman's correlation analysis, significant to moderate positive and negative relationships were established for site B9H003 and the selected water flow and climate parameters (Table 5.9). The results suggest that site B9H003 appears to be susceptible to variations in the local climate.

As in the case of B9H002, the correlation matrix indicated that there was a moderate to strong positive correlation between EC and all major ions (calcium, chloride, magnesium, and sodium). Another significant relationship among the water quality parameters was the strong negative correlation between nitrate and pH. This inverse relationship is extensively supported by previous literature, namely, that as nitrate increases, so pH declines, thus leading to a freshwater source becoming more acidic. It should be noted that the primary productivity of freshwater organisms declines rapidly below a pH of 5 (Enoch, 2018).

Water flow had moderate negative correlations with EC and calcium, while average rainfall had moderate negative correlations with EC, pH, calcium, and magnesium. Average maximum temperature had moderate negative correlations with pH and calcium, and average minimum temperature had moderate negative correlations with EC, pH, calcium, and magnesium. Since the correlations of these parameters were all inversely related, variations in the water flow, average rainfall and in the minimum and maximum temperatures of the region all impacted on the pollutants and nutrients responsible for the physicochemical quality of the water at this site on the Shingwedzi River.

Table 5.9: Spearman's correlation matrix for site B9H003 on the Shingwedzi River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,607	**1**												
Calcium	0,848	0,628	**1**											
Chloride	0,885	0,458	0,656	**1**										
Magnesium	0,936	0,634	0,868	0,817	**1**									
Sodium	0,958	0,559	0,755	0,923	0,890	**1**								
Phosphate	-0,131	-0,382	-0,265	0,077	-0,176	-0,030	**1**							
Sulphate	0,592	0,441	0,558	0,523	0,535	0,562	0,086	**1**						
Ammonia	-0,253	-0,177	-0,141	-0,294	-0,258	-0,306	-0,104	-0,137	**1**					
Nitrate	-0,330	-0,579	-0,305	-0,263	-0,355	-0,320	0,355	-0,007	0,346	**1**				
Water flow	-0,331	-0,241	-0,412	-0,053	-0,294	-0,220	0,284	-0,121	-0,183	0,032	**1**			
Average Rainfall	-0,315	-0,319	-0,393	-0,116	-0,312	-0,198	0,335	-0,173	-0,062	0,098	0,544	**1**		
Average Max. Temp.	-0,207	-0,312	-0,330	-0,136	-0,206	-0,126	0,133	-0,253	-0,020	0,111	0,031	0,321	**1**	
Average Min. Temp.	-0,377	-0,443	-0,495	-0,224	-0,375	-0,256	0,248	-0,321	-0,064	0,166	0,340	0,638	0,815	**1**

5.3.1.3. Synthesis: Water quality and climate impacts for the Shingwedzi River

A large portion of the Shingwedzi River is located within the borders of the KNP; thus, it is essential that the quality of its water should be of acceptable standard for conservation initiatives. For the observed time period, the physicochemical quality of the water in the Shingwedzi River could be described overall as tolerable but should be highlighted as a potential high risk area and be carefully monitored to limit or reduce ongoing pollution.

No spatial variability for water quality between the sites on the Shingwedzi River was established. The mean values of the water quality parameters were similar for sites B9H002 and B9H003, thus indicating that the physicochemical quality of the water remained stable between the sites. The results from the completed MK analyses supported this observation, i.e., that the water quality between the sites displayed little spatial variation, and rather became more degraded at both sites over time. The entire lower portion of the river closest to the KNP was found to be under stress and the quality of the water flowing into the KNP exhibited a further trend toward degrading water quality. The main water quality parameters of concern for the Shingwedzi River were those presenting with an increasing trend, specifically EC and the other major ions, which include calcium, chloride, magnesium, and sodium. This finding is particularly relevant for current research into the salinisation of KNP rivers, such as the Shingwedzi River, which is one of the least studied rivers.

The correlation analyses conducted for the sites on the Shingwedzi River indicated that the river is susceptible to climate variability. Overall, the water quality of the Shingwedzi River exhibited a moderate to strong correlation with climate variability. Correlation analyses established that some parameters, specifically at the physicochemical water quality monitoring sites, could be associated with variations in water flow, average rainfall, and average minimum and maximum temperature. These parameters reflected monotic relationships, varying in the opposite direction to the climate parameters.

In conclusion, it can be stated that the water quality of the Shingwedzi River has declined over time and has placed the entire lower portion of the river and the KNP at increased risk of degradation. Climate variability has also played a role in this degradation as is evident from the established correlations between water quality and the respective climate parameters.

A discussion of the established water quality trends, pollution hot spots, high risk areas and the relationships between water quality and climate variability for sites on the Letaba River now follows.

5.3.2. *The Letaba River*

The physicochemical quality of the water in the Letaba River was analysed at two sites, namely, B8H008 and B8H009 (Figure 5.10). For site B8H008, data were analysed between 1977 and 2018 and for site B8H009, between 1976 and 2018. The microbial quality of the water in the Letaba River was analysed at two sites, namely "Letaba Microbial - Downstream Giyani" and "Letaba Microbial - Giyani Upstream STW". Data for both sites were analysed between 2001 and 2015.

The water quality data for the Letaba River were all non-normally distributed. The distribution of data around the respective means for each water quality parameter was similar for sites B8H008 and B8H009. However, the overall water quality in terms of the mean concentrations of the various parameters differed significantly between the sites. Box plots indicated that the mean values for all water quality parameters, except for nitrate, were generally higher at site B8H008 than at site B8H009. Since site B8H008 is located downstream from site B8H009 (Figure 5.10), it is evident that the physicochemical quality of the water deteriorated further downstream, towards the KNP. This is most likely due to the addition of pollutants from several sources, including agriculture and forestry (Shikwambana et al., 2021), and the contributing tributaries as the river flows downstream toward the KNP.

The box plots for *E. coli* indicated that the mean microbial quality of the water differed significantly between the two sites. This is mostly due to the large outliers for the "Letaba Microbial - Downstream Giyani" site where the *E coli* CFU/100 ml counts were observed to rise to more than 250 000 CFU/100 ml over the observed time period. The microbial quality of the water at both sites was poor, however, more severe at the "Letaba Microbial - Downstream Giyani" site than at the "Letaba Microbial - Giyani Upstream STW" site. Given that the former site is located downstream of the Giyani WWTWs, the high incidence of extreme pollution events can be explained in terms of the site's location. This is discussed in depth in the following section.

5.3.2.1. *Time Series Trend Analysis for Sites on the Letaba River*

The MK analyses for site B8H008 on the Letaba River (Figure 5.13) computed *p*-values lower than the significance level of $a=0.05$ for pH, chloride, sulphate, ammonia, and nitrate. A trend was detected for these parameters; thus, *Ha* was accepted. Large positive *S* values revealed strong upward trends for pH, chloride and sulphate, while large negative *S* values revealed strong downward trends overall for ammonia and nitrate. The MK analyses for EC, calcium, magnesium, sodium, and phosphate computed *p*-values greater than the significance level of *a=0.05;* thus, *H0* was accepted for these parameters and no trend was found.

EC and the calcium, chloride, magnesium, and sodium concentrations all exhibited similar trends in their time series. As discussed in Chapter 3, calcium, chloride, magnesium, and sodium all involve electrically charged ions that can affect the EC levels of a freshwater source. Additionally, EC and the calcium and magnesium concentrations fluctuated between ideal and acceptable standards for domestic use over the observed time period, while the chloride and sodium concentrations fluctuated between ideal and tolerable levels. EC and the magnesium concentrations approached tolerable levels between 1985 and 1987 and between 2003 and 2005, respectively, while the chloride and sodium concentrations were consistently established to be of a tolerable standard.

DWAF (1996a) states that these parameters (calcium, chloride, magnesium, and sodium) should be analysed together since an increase or decrease in one would be likely to cause an increase or decrease in another, and ultimately affect the EC of the waterbody. Together, these parameters control the biological processes in freshwater organisms that are associated with protein synthesis, enzyme activation, energy transfer, and cellular homeostasis. When present in high quantities simultaneously, they may reach concentrations which are toxic to aquatic organisms (van Dam et al., 2010). Changes to EC can, therefore, affect the physiological functioning of aquatic organisms. Such changes may affect the adaptive capacity of individual species, the structure of their communities, and disrupt the microbial and ecological processes (du Plessis, 2014; Kimambo et al., 2019). These parameters (calcium, chloride, magnesium, and sodium) also tend to increase in concentration further downstream. This is due to the addition of salts, fertilisers, industrial and domestic chemicals and through natural processes, such as the leaching of salts into soils (DWAF, 1996a; Enoch, 2018). Anthropogenic sources primarily include, but are not limited to, agriculture and domestic and industrial land use types (Ashton et al., 1995).

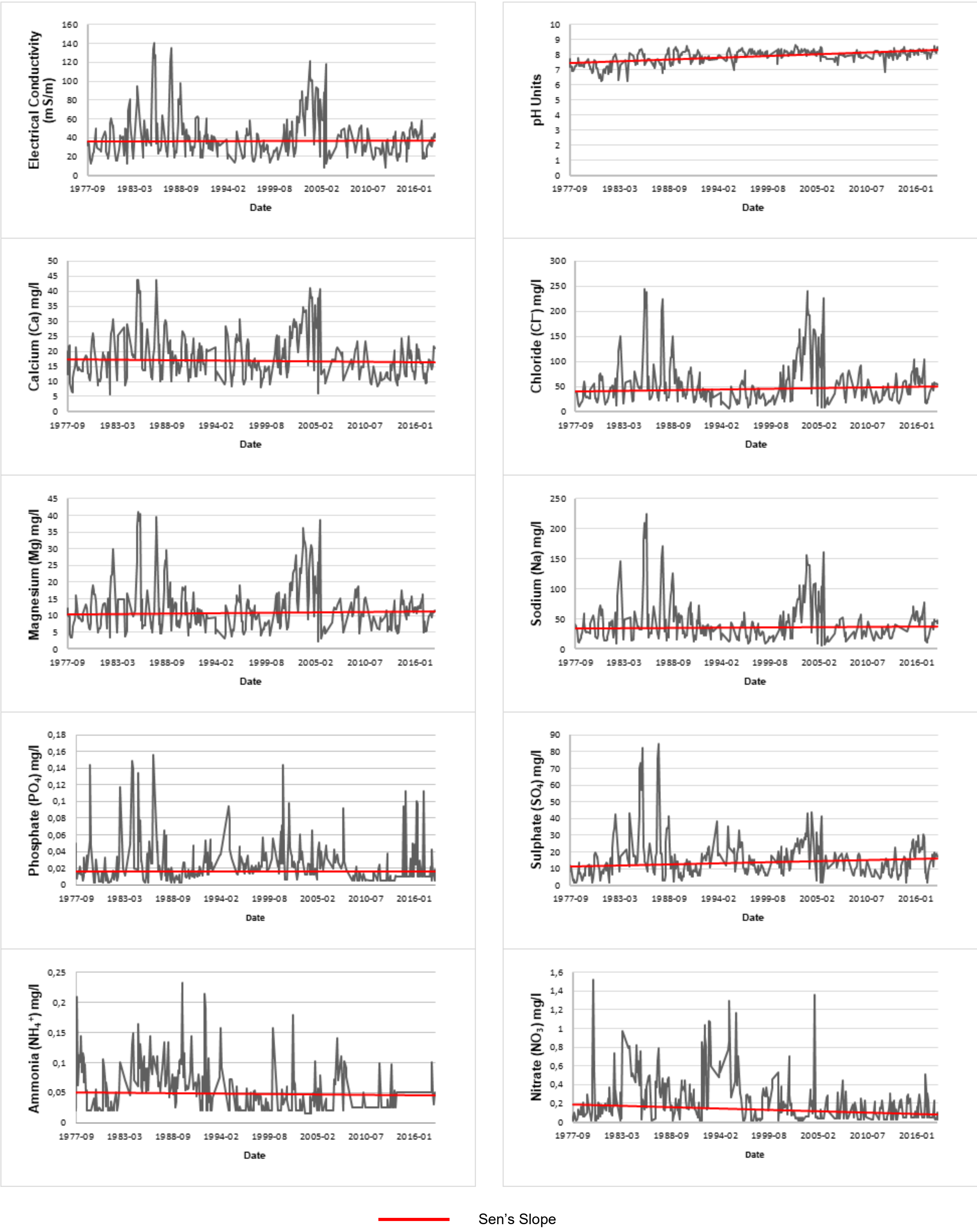

Figure 5.13: MK analyses for physicochemical water quality at site B8H008 on the Letaba River for the analysed time period.

Notably, land use between site B8H009 (Figure 5.10; Figure 5.14), upstream of B8H008 (Figure 5.13), appears to be mostly agricultural. The concentration of farms is dense in the vicinity of site B8H009 and becomes sparser downstream, closer to site B8H008, towards the KNP. Calcium, chloride, magnesium, and sodium are all ingredients of fertilisers; thus, runoff from farmlands in the higher rainfall periods are likely to be responsible for sporadic increases in the concentrations of these parameters and may contribute to salinity. Salinity usually results from a combination of sodium, calcium, magnesium, potassium, chloride, sulphate, carbonate, and bicarbonate (Weber-Scannell & Duffy, 2007; Singh et al., 2019). Thus, EC, closely associated with high concentrations of these elements and compounds, is an indicator of the salinity of a waterbody (du Plessis, 2019). Although few trends were evident for site B8H008, there were multiple indicators of increased salinisation and acidification; thus, the site should be monitored as a high risk area. Increased salinity/acidity poses a serious threat to South African water resources, for both conservation and economic reasons. As the incidence of these water quality problems increases, or as they are sustained for longer periods of time, so water stress and scarcity increase and the freshwater available for abstraction decreases (Tanner et al., 2022). For instance, UNEP (2016) states that increasing salinity pollution previously adversely affected poor farmers who were no longer able to rely on surface water as a source of irrigation. Acidification and salinisation have toxic effects for aquatic communities. These processes alter the chemical composition of the aquatic environment and often contribute to the release of other chemicals/metals that are toxic to aquatic species (Weber-Scannell & Duffy, 2007; Singh et al., 2019; Zak et al., 2021).

For irrigation use, the pH, sulphate, ammonia, and nitrate concentrations were at an ideal level for domestic use over the observed time period. EC and pH, and the chloride and sodium concentrations fluctuated between ideal and tolerable levels, while the ammonia and nitrate concentrations were of an ideal standard for irrigation use.

In terms of the aquatic ecosystem standards, the following trends were established. The phosphate and ammonia concentrations were at an ideal level, the nitrate concentrations at an ideal to acceptable level, but once again, the chloride concentrations fell within unacceptable standards.

At site B8H009, MK analyses computed *p*-values lower than the significance level of *a=0.05* for EC, pH, calcium, chloride, sodium, and sulphate (Figure 5.14). Thus, a trend was established which applied to these parameters as follows. Large positive *S* values revealed significant upward trends for EC and pH, and the calcium, chloride, and sodium concentrations over the observed time period, while a large negative *S* value revealed a strong downward trend overall for sulphate. The MK analyses for the magnesium, phosphate, ammonia, and nitrate concentrations determined computed *p*-values greater than the significance level of *a=0.05;* thus, *H0*, indicating no trends was accepted.

Overall, the quality of the water at site B8H009 was markedly better in comparison to site B8H008. This was in part due to the accumulation of inorganic ions that were noticeable at B8H008 and had reached or were approaching tolerable levels for domestic use and irrigation. As mentioned, the concentrations of ions tend to increase further downstream as a result of the addition of salts, fertilisers, industrial and domestic chemicals, as well as through natural processes (DWAF, 1996a).

For domestic use, EC and the calcium, chloride, magnesium, sodium, sulphate, and nitrate concentrations were within the ideal range. pH was at a tolerable level in terms of domestic use until 1992, whereafter it improved to an ideal standard. The ammonia concentrations were also within ideal to acceptable ranges for domestic use.

In terms of the irrigation water use standards, the following was observed. Chloride, sodium, ammonia, and nitrate concentrations were mostly at ideal levels, while EC fluctuated between ideal and acceptable levels. On the other hand, pH fluctuated between ideal and tolerable levels and prior to 1992, was mostly of a tolerable standard.

For the observed time period and in respect of aquatic ecosystems, the phosphate concentrations were of an ideal standard. Additionally, the ammonia and nitrate concentrations fluctuated between ideal and acceptable levels. On the other hand, the chloride concentrations for aquatic ecosystems were of an unacceptable standard.

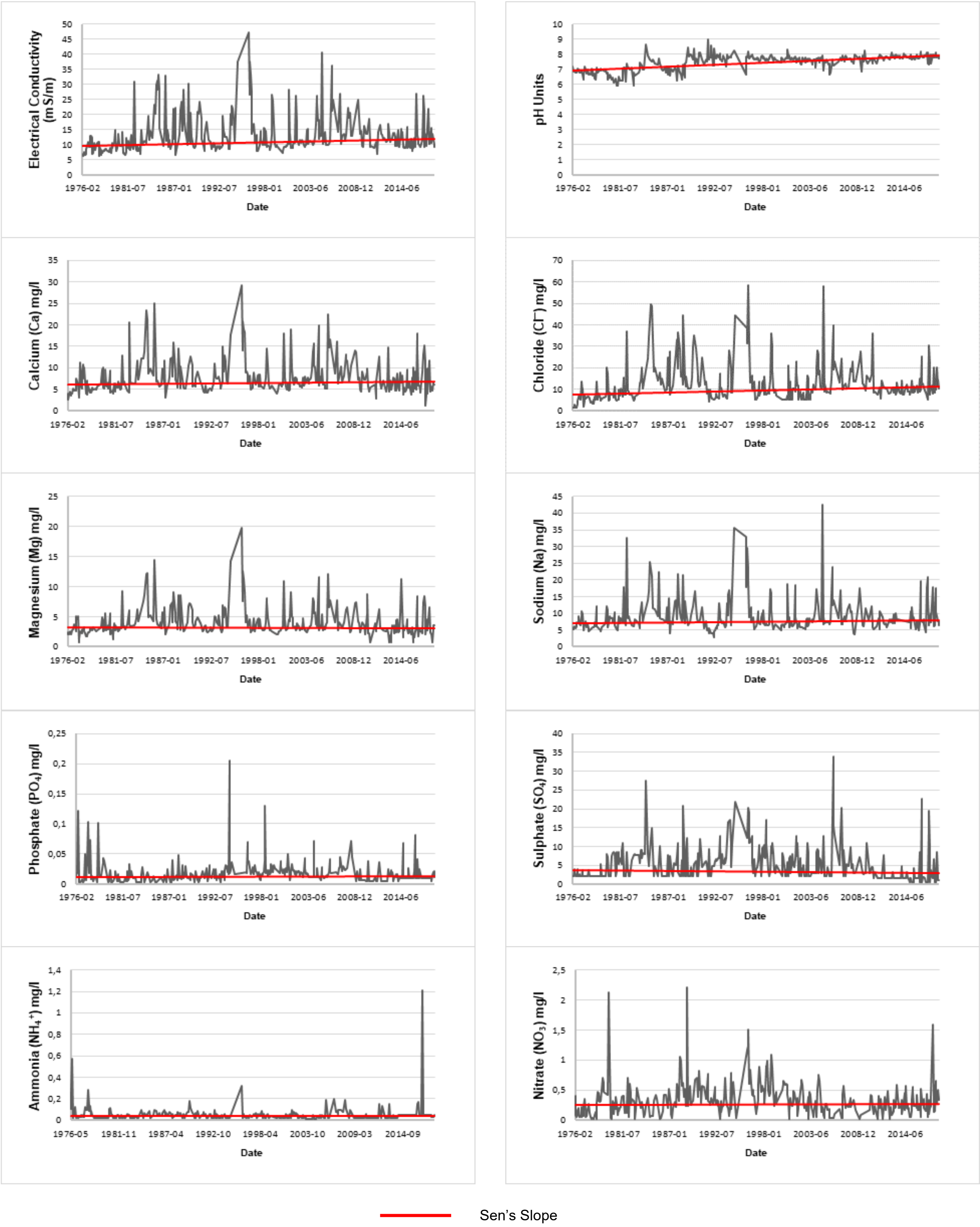

Figure 5.14: MK analyses for physicochemical water quality at site B8H009 on the Letaba River for the analysed time period.

The MK analysis at site “Letaba Microbial - Giyani Upstream STW” for *E. coli* on the Letaba River (Figure 5.15) computed a *p*-value greater than the significance level of *a=0.05;* thus, *H0* was accepted. No significant trend was evident in the microbial quality of the water observed at this site.

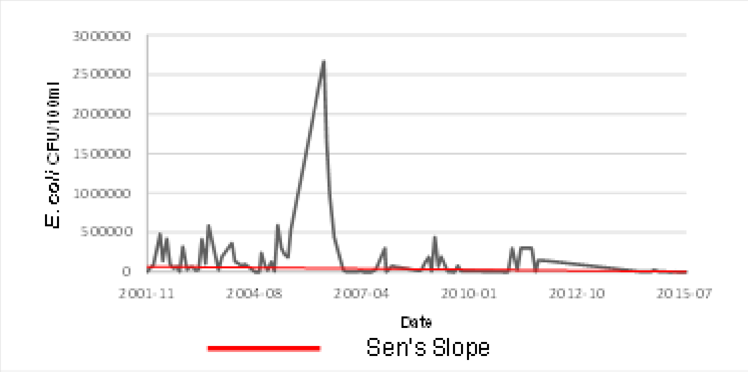

Figure 5.15: MK analysis for the “Letaba Microbial - Giyani Upstream STW” site on the Letaba River for the analysed time period.

This site is located just over three kilometres (3 km) upstream of the “Letaba Microbial - Downstream Giyani” site and showed marked variations in the microbial quality of the river water. Most of the observations primarily fell within unacceptable levels for domestic use while they fluctuated between tolerable and unacceptable counts for irrigation use. The recorded CFU/100 ml values were frequently above 1 000 CFU/100 ml and reached an all-time high of 29 800 CFU/100 ml in 2003. This site is located upstream of the Giyani WWTWs site and is within an urban area, thus the unacceptable *E. coli* counts may be attributed, but are not solely limited to, sewage overflows or spillages, malfunctioning sanitation systems, or a complete lack of sanitation facilities. Much of the area surrounding this site was historically dedicated to livestock rearing, which may also contribute to unacceptable coliform loads in the river (DWA, 2013).

The MK analysis at site “Letaba Microbial - Downstream Giyani” for *E. coli* (Figure 5.16) computed a *p*-value lower than the significance level of *a=0.05;* thus, *Ha* was accepted. The site is located near a WWTWs and an irrigation abstraction site and was one of the few microbial sites in the study area that exhibited a significant trend in microbial water quality. A large negative *S* value revealed that the *E. coli* concentrations at the site had decreased over the analysed time period.

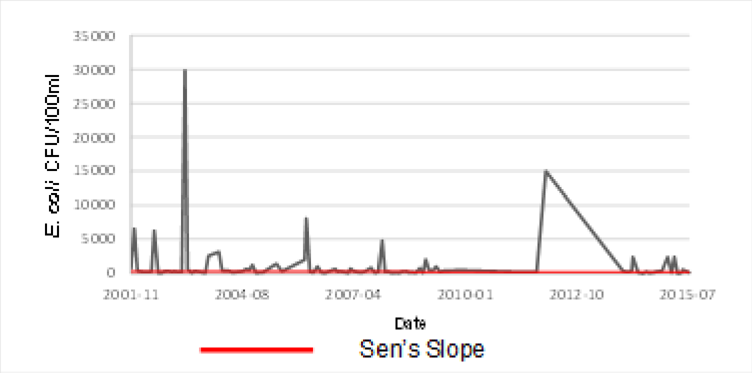

Figure 5.16: MK analysis for the "Letaba Microbial - Downstream Giyani" site on the Letaba River for the analysed time period.

Although the trend overall was declining, most observations in the dataset showed that the *E. coli* counts were primarily of an unacceptable standard for all water uses. The water at the site was not suitable or safe for consumption, neither for conservation. The CFU/100 ml value at this site reached an all-time high of 2 669 393 CFU/100 ml in May 2006. As mentioned, there are no TWQRs for *E. coli* in aquatic ecosystems; however, aquatic ecosystems are sensitive to the impacts of *Faecal coliforms* as increased levels disrupt the nutrient content in a waterbody, thus leading to nutrient enrichment and the growth of algae and other nuisance plants that negatively affect the aquatic species and the ecosystem itself (du Plessis, 2014). Owing to consistently elevated *E. coli* counts, the site should be considered a pollution hotspot and an area of concern in terms of both human and aquatic health. The obtained results were not surprising, however, given that this site is located less than a kilometre downstream of the Giyani WWTWs. This facility is a bio-filter WWTWs with a capacity of 2.1 Mℓ/d and a medium-sized plant by DWS standards. The DWA emphasised in 2013 that *E. coli* is a "constituent of concern" for the facility. Despite this concern, the effluent discharged into the environment/river by the facility was of a poor to unacceptable quality. The facility also requires upgrading, as well as maintenance, to ensure that it is functional (DWA, 2013; DWS, 2023a; DWS, 2023b).

5.3.2.2. Correlation Analysis Results for Sites on the Letaba River

Table 5.10 provides the coefficients of correlation for the Spearman's correlation analysis completed for site B8H008. The results indicate significant correlations such as that variations in water flow and average minimum temperature could be associated with changes in the quality of the water. Thus, site B8H008 on the Letaba River was found to be susceptible to variations in the local climate over the observed time period.

The correlation matrix indicated that there were moderate to strong positive correlations among EC and pH levels, and the calcium, chloride, magnesium, sodium, and sulphate concentrations. Other significant relationships among the water quality parameters included a moderate negative correlation between nitrate and the respective pH, chloride, and magnesium concentrations. This inverse relationship is well known and is due to the acidity that arises with increased concentrations of nitrate, thus causing a decline in pH, as well as decreased chloride and magnesium concentrations. This can be explained by the fact that these parameters are alkaline minerals.

The significant correlations that were established between water flow and EC, calcium, chloride, magnesium, and sodium respectively were moderate and negative, thus indicating an inverse response. Average minimum temperature also demonstrated moderate negative correlations with EC and the calcium, chloride, magnesium, and sodium concentrations. Like the relationships between water flow and these parameters, the variations in the average minimum temperature inversely affected the concentrations of these mentioned parameters, and thus their toxicity to the surrounding ecosystems.

Conversely, the coefficients of correlation derived from the Spearman's correlation analysis for site B8H008 and the corresponding water flow and climate sites for the Letaba River indicated no significant correlations with climate variability (Table 5.11). Climate parameters could not be associated or directly linked with changes/variability in water quality; however, moderate to strong positive correlations between the various water quality parameters were evident. Regarding the major ions which influenced the EC of the Letaba River at this site, calcium and chloride were strongly correlated with EC and were thus most likely to primarily contribute ions to conductivity here.

Table 5.10: Spearman's correlation matrix for site B8H008 on the Letaba River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,386	**1**												
Calcium	0,889	0,328	**1**											
Chloride	0,963	0,388	0,851	**1**										
Magnesium	0,949	0,426	0,897	0,953	**1**									
Sodium	0,930	0,376	0,845	0,946	0,929	**1**								
Phosphate	-0,133	-0,190	-0,026	-0,169	-0,176	-0,177	**1**							
Sulphate	0,769	0,280	0,714	0,756	0,718	0,751	0,121	**1**						
Ammonia	0,039	-0,244	0,003	0,076	-0,007	0,084	0,038	0,019	**1**					
Nitrate	-0,269	-0,363	-0,153	-0,319	-0,326	-0,276	0,272	-0,041	0,244	**1**				
Water flow	-0,605	-0,260	-0,508	-0,594	-0,590	-0,583	0,245	-0,454	-0,089	0,289	**1**			
Average Rainfall	-0,247	-0,134	-0,255	-0,251	-0,278	-0,251	0,207	-0,127	-0,100	0,132	0,600	**1**		
Average Max. Temp.	-0,225	-0,185	-0,289	-0,186	-0,240	-0,186	0,093	-0,169	-0,030	-0,087	0,390	0,416	**1**	
Average Min. Temp.	-0,367	-0,254	-0,395	-0,338	-0,387	-0,330	0,193	-0,231	-0,046	0,065	0,590	0,617	0,880	**1**

Table 5.11: Spearman's correlation matrix for site B8H009 on the Letaba River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,330	**1**												
Calcium	0,846	0,238	**1**											
Chloride	0,832	0,318	0,706	**1**										
Magnesium	0,755	0,148	0,733	0,719	**1**									
Sodium	0,771	0,202	0,674	0,788	0,718	**1**								
Phosphate	0,060	0,165	0,112	0,034	0,047	-0,042	**1**							
Sulphate	0,393	0,026	0,454	0,353	0,539	0,361	0,201	**1**						
Ammonia	0,029	-0,003	0,001	0,103	0,019	-0,005	0,033	-0,053	**1**					
Nitrate	0,134	0,139	0,132	0,151	0,165	0,117	0,238	0,147	0,028	**1**				
Water flow	-0,061	-0,111	-0,038	-0,098	-0,034	-0,051	0,046	0,035	0,040	-0,158	**1**			
Average Rainfall	0,233	-0,030	0,232	0,189	0,216	0,242	0,024	0,184	0,011	-0,174	0,459	**1**		
Average Max. Temp.	0,096	0,117	0,076	0,094	0,041	0,041	0,011	-0,013	0,033	-0,313	0,278	0,431	**1**	
Average Min. Temp.	0,175	-0,011	0,190	0,158	0,178	0,134	0,034	0,195	0,005	-0,283	0,448	0,733	0,814	**1**

The coefficients of correlation established for water quality at site "Letaba Microbial - Giyani Upstream STW" and the corresponding water flow and climate sites (Table 5.12) indicated no significant correlations.

Table 5.12: Spearman's correlation matrix for the "Letaba Microbial - Giyani Upstream STW" site on the Letaba River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	0,084	**1**			
Average Rainfall	0,280	0,304	**1**		
Average Max. Temp.	0,138	0,168	0,591	**1**	
Average Min. Temp.	0,194	0,267	0,701	0,893	**1**

The correlation matrix indicated that variations in *E. coli* at this site could not be directly associated with climate variability as there was limited to no evidence of any relationships in the results obtained. Thus, increases or decreases in *E. coli* counts were more likely to be associated with point source pollutants such as those issuing from WWTWs. Similarly, the coefficients of correlation derived from the Spearman's correlation matrix for site "Letaba Microbial - Downstream Giyani" showed that variations in the *E. coli* counts could also not be associated with climate variability (Table 5.13).

Table 5.13: Spearman's correlation matrix for the "Letaba Microbial - Downstream Giyani" site on the Letaba River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	0,172	**1**			
Average Rainfall	0,060	0,350	**1**		
Average Max. Temp.	0,034	0,145	0,526	**1**	
Average Min. Temp.	0,031	0,278	0,651	0,883	**1**

There was little to no relationship between the *E. coli* counts and the selected climate parameters (i.e.: average rainfall, average minimum and maximum temperature). Thus, the increases or decreases in the *E. coli* counts were more likely to be associated with diffuse and point-source pollutants of an anthropogenic nature, such as those issuing from WWTWs, than with changes to the chemistry of the waterbody brought about by climatic factors.

5.3.2.3. Synthesis: Water Quality and Climate Impacts for the Letaba River

For the observed time period, the physicochemical quality of the water in the Letaba River could be classified as being of an acceptable standard. Although some water quality parameters fluctuated to tolerable levels, most of the parameters remained within ideal to acceptable levels for domestic use, irrigation, and aquatic ecosystems. The microbial water quality of the Letaba River could be described as substantially degraded as a result of the unacceptable water quality standards it reached. *E. coli* counts at both sites were within the unacceptable range for all water uses over the observed time period.

The mean values for the various water quality parameters differed significantly between sites B8H008 and B8H009, thus indicating the high spatial variability in the water quality of the Letaba River, with the physicochemical quality of the water deteriorating downstream, closer to the KNP. This supports previous research findings that the quality of the water in the Letaba River close to the KNP has deteriorated. This has historically been due to salinisation and nutrient enrichment resulting from partially treated or untreated domestic wastewater and agricultural runoff (Pollard & du Toit, 2011). The microbial quality of the water also differed significantly between sites, deteriorating downstream, especially following on the addition of wastewater from the Giyani WWTWs. Both sites can be classified as high risk on account of the high level of microbial pollution and the accompanying health risks.

Temporal trends in water quality also varied between the sites. The physicochemical water quality parameters at both sites indicated significant variations in terms of increasing or decreasing trends, or none. The sites exhibited some similarities in that certain water quality parameters, specifically pH and chloride, became more degraded over time. The trends in microbial water quality also varied between the sites. While no trend could be observed upstream, a decreasing trend downstream of the Giyani WWTWs was clear, with some *E. coli* counts as high as 2 669 393 CFU/100 ml. The main water quality parameters of concern in the Letaba River are those with an increasing trend and/ or at tolerable or unacceptable levels which include EC, chloride, sodium, and *E. coli.*

The correlation analyses indicated that climatic influences on water quality varied spatially. Overall, the quality of water in the Letaba River exhibited a weak response to climate variability. No significant relationship was evident between *E. coli* and climate variability.

In conclusion, it can be stated that the water quality of the Letaba River has remained mostly the same. The river is, however, somewhat degraded, with water quality deteriorating downstream, towards the KNP. This puts the ecosystems of the KNP at risk as the lower portion of the river runs into the conservation area. However, it is unlikely that changes to the quality of the water are caused by variations in the local climate. Rather, they can be attributed to anthropogenic impacts along the river, which, as such, need to be monitored carefully.

A discussion of the water quality trends, pollution hot spots, high risk areas and the relationship between water quality and climate variability for sites on the Olifants River now follows.

5.3.3. The Olifants River

Two sites on the Olifants River, namely B7H007 (1976 - 2018) and B7H015 (1983 - 2021), were analysed to understand the physiochemical quality of the river water (Figure 5.10). The microbial water quality on the Olifants River was analysed at two sites, namely "Olifants Microbial - L12 Olifants River" (2009 - 2015) site and "Olifants Microbial - KNP Rest Camp" site (2007 - 2015).

Water quality data for the Olifants River showed a mostly non-normal distribution, with only 4.5% of the data following a normal distribution. The distribution of data for each of the respective water quality parameters was highly varied between sites B7H007 and B7H015 and differed largely in terms of the mean concentrations of the various parameters. The box plots indicated that the mean values for EC, calcium, chloride, magnesium, sodium, and sulphate were significantly larger at site B7H015, downstream from site B7H007, meaning that the water quality deteriorated closer to the KNP. This is likely to be on account of the location of site B7H015, which is just downstream of the Phalaborwa mining complex. The box plots for *E. coli* indicated that the mean *E. coli* count was similar for the two sites and that there was no spatially significant trend.

5.3.3.1. *Time Series Trend Analysis for Sites on the Olifants River*

The results of the MK analyses for the physicochemical water quality parameters at site B7H007 showed varying trends (Figure 5.17). The computed *p*-values for pH, calcium, magnesium, sodium, phosphate, sulphate, and nitrate were lower than the significance level of *a=0.05;* thus, *Ha* was accepted. A strong upward trend was evident from the large positive *S* values for these parameters, apart from sodium, which displayed a large negative *S* value and declining concentrations. The MK analyses for EC, chloride and ammonia indicated no trends.

Most previous research has historically condemned the quality of the water in the Olifants River as being the poorest of all the rivers in South Africa (Ashton and Dabrowski, 2011; Biggs et al., 2017; Marr et al., 2017a). However, for the observed time period, the water quality in terms of the selected parameters, specifically at site B7H007, was good. It is thus clear that this site is not an accurate representation of the overall water quality for the catchment. Additionally, the physiochemical parameters measured in this research, may differ[2] from those researched previously, and may in part explain the contradictory results.

For domestic use, the pH, sodium, sulphate, and nitrate concentrations were within ideal levels, with EC and the calcium, chloride, magnesium, and ammonia concentrations fluctuating between ideal and acceptable standards. The ammonia and nitrate concentrations were of an ideal standard. On the other hand, the EC, chloride and sodium concentrations fluctuated between ideal and acceptable standards for irrigation use, with pH fluctuating between ideal and tolerable levels.

In terms of aquatic ecosystems, the phosphate concentrations were within the ideal range. Ammonia and nitrate concentrations were found to be of an ideal to acceptable standard, with only one observation for nitrate, in 1977, being at a tolerable level. For this site, chloride was at an unacceptable level and should once again be highlighted as a risk area for aquatic ecosystems.

[2] A different method might also have been used.

Figure 5.17: MK analyses for physicochemical water quality at site B7H007 on the Olifants River for the analysed time period.

The MK analysis of the data for site B7H015 detected a promising trend for most water quality parameters (Figure 5.18). The site is located within the KNP and is thus a crucial point for water quality control for the conservation area. The Phalaborwa mining complex, bordering on the KNP, is located just under eight kilometres (8 km) north-east of the site and is at the confluence of the Olifants and Ga-Selati Rivers. As such, the former receives an influx of pollution from the Ga-Selati tributary (Riddell et al., 2019a) which consequently affects the quality of the KNP's water resources.

The computed *p*-values for all physicochemical water quality parameters were lower than the significance level of *a=0.05;* thus, *Ha* was accepted. Trends were established over the observed time period for all parameters at this site. Large negative *S* values revealed strong downward trends for all parameters, except pH, thus indicating an improvement in water quality between 1983 and 2018. However, it should be noted that a large positive *S* value indicated an increasing trend for pH, which suggests that recordings show the water has become more alkaline over time.

In terms of the TWQRs, pH, and the ammonia and nitrate concentrations were within ideal levels for domestic use. EC fluctuated between ideal and tolerable levels between 1983 and 1998, whereafter it fell to below 150 mS/m to meet ideal to acceptable standards. The chloride and sodium concentrations fluctuated between ideal and acceptable standards for domestic use.

For domestic use, the calcium concentrations fluctuated between ideal and tolerable ranges. A tolerable level for calcium for domestic use was at a concentration level of >80 mg/ℓ; however, no guideline is provided for what constitutes an unacceptable level of calcium. What has been established, however, is that high concentrations of calcium, in conjunction with magnesium, contribute to water hardness (DWAF, 1996a). In this research, the magnesium concentrations also fluctuated between ideal and unacceptable levels. Between 1983 and 1994, the calcium concentrations ranged from 83 - 107 mg/ℓ, while between 1983 and 2003, the magnesium concentrations rose to unacceptable levels of 101 - 177 mg/ℓ, whereafter they declined (improved). It is worth noting that even at low concentrations, various combinations of calcium and magnesium can be toxic to aquatic life in freshwater bodies. For instance, in water of a low ionic strength, with a low concentration of calcium, even a small elevation in magnesium may affect sensitive species (van Dam et al., 2010). However, van Dam et al. (2010) found that much higher concentrations of magnesium, accompanied by higher concentrations of calcium, reduce the risks to certain aquatic species.

Weyhenmeyer et al. (2019) found that the high calcium levels causing alkalinity in waterbodies are strongly associated with a pH of 8.0 - 9.0. The MK analysis for this site is consistent with this observation as the pH remained between 8.0 - 9.0 and indicated a trend toward alkalinity. Elevated concentrations of calcium are also often associated with higher sulphate concentrations. The sulphate concentrations at this site became elevated to unacceptable ranges between 1983 and 1994. However, between 1995 and 1999, they decreased to tolerable levels, and then to ideal levels between 2000 and 2018. As long as activities (industry and mining) that contribute sulphate to wastewater are controlled and even diminished, to the extent that both sulphate and calcium concentrations decline, freshwater bodies can recover (Weyhenmeyer et al., 2019).

This is evident from the MK analyses, which indicated similar patterns in the time series trends established for sulphate and calcium and an overall downward trend in both parameters. These findings suggest that pollutants resulting from the long-term copper mining activities at Phalaborwa mining complex were properly treated before effluent was discharged into the river systems and that since the 1980s, pollution control has improved. This is a promising outcome for the KNP as copper sulphate is highly toxic to fish and invertebrates (de Villiers & Mkwelo, 2009). Increased sulphate concentrations have negative implications for the structure and functioning of freshwater ecosystems, as they enhance the mobilisation of heavy metals and other nutrients. Additionally, elevated sulphate concentrations might also alter nitrogen and phosphorus cycling and cause an imbalance in the nitrogen-phosphorus ratio (Zak et al., 2021). Therefore, owing to these given negative implications and/ or effects, increases in calcium and sulphate concentrations should be closely monitored and in the event of an increasing trend, their possible sources should be investigated, and appropriate action be taken to avoid further degradation of the environment.

Overall, the quality of the water at site B7H0015 was poorer than that at site B7H007, located approximately 60 km upstream. This may be due to the primary land use in the area surrounding B7H007 being dedicated to conservation, while on the other hand, the Phalaborwa mine and mining town, located downstream, affect the quality of the water at site B7H015. Since mining activities in the Phalaborwa region are continuing indefinitely, the pollutants associated with copper mining, for example, calcium, magnesium, and sulphate, require ongoing and more frequent monitoring to ensure that

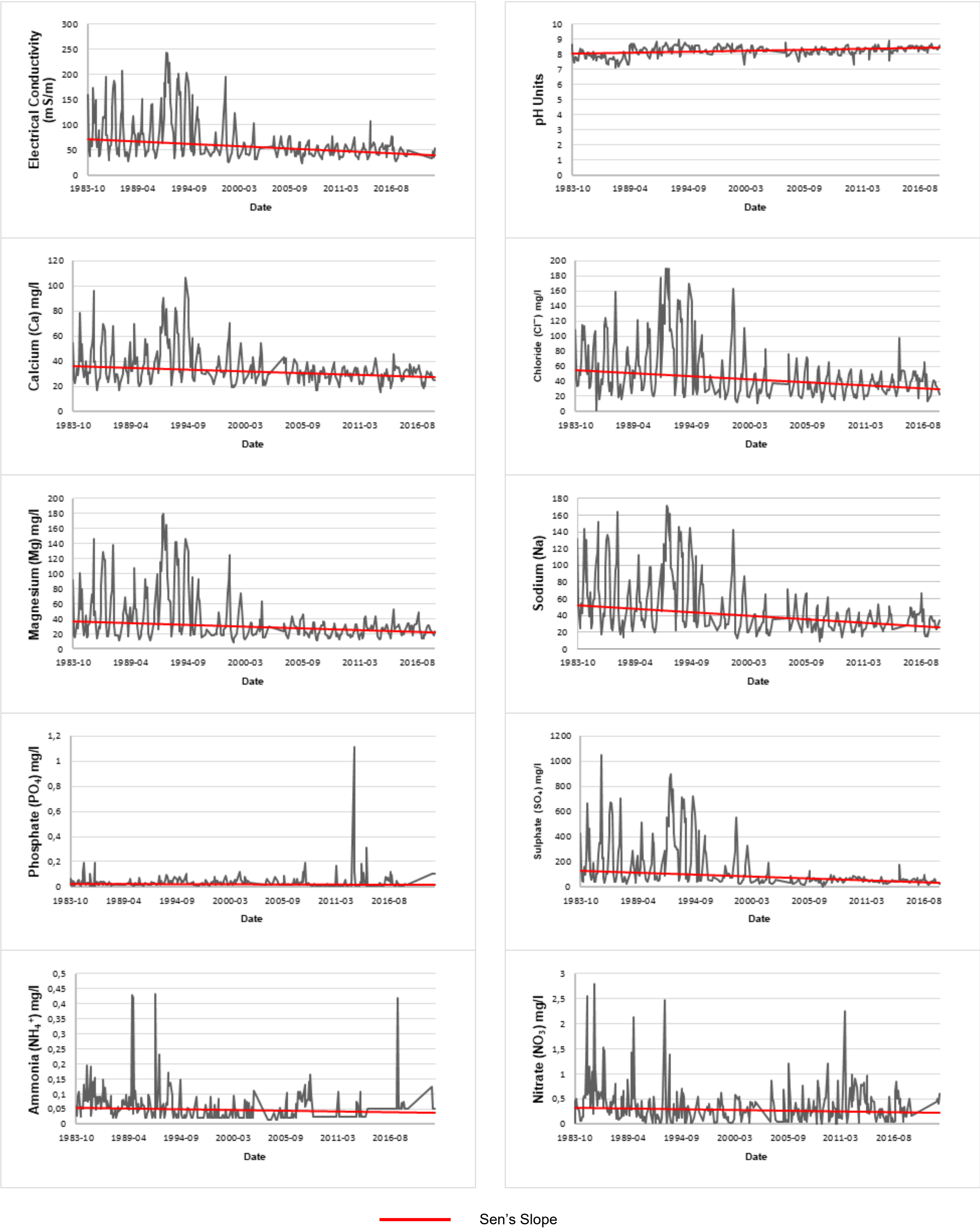

Figure 5.18: MK analyses for physicochemical water quality at site B7H015 on the Olifants River for the analysed time period.

potentially harmful concentrations entering the Olifants River, located just under eight kilometres (8 km) from the KNP, are mitigated.

Over the observed time period, the ammonia and nitrate concentrations were within the ideal ranges, while the EC, pH, chloride, and sodium concentrations fluctuated between ideal and tolerable ranges for irrigation use. Between 1983 and 1994, the sodium concentrations were consistently tolerable, whereafter they decreased to ideal and acceptable ranges.

The ammonia and phosphate concentrations were within ideal ranges, apart from one observation for phosphate which rose above the ideal threshold in 2003. The nitrate concentrations fluctuated between ideal and tolerable ranges for aquatic ecosystems, with observations between 1983 and 1994, mostly within the tolerable range, whereafter they decreased to acceptable ranges. Chloride concentrations reached unacceptable standards for aquatic ecosystems and should be highlighted as a risk area for aquatic ecosystems.

The MK analysis at site “Olifants Microbial - L12 Olifants River” for *E. coli* (Figure 5.19), determined no significant trend.

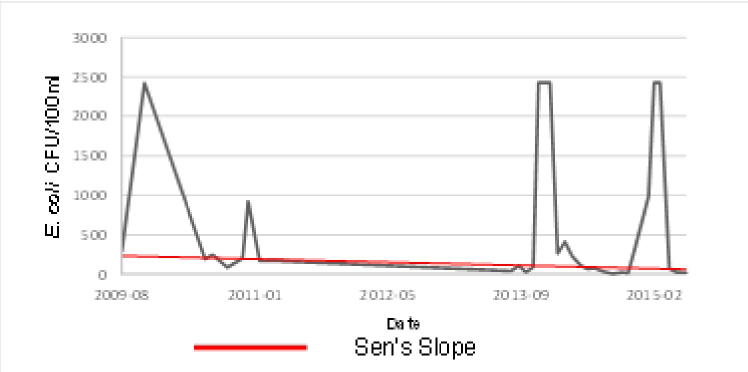

Figure 5.19: MK analysis for site “Olifants Microbial - L12 Olifants River” on the Olifants River for the analysed time period.

Over the observed time period, the *E. coli* counts ranged widely from 6 - 2 420 CFU/100 ml. The microbial quality of the water was thus mostly of an unacceptable standard for domestic use. Between 2009 and 2015, the CFU/100 ml counts were also consistently of an unacceptable level for irrigation use. There was no immediately obvious cause for the elevated levels of *E. coli* at this site. The only possible source of pollution was Tswenyane, a rural area with a population of only 816 people, located less than two kilometres (2 km) upstream of the site (CityFacts, 2018). As indicated by the results of the MK analysis, if, before being discharged into the river, the wastewater from this region was either only partially treated or not at all, it could have contributed to elevated *E. coli* counts.

Unfortunately, since there were limited data for this site and no data for the year 2012, this created a large gap in the dataset. For these reasons, it is difficult to assess the true severity of historical microbial pollution in the river at this site. Improved monitoring and more frequent data collection initiatives are required at sites such as this to provide a more detailed and informed overview of the current quality of the water. Considering the importance of this river, it is distressing that the monitoring at this site is so infrequent. As such, this site should be highlighted as an area of concern in terms of its unacceptable *E. coli* levels, which on the one hand increase the risk of water-related illnesses and the degradation of ecosystems, and on the other, a lack of data.

The MK analysis for determining the *E. coli* levels at site "Olifants Microbial - KNP Rest Camp" (Figure 5.20) established a weak trend. A negative *S* value indicated a weak downward trend in microbial contamination at this site. However, further inspection of the data revealed that the CFU/100 ml count was highest at 2 500 CFU/100 ml in 2007, decreased for several years, and then increased again to 1 203 - 1 733 CFU/100 ml in 2014. Despite the overall declining trend, *E. coli* contamination at this site remains a cause for concern.

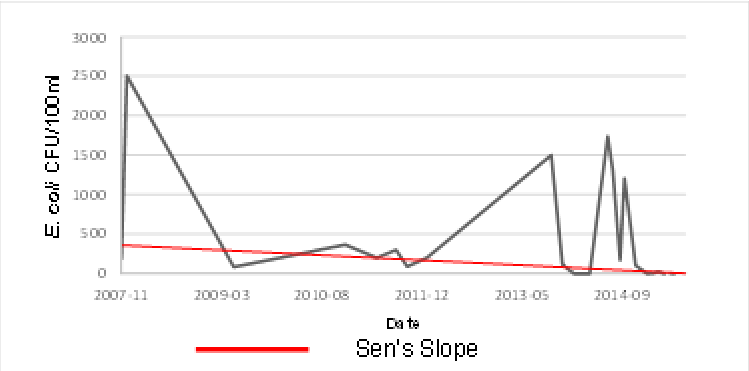

Figure 5.20: MK analysis for site "Olifants Microbial - KNP Rest Camp" on the Olifants River for the analysed time period.

Once again, it should be noted that there were limited data available for analysis at this site so that what transpires may not be a completely accurate representation of the actual microbial quality of the water (i.e., the overall average *E. coli* counts could be higher or lower). Multiple gaps were present in the data and the dataset ranged across only six years. However, *E. coli* did reach unacceptable counts for domestic use in 65%

of the observations, and unacceptable counts for irrigation use in 18.5% of the observations. The site should be flagged as a high risk area and monitoring should be improved upon to gain a deeper and more accurate understanding of the current trends in microbial pollution. This is especially important since the site is well located within the KNP (more than 50 km from the western border). As previously mentioned, *E. coli* may disrupt the nutrient content of an aquatic ecosystem, leading to nutrient enrichment that restricts oxygen flow in the water (du Plessis, 2014). Imbalances in one part of an ecosystem will cause whiplash effects in other parts, thus causing a "cascade of environmental pressures" for the other parts (Riddell et al., 2019a, p.3).

5.3.3.2. Correlation Analysis Results for Sites on the Olifants River

The established coefficients of correlation derived from the Spearman's correlation analysis for site B7H007 and the selected water flow and climate sites on the Olifants River showed moderate to strong positive and negative relationships between water quality, water flow and variations in the local climate (Table 5.14).

The correlation matrix indicated that there were moderate to strong positive correlations between EC, pH, calcium, chloride, magnesium, sodium, and sulphate. Thus, increases in any one of these parameters could be associated with increases in another. Significant correlations between water flow and several water quality parameters were evident. Water flow and EC had a strong negative correlation, indicating that increases or decreases in water flow would inversely affect EC. The same was true for water flow and magnesium. Water flow also had moderate negative correlations with pH, chloride, and sodium, inversely affecting the concentrations of these water quality parameters at the site.

Average daily rainfall and average minimum temperature both had moderate negative correlations with EC and magnesium, respectively. Increased rainfall and lower temperatures thus reduced the conductivity and concentration of magnesium at this site. This, along with the strong positive correlation between EC and magnesium, indicated that magnesium was the primary controller of conductivity at the site.

Table 5.14: Spearman's correlation matrix for site B7H007 on the Olifants River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,455	**1**												
Calcium	0,733	0,333	**1**											
Chloride	0,890	0,371	0,605	**1**										
Magnesium	0,920	0,507	0,693	0,841	**1**									
Sodium	0,870	0,309	0,571	0,913	0,808	**1**								
Phosphate	-0,093	-0,012	-0,009	-0,083	-0,116	-0,090	**1**							
Sulphate	0,537	0,408	0,539	0,452	0,482	0,400	0,028	**1**						
Ammonia	-0,083	-0,105	-0,094	-0,035	-0,048	-0,079	-0,057	-0,098	**1**					
Nitrate	0,016	0,056	0,173	0,042	0,079	-0,014	0,057	0,032	0,205	**1**				
Water flow	-0,540	-0,360	-0,293	-0,474	-0,586	-0,478	0,286	-0,096	-0,093	-0,035	**1**			
Average Rainfall	-0,373	-0,275	-0,249	-0,290	-0,438	-0,283	0,221	-0,244	-0,063	-0,099	0,593	**1**		
Average Max. Temp.	-0,226	0,004	-0,040	-0,184	-0,238	-0,223	0,173	0,025	-0,001	-0,079	0,403	0,412	**1**	
Average Min. Temp.	-0,420	-0,249	-0,264	-0,309	-0,478	-0,336	0,321	-0,162	-0,004	-0,184	0,613	0,737	0,784	**1**

Magnesium sulphate is a common pollutant found near mines and in mining wastewater. Since the Olifants River is significantly affected by mining along its reaches, excessive levels of magnesium (and therefore EC) are likely to originate from these mines. Although magnesium is not innately toxic, it is a prime ameliorator of the toxicity of other metals (van Dam et al., 2010).

The Spearman's correlation analysis completed for site B7H015 established the coefficients of correlation among water quality, water flow and the climate parameters at this site (Table 5.15). These concur with the results obtained for site B7H007. Moderate to strong positive and negative correlations were found between water quality, water flow and the respective climate parameters. The general relationship established was that the variations in water flow and the local climate had a moderate to strong association with the variations in water quality at the site.

Water flow had strong negative correlations with EC, pH, chloride, magnesium and sodium respectively, and a moderate negative correlation with calcium. This indicates that increases or decreases in water flow inversely affected these parameters. Thus, seasonal changes or climate-induced changes to water flow can be said to influence the conductivity, acidity and salinity of the river water at this site.

Average daily rainfall and average minimum temperature both had moderate negative correlations with EC, pH, chloride, magnesium, and sodium, respectively. Increased rainfall and lower temperatures thus reduced the conductivity and concentration of these parameters at this site. This, along with strong positive correlations of EC with chloride, magnesium, and sodium indicated that these were the primary influencers of conductivity at the site.

Table 5.15: Spearman's correlation matrix for site B7H015 on the Olifants River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,459	**1**												
Calcium	0,889	0,439	**1**											
Chloride	0,927	0,480	0,801	**1**										
Magnesium	0,932	0,534	0,836	0,903	**1**									
Sodium	0,919	0,504	0,803	0,925	0,899	**1**								
Phosphate	0,157	0,177	0,134	0,126	0,202	0,169	**1**							
Sulphate	0,790	0,274	0,720	0,730	0,701	0,743	0,101	**1**						
Ammonia	0,141	0,085	0,086	0,174	0,203	0,156	0,141	0,105	**1**					
Nitrate	-0,138	-0,026	-0,092	-0,088	-0,107	-0,117	0,007	-0,182	0,140	**1**				
Water flow	-0,624	-0,527	-0,497	-0,636	-0,688	-0,614	-0,010	-0,335	-0,219	0,165	**1**			
Average Rainfall	-0,339	-0,375	-0,293	-0,356	-0,376	-0,322	0,191	-0,243	-0,170	0,103	0,626	**1**		
Average Max. Temp.	-0,186	-0,208	-0,132	-0,198	-0,217	-0,206	-0,096	-0,169	-0,131	-0,218	0,254	0,393	**1**	
Average Min. Temp.	-0,324	-0,321	-0,246	-0,325	-0,364	-0,302	0,074	-0,191	-0,177	-0,125	0,559	0,705	0,757	**1**

The coefficients of correlation derived from the Spearman's correlation analysis completed for *E. coli* at site "Olifants Microbial - L12 Olifants River" indicated significant positive correlations between *E. coli,* water flow, and the selected climate parameters (Table 5.16).

Table 5.16: Spearman's correlation matrix for site "Olifants Microbial - L12 Olifants River" on the Olifants River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	0,675	**1**			
Average Rainfall	0,308	0,485	**1**		
Average Max. Temp.	0,374	0,410	0,457	**1**	
Average Min. Temp.	0,549	0,576	0,650	0,831	**1**

The correlation matrix indicates that variations in *E. coli* at this site could, to varying degrees, be associated with changes in water flow and climate variability. Both water flow and average minimum temperature were strongly and positively correlated with *E. coli*, while average rainfall and average maximum temperature were moderately and positively correlated with *E. coli.* This indicates that as rainfall, water flow, and temperatures increased or decreased, so did the concentration of *E. coli* at this site.

Previous research supports the finding that *E. coli* counts may in some cases be influenced by climate parameters. Shamsudin et al. (2016) used Pearson correlation analyses to determine the relationships between *E. coli* counts and various physical water quality parameters. They found that temperature is highly correlated with *E. coli* growth (R = 0,763). In fact, high water temperatures enhance the growth of microorganisms, and *Faecal coliforms* show optimal growth at 35 - 37˚C (Shamsudin et al., 2016). Furthermore, *E. coli* counts have previously been higher during high flow rather than during low flow periods (Dwivedi et al., 2013). Hyer (2007) found that median *E. coli* counts were significantly higher under stormflow conditions than during low flow periods in Shenandoah National Park between 2005 and 2006. The sampling results indicated that *E. coli* counts increased by at least one order of magnitude at each site during high rainfall and high waterflow conditions.

Conversely, no significant correlations were established for site "Olifants Microbial - KNP Rest Camp" (Table 5.17). Thus, increases or decreases in *E. coli* counts were more likely to be associated with point source pollutants, such as those issuing from WWTWs, and diffuse pollutants, such as runoff containing animal waste (van Vuuren, 2017b), originating outside the KNP borders. Contributing factors inside the KNP could include domestic wastewater from the Olifants Rest Camp, less than a kilometre from this monitoring site, and runoff containing animal waste originating from the park's wildlife.

Table 5.17: Spearman's correlation matrix for site "Olifants Microbial - KNP Rest Camp" on the Olifants River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	-0,136	**1**			
Average Rainfall	0,070	0,618	**1**		
Average Max. Temp.	-0,180	0,292	0,284	**1**	
Average Min. Temp.	-0,175	0,628	0,621	0,746	**1**

5.3.3.3. Synthesis: Water Quality and Climate Impacts for the Olifants River

According to the TWQRs, physicochemical quality of the water in the Olifants River for the observed time period can generally be classified as acceptable to tolerable. Although several water quality parameters fluctuated to tolerable levels, most remained within acceptable levels for domestic use, irrigation, and aquatic ecosystems. Overall, the microbial quality of the water in the Olifants River appears substantially degraded and mostly of an unacceptable standard. The *E. coli* counts at both sites were within unacceptable levels for all uses. Therefore, these sites and their environs should be highlighted as an area of concern on account of the increased probability of significant human health risks and of degrading ecosystems. However, small datasets with substantial amounts of missing data for both sites presented limitations in determining the true severity of microbial pollution in the river. As such, this issue should be dealt with.

The mean values for the water quality parameters differed significantly for sites B7H007 and B7H015, thus indicating a high spatial variability in terms of water quality for the Olifants River, with the physicochemical quality deteriorating downstream near the KNP. This is most likely primarily due to the location of site B7H015 just downstream of the Phalaborwa mining complex, as well as to the diffuse source pollution emanating from various points along the river's reaches (van Vuuren, 2017b). The microbial quality of the water was also similar for the two sites, remaining highly degraded and of an unacceptable standard as it flows closer toward and into the KNP.

The temporal trends in physicochemical water quality at both sites indicated significant differences in terms of increasing, decreasing, or no trends. Despite the overall water quality being worse downstream, the trends at site B7H015 indicated decreasing EC as well as concentrations of calcium, chloride, magnesium, sodium, phosphate, sulphate, ammonia, and nitrate, suggesting that the water quality had in fact improved. This is a promising development for the river, particularly at this site that is near the Phalaborwa Mining Complex and the KNP, as mainly over the past number of years, the quality of the water, has been highly degraded, threatening human health and the functioning of the ecosystem (Heath et al., 2010, Marr et al., 2017a; Oberholster et al., 2017).

The trends in microbial water quality also varied between the sites. While no trend was present upstream, a clear downward trend was evident downstream, on the KNP side of its border. The microbial quality of the water in the Olifants River thus improved downstream towards and within the KNP, an indication that the quality of the water may have improved to the future benefit of wildlife and conservation efforts in the park. The main water quality parameters of concern for the Olifants River are those presenting with an increasing trend, specifically pH, chloride, as well as *E. coli*. Calcium and magnesium have also contributed significantly to the hardness of the water at site B7H015, and it is worth noting that the combination of these parameters in certain concentrations can adversely affect conservation efforts in the KNP.

The correlation analyses conducted for the physicochemical water quality sites on the Olifants River indicated that water quality is affected by variations in the local climate. This deduction can be made in the light of the moderate to strong correlation that was found between water quality, water flow and climate parameters. The correlation analyses indicated that some of the parameters (especially EC, chloride, and magnesium) at these water quality monitoring sites could be associated with variations in water flow, average rainfall, and average minimum temperature. These parameters reflected monotic, inverse relationships, varying in the opposite direction. The effect of climate variability on microbial water quality differed between sites. *E. coli* at the "Olifants Microbial - L12 Olifants River" site exhibited strong negative correlations with water flow and average minimum temperature, as well as moderate positive correlations with average rainfall and average maximum temperature. On the other hand, the

“Olifants Microbial - KNP Rest Camp” site exhibited weak correlations between the same parameters.

In conclusion, it can be stated, that water quality at the analysed sites on the Olifants River, historically regarded as poor, exhibited an overall trend towards improving, especially in particular areas, namely, towards and within the KNP, where it is paramount for the available water to be of an ideal to acceptable standard. However, the microbial quality of the water remains problematic, and the sources of the *Faecal coliforms* need to be identified and addressed. Furthermore, contrary to the prevailing quality of the water in the rivers previously discussed, that of the Olifants river is affected more by climate variability - a finding that should be taken into consideration for future research, monitoring, and management.

5.3.4. Water Quality Compliance for the Olifants WMA

Compliance graphs for the Olifants WMA (Figure 5.21) enabled an in-depth analysis of the temporal trends present in the region. The percentages for ideal, acceptable, tolerable, or unacceptable measurements for domestic use or aquatic ecosystems for the full study period, as well as for the most recent five years were examined. Historically, the Olifants WMA has been regarded as one of the most degraded rivers in South Africa (Heath et al., 2010; Ashton & Dabrowski 2011; Marr et al., 2017a). It is clear, however, from the comparison made in respect of the different time periods that water quality management, at least for the selected sites, supported a marginal improvement in the quality of water flowing into the KNP between 2014 and 2018.

As was established by the time series trend analyses, the physicochemical quality of the water has mostly been of an ideal to acceptable standard. *E. coli* pollution was the most impactful factor by far to affect water quality at the selected sites. The *E. coli* counts were predominantly of an unacceptable standard; however, in recent years, when comparing the full study period with the last five years, for instance, they have improved by six percent (6%).

Water quality, in terms of its sulphate, sodium, magnesium, chloride concentrations and EC, has shown significant shifts towards ideal ranges. This suggests that while salinity in the WMA remains a primary concern, the pollution loads have been slowly decreasing. The time series trend analyses support this observation in that 30% of the parameters in the WMA experienced declining trends over the observed time periods (Table 5.28). While changes to the nitrate, calcium and pH levels were also observed, these improvements were far less significant, shifting only by one to three percent (1 - 3%).

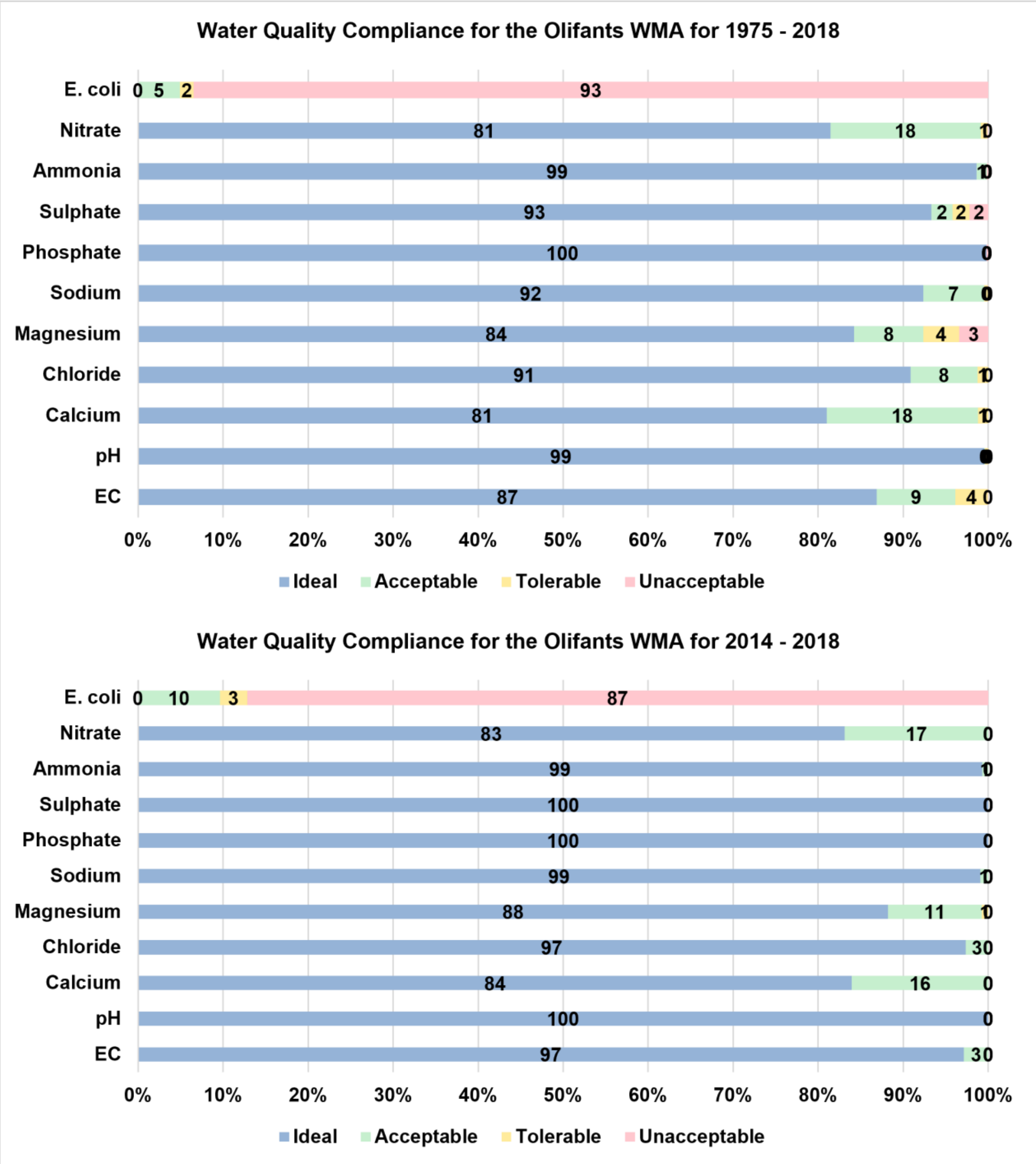

Figure 5.21: Percentage of compliance of national in-stream water quality guidelines at selected monitoring sites in the Olifants WMA.

A discussion of the water quality trends, pollution hot spots, high risk areas and the relationships between water quality and climate variability for sites in the Inkomati-Usuthu WMA now follows.

5.4. Analyses for the Inkomati-Usuthu WMA

As described in Chapter 2, the Inkomati-Usuthu WMA includes the Sabie and Crocodile rivers (Figure 5.22). The Crocodile River is renowned for being one of South Africa's most biologically diverse rivers, second only to the Sabie River (van Vuuren, 2017b; Roux et al., 2018; Riddell et al., 2019a). The recent quality of water in the Sabie River is generally good (van Vuuren, 2017b; Riddell et al., 2019a) even though historically it has been highly impacted through mining pollution (Barker, 2006; Riddell et al., 2019a). On the Crocodile River, near the KNP, land degradation, over-abstraction and river regulation are the largest impacts on the river despite the generally good quality of its water (Riddell et al., 2019b).

The natural quality of the water in the Inkomati-Usuthu WMA is controlled by chemical weathering and the contribution of mostly sulphates and chloride (Huizenga, 2011). The WMA is predominantly affected by land use types such as commercial forestry and agriculture, and rural and urban development along the Sabie River; and by commercial forestry, agriculture (fruit orchards, vegetable plots and sugarcane fields), as well as urban and rural settlements (Roux et al., 2018; DWS, 2019) along the Crocodile River.

The selected water quality, water flow and climate monitoring sites used in the data analyses for the Inkomati-Usuthu WMA are presented in Figure 5.22. A discussion of the water quality trends, pollution hot spots, high risk areas and the relationships between water quality and climate variability now follows.

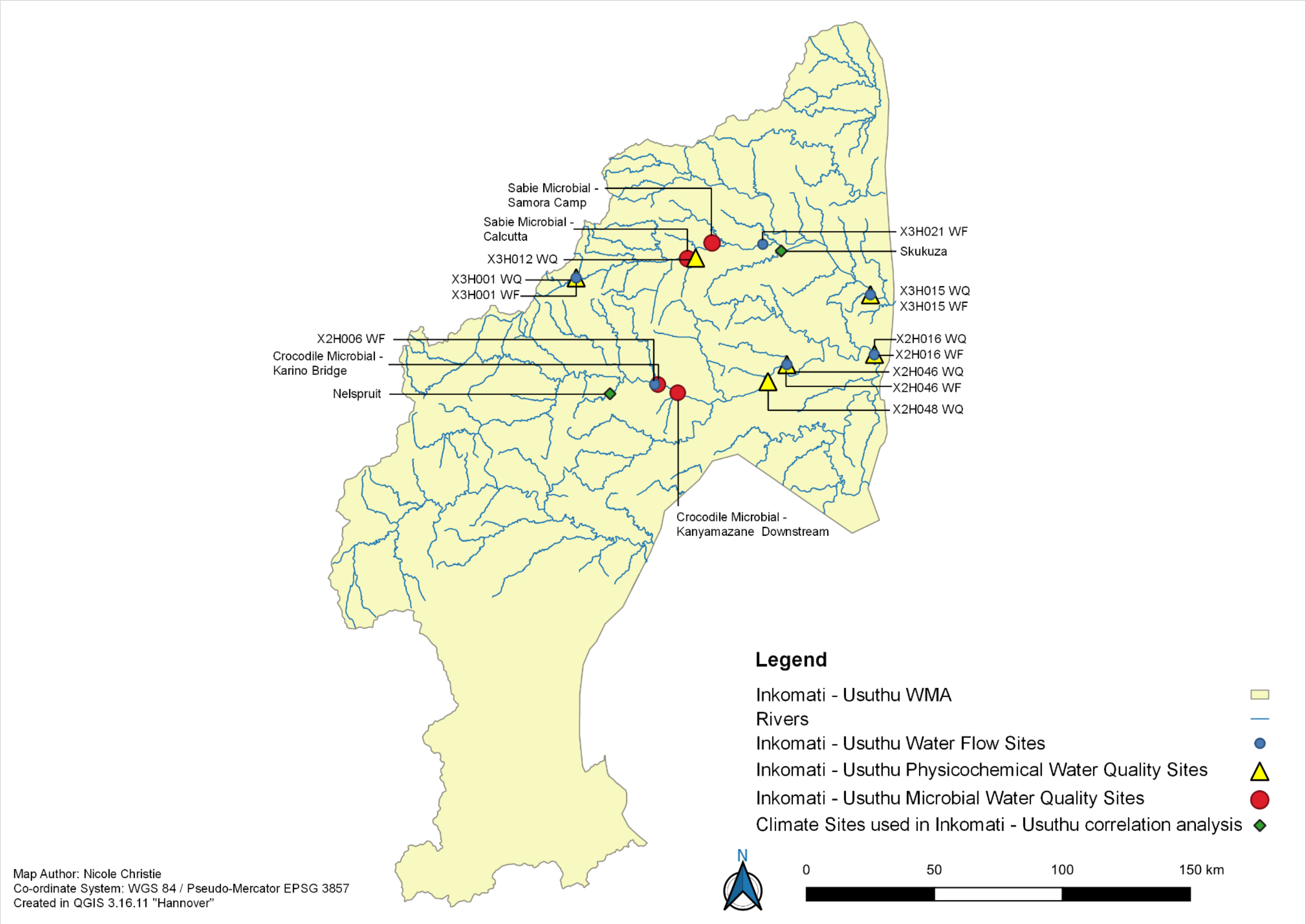

Figure 5.22: Map of the Inkomati-Usuthu WMA - water quality, water flow and climate monitoring sites.

5.4.1. The Sabie River

The physicochemical quality of the water of the Sabie River was analysed at three sites, namely X3H001 (1976 - 2018), X3H012 (1984 - 2018) and X3H015 (1984 - 2017), while the microbial quality of the water of the Sabie River was analysed at two sites, namely "Sabie Microbial - Samora Camp" (2002 - 2016) and "Sabie Microbial - Calcutta" (2006 – 2020). Water quality data for the Sabie River were all non-normally distributed.

The location of the three physicochemical water quality monitoring sites within proximity of one another provided the opportunity to gain a deeper understanding of the spatial trends in the quality of the water as the river flows downstream, with the dilution factor of the river and the addition of various other pollutants also taken into consideration. A more detailed spatio-temporal analysis was possible, beginning with site X3H001, approximately 50 km outside the KNP, and ending at site X3H015, approximately 70 km within the KNP border.

The distribution of data for each of the respective water quality parameters was similar for sites X3H001, X3H012 and X3H015. However, overall, the water quality differed in terms of the mean concentrations of the various parameters. The box plots indicated that the mean values for EC, pH, calcium, chloride, magnesium, sodium, phosphate, and sulphate were lowest at site X3H001 and highest at site X3H015. This suggests that the quality of the water deteriorated downstream, as the river flows into and through the KNP. High mean values for these parameters were in part due to large outliers in the data which indicated extreme pollution events at the sites. The mean values for ammonia and nitrate were highest at site X3H001, the site furthest upstream, and similar for sites X3H012 and X3H015. This indicates that in terms of these parameters, the quality of the water improved as the river flowed closer to the KNP and that as a result, the upstream sources of the relevant pollutants need to be more effectively managed.

The box plots for *E. coli* indicated that mean microbial water quality between sites was similar. However, the distribution of data around the mean varied significantly, with the "Sabie Microbial - Calcutta" site having larger outliers than the "Sabie Microbial - Samora Camp" site. The microbial quality of the water was better downstream, thus indicating that the water quality tends to improve as the river flows closer to the KNP. The results of the various analyses detailing further trends in water quality and its relationship to climate variability and water flow are discussed in depth in the following sections.

5.4.1.1. Time Series Trend Analysis for Sites on the Sabie River

The results of the MK analyses for physicochemical water quality parameters at site X3H001 on the Sabie River found a consistent trend in water quality (Figure 5.23). The computed *p*-values were lower than the significance level of $a=0.05$; thus, *Ha* was accepted. Large positive *S* values revealed strong upward trends for all parameters, indicating increasing concentrations of physiochemical pollutants. This trend is significant in light of the fact that in recent years the quality of the water in the Sabie River has been regarded as being among the most pristine in South Africa and a favourable habitat to an abundance of biologically diverse species (van Vuuren, 2017a; Riddell et al., 2019a). The increasing trend observed in these water quality parameters may be an indication of the first signs that the quality of the water in the river is gradually declining and that its buffering capacity is decreasing as a result of the increased pollution load.

Notwithstanding the upward trends indicated by the MK analyses, the overall physicochemical quality of the water remained good. EC and the calcium, chloride, magnesium, sodium, phosphate, sulphate, and nitrate concentrations were all within the ideal standard for domestic use. The ammonia concentrations fluctuated between ideal and acceptable standards for domestic use. Furthermore, owing to a pH < 6.0 between 1980 and 1989, the pH levels fluctuated between ideal and tolerable standards. This observation is consistent with previous research findings, which indicate that despite the strict pollution legislation that had been promulgated in the 1940s, the river was still, being influenced by AMD well into the 1980s, (van Vuuren, 2017a; Riddell et al., 2019a).

In terms of the irrigation use standards, EC and the chloride, sodium, ammonia, and nitrate concentrations were within ideal ranges, while, owing to the prevalence of more acidic pH levels between 1980 and 1989, the pH levels fluctuated between ideal and tolerable levels.

For aquatic ecosystems, the phosphate concentrations were within ideal standards, whereas the ammonia and nitrate concentrations were within ideal to acceptable standards. On the other hand, the chloride concentrations, even in the pristine Sabie River, were of an unacceptable standard for aquatic ecosystems.

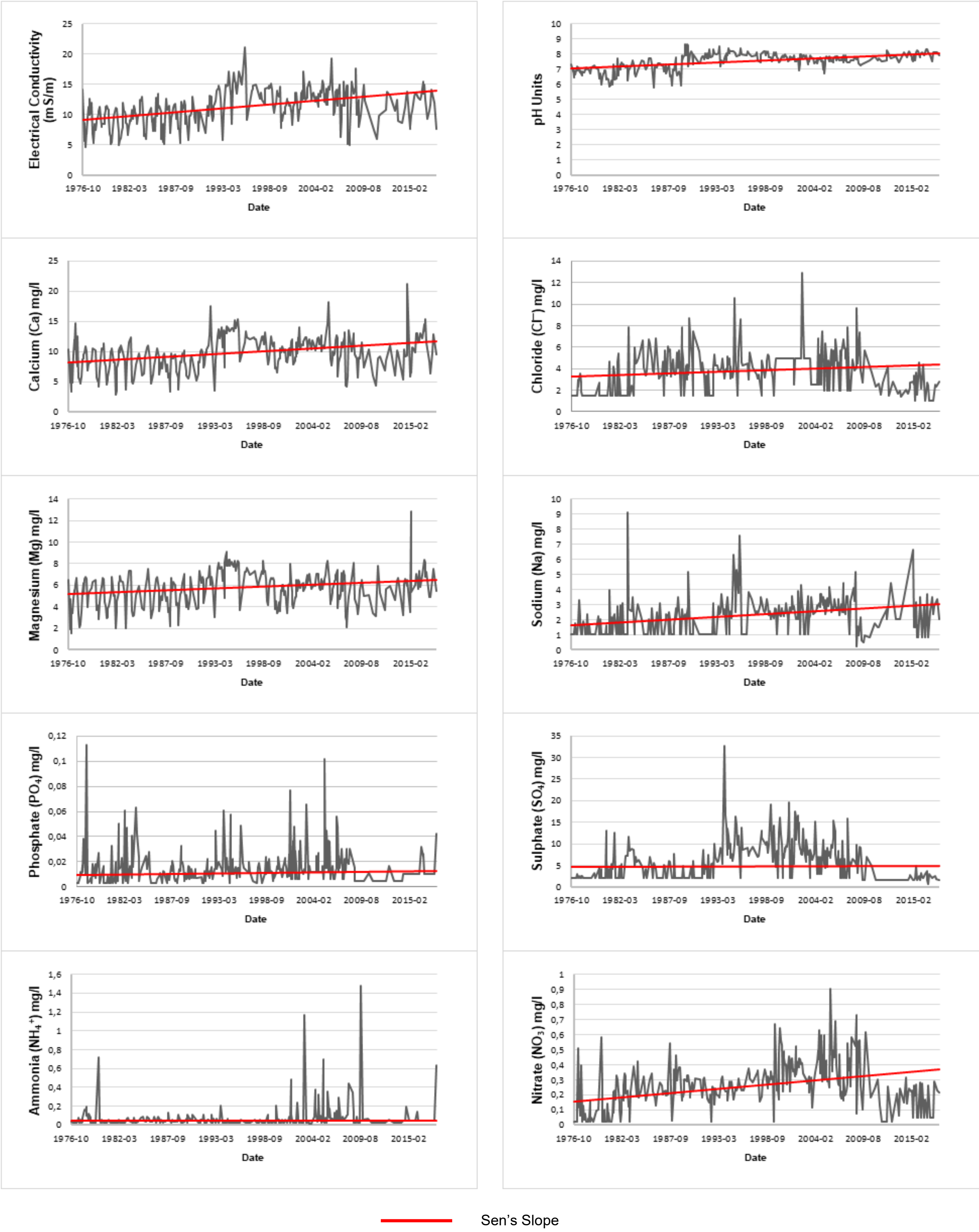

Figure 5.23: MK analyses for physicochemical water quality at site X3H001 on the Sabie River for the analysed time period.

The results of the MK analyses for the physicochemical water quality parameters at site X3H012 on the Sabie River showed varying trends (Figure 5.24). The computed *p*-values for EC and pH, and the calcium, magnesium, sodium, sulphate, and nitrate concentrations were lower than the significance level of *a=0.05;* thus, *Ha* was accepted. Large positive *S* values revealed strong upward trends for EC, pH, calcium, magnesium, and sodium. On the other hand, large negative S values revealed strong downward trends for sulphate and nitrate. The computed *p*-values for chloride, phosphate and ammonia were greater than the significance level of *a=0.05;* thus, *H0* was accepted. There was no evidence of any trends for these parameters at this site over the observed time period.

Overall, the physicochemical quality of the water at the site was good. All parameters, namely, EC and pH, and the calcium, chloride, magnesium, sodium, sulphate, ammonia, and nitrate concentrations, were within ideal ranges for domestic use. Only one observation, namely that for EC, was elevated to an unacceptable level in 2006.

For irrigation use, the EC, chloride, ammonia, and nitrate concentrations were of an ideal standard. Two observations for EC, namely, one in 1999; the other in 2006, fluctuated at acceptable levels. The pH levels fluctuated between ideal and tolerable, while the sodium concentrations fluctuated between ideal and acceptable levels.

The phosphate and ammonia concentrations were within ideal levels for aquatic ecosystems, whereas the nitrate concentrations were within ideal to acceptable ranges. On the other hand, the chloride concentrations over the observed time period were of an unacceptable standard for aquatic ecosystems.

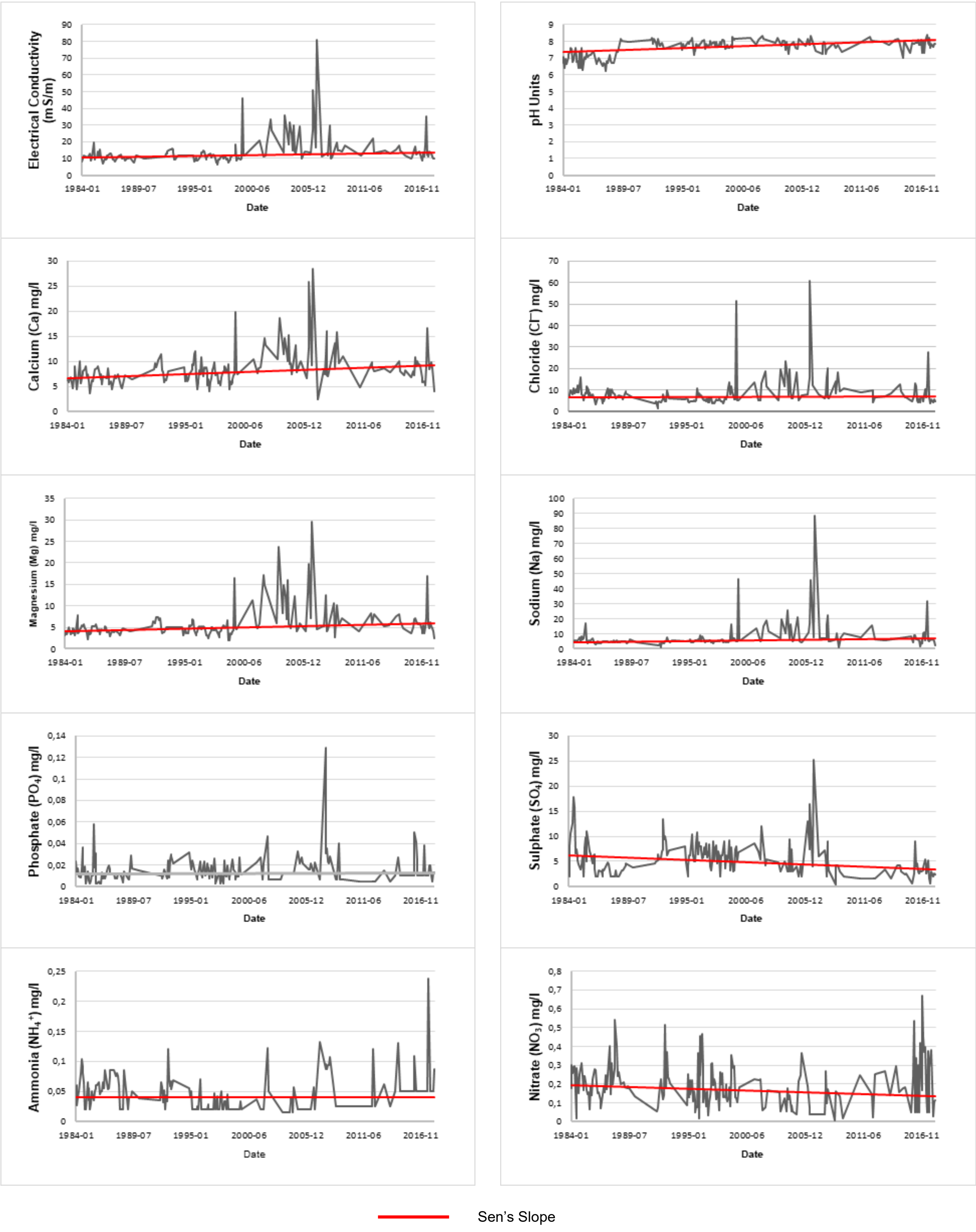

Figure 5.24: MK analyses for physicochemical water quality at site X3H012 on the Sabie River for the analysed time period.

For site X3H015 MK analyses indicated varying trends in the physicochemical quality of the water (Figure 5.25). In respect of the EC and pH levels, and the calcium, chloride, magnesium, sodium, phosphate, and ammonia concentrations, *p*-values were lower than the significance level of *a=0.05;* thus, *Ha* was accepted. Strong upward trends for EC, pH, calcium, chloride, magnesium, sodium, and phosphate were evident from the large positive *S* values. A large negative *S* value indicated an overall decrease in ammonia levels over time. The computed *p*-values for sulphate and nitrate suggested no trends.

Overall, the physicochemical quality of the water at site X3H015 was good, while the water quality parameters displayed similar properties to those at site X3H012. EC and pH, and the calcium, chloride, magnesium, sodium, sulphate, ammonia, and nitrate concentrations were all within the ideal standards for domestic use. Only one observation for EC in 1999 was elevated to an acceptable level.

For irrigation use, the chloride, sodium, ammonia, and nitrate concentrations were of an ideal standard, while EC fluctuated between ideal and acceptable ranges. The pH levels fluctuated between ideal and tolerable, while the levels for the sodium concentrations fluctuated between ideal and acceptable.

For aquatic ecosystems, the phosphate and ammonia concentrations were ideal, while the nitrate concentration level ranged from ideal to acceptable. On the other hand, the chloride concentration levels over the observed time period were of an unacceptable standard.

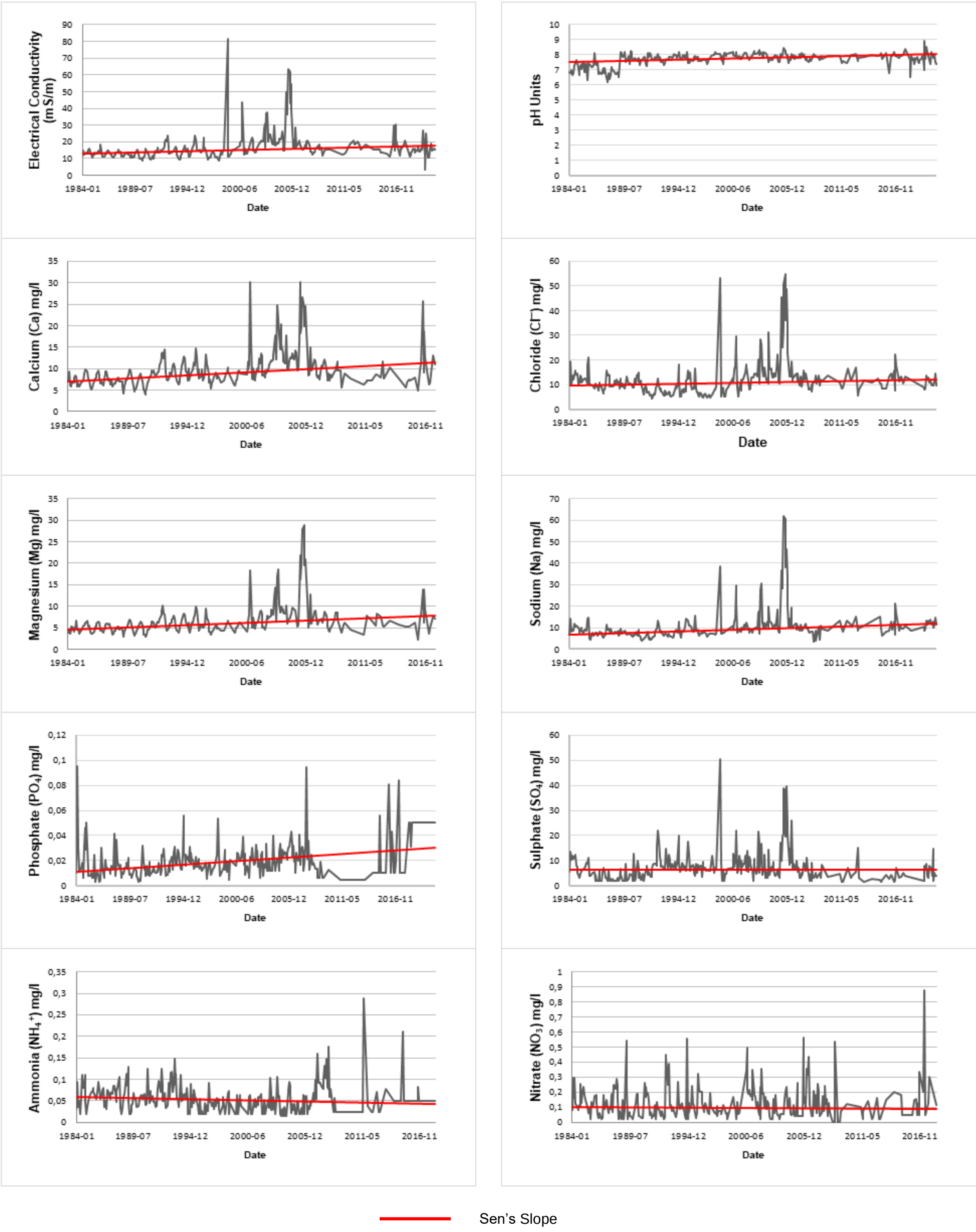

Figure 5.25: MK analyses for physicochemical water quality at site X3H015 on the Sabie River for the analysed time period.

The dataset for site “Sabie Microbial - Calcutta” was one of the most extensive microbial water quality monitoring datasets, with 116 observations. However, multiple gaps were still present; for instance, no statistics were recorded for the year 2009. The MK analysis at this site (Figure 5.26) computed no significant trend.

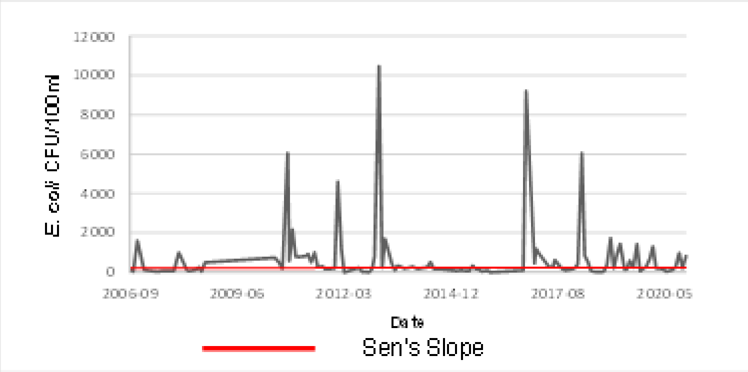

Figure 5.26: MK analysis for site “Sabie Microbial - Calcutta” for the analysed time period.

Despite the physicochemical quality of the Sabie River water being good, most of the microbial observations (96%) were of an unacceptable standard for domestic use. However, apart from 14% of the observations which rose to unacceptable levels, the *E. coli* counts met the tolerable standard for irrigation use. The site should therefore be flagged as a high risk area on account of its persistently unacceptable *E. coli* counts. As such, improvements in monitoring are necessary to gain a deeper understanding of the current trends relating to microbial pollution at this site. This is especially important since the site is located just outside the KNP and may lead to negative consequences for wildlife in the park (du Plessis, 2014; Riddell et al., 2019a).

Figure 5.27 indicates that the *p*-value for *E. coli* at site “Sabie Microbial - Samora Camp” on the Sabie River was greater than the significance level of $a=0.05$ and thus exhibited no significant trends. Since the dataset for this site contained 75 observations, and was, therefore, one of the more extensive datasets, it allowed for a detailed analysis of the microbial quality of the water. However, multiple gaps were still present in the dataset. For instance, no statistics were recorded for the year 2005.

Although the physicochemical quality of the water in the Sabie River was good, most of the observations for *E. coli* (97%) were within the unacceptable range for domestic use. In terms of irrigation use, however, only 12% of the observations that showed elevated levels of *E. coli* were of an unacceptable standard, with the remaining observations within tolerable counts.

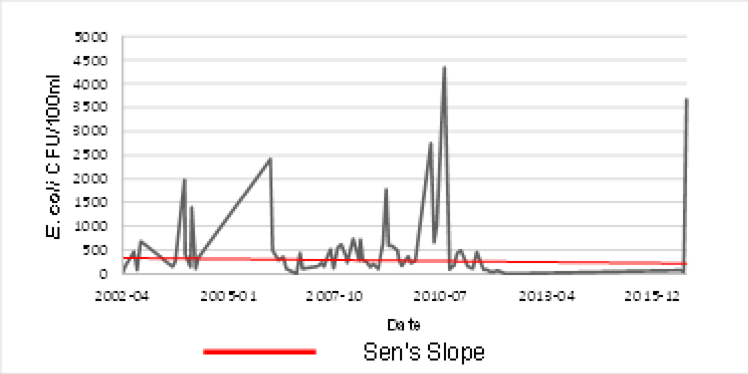

Figure 5.27: MK analysis for site “Sabie Microbial - Samora Camp” for the analysed time period.

As a result of their ability to disrupt the nutrient content of an aquatic ecosystem, unacceptable *E. coli* counts cause long-term negative consequences for wildlife in the park (du Plessis, 2014; Riddell et al., 2019a). Thus, the site “Sabie Microbial - Samora Camp” should also be flagged as a high risk area. Owing to the location of this site, just outside the park, it is especially important that the practice of monitoring be improved and that a deeper understanding of the current trends in microbial pollution be established.

5.4.1.2. Correlation Analysis Results for Sites on the Sabie River

The completed Spearman’s correlation analysis provided coefficients of correlation for site X3H001 (Table 5.18). The general relationships indicated that variations in the local climate had a moderate to strong association with variations in the quality of the water at the site. The most influential parameter for water quality was water flow, followed by the climate parameters, namely average rainfall, and average minimum temperature.

Significant correlations between water flow and several water quality parameters were evident, as follows. Water flow had strong negative correlations with EC and calcium and magnesium concentrations. This indicates that an increase or decrease in water flow inversely affected these parameters. As such, depending on the average water flow, their concentrations became more-or-less diluted. Average rainfall and average minimum temperature both had moderate negative correlations with the calcium and magnesium concentrations. Thus, an increase in rainfall and lower temperatures

Table 5.18: Spearman's correlation matrix for site X3H001 on the Sabie River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,597	**1**												
Calcium	0,888	0,515	**1**											
Chloride	0,275	0,242	0,110	**1**										
Magnesium	0,796	0,476	0,847	0,012	**1**									
Sodium	0,476	0,330	0,381	0,325	0,313	**1**								
Phosphate	0,240	0,157	0,238	0,154	0,199	0,338	**1**							
Sulphate	0,429	0,238	0,355	0,365	0,225	0,302	0,252	**1**						
Ammonia	0,009	-0,069	-0,042	0,143	-0,045	0,058	0,146	-0,114	**1**					
Nitrate	0,368	0,252	0,280	0,433	0,199	0,360	0,233	0,478	0,146	**1**				
Water flow	-0,543	-0,240	-0,599	0,067	-0,674	-0,165	-0,158	0,020	-0,032	-0,068	**1**			
Average Rainfall	-0,296	-0,159	-0,332	0,085	-0,429	-0,048	0,047	0,125	-0,034	-0,057	0,653	**1**		
Average Max. Temp.	-0,132	0,036	-0,172	0,024	-0,228	-0,048	0,035	0,002	0,021	-0,201	0,443	0,446	**1**	
Average Min. Temp.	-0,282	-0,103	-0,327	0,066	-0,410	-0,075	0,014	0,120	-0,028	-0,147	0,673	0,754	0,827	**1**

reduced the concentrations of magnesium and thus conductivity at this site. This trend, along with the strong positive correlation of EC with calcium indicated that these parameters were the primary influencers of conductivity at the site.

The established coefficients of correlation derived from the Spearman's correlation analysis for site X3H012 showed varying relationships between the respective parameters (Table 5.19). Several moderate to strong positive correlations as well as several moderate negative correlations were evident from the matrix.

A significant negative correlation was determined between water flow and calcium at this site. Rainfall and minimum temperature also presented moderate negative correlations with calcium at this site. Thus, with decreases in rainfall and water flow, and variations in temperature the calcium concentration levels at this site increased.

Water flow, rainfall and minimum temperature also had moderate negative correlations with magnesium. As with calcium, these parameters inversely affected the magnesium concentrations at this site. Since the calcium and magnesium levels are usually analysed together on account of their natural interaction (DWAF, 1996a), the effect of climate on both parameters is significant. Magnesium influences the biological processes in freshwater organisms and when present in large quantities and in conjunction with calcium, it can approach toxic levels. As previously mentioned, increased magnesium concentrations can lead to the proliferation of algae due to it being the central atom in the *Chlorophyll* molecule (van Dam et al., 2010; Kimambo et al., 2019; Salman et al., 2023).

The coefficients of correlation derived from the Spearman's correlation analysis for site X3H015 (Table 5.20) concurred with the results for site X3H012. Moderate to strong positive and negative correlations occurred between several water quality parameters, water flow and climate parameters.

Significant correlations between water flow and calcium and magnesium were once again evident. Water flow had moderate negative correlations with both calcium and magnesium at this site. Thus, with a decrease in the water flow, there was an increase in the calcium and magnesium concentrations. As mentioned, the combination of calcium and magnesium, when present in high concentrations, can have significant impacts on the physicochemical quality of the water. This can lead to aquatic toxicity, as well as to the presence of C*hlorophyll,* which is responsible for eutrophication (van Dam et al., 2010; Kimambo et al., 2019; Salman et al., 2023).

Table 5.19: Spearman's correlation matrix for site X3H012 on the Sabie River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,448	**1**												
Calcium	0,831	0,482	**1**											
Chloride	0,565	0,072	0,276	**1**										
Magnesium	0,900	0,540	0,881	0,416	**1**									
Sodium	0,615	0,261	0,333	0,663	0,466	**1**								
Phosphate	0,083	0,010	0,114	0,167	0,098	0,023	**1**							
Sulphate	-0,007	0,046	-0,009	-0,034	-0,011	0,009	0,228	**1**						
Ammonia	0,113	0,071	0,001	-0,043	0,098	0,013	0,154	-0,228	**1**					
Nitrate	-0,282	-0,143	-0,402	-0,006	-0,328	-0,171	0,054	-0,017	0,010	**1**				
Water flow	-0,175	-0,276	-0,427	0,379	-0,328	0,229	0,130	0,116	0,004	0,274	**1**			
Average Rainfall	-0,112	-0,156	-0,325	0,305	-0,275	0,179	0,159	0,139	0,005	0,136	0,606	**1**		
Average Max. Temp.	-0,185	-0,103	-0,329	-0,024	-0,264	-0,063	0,031	-0,104	0,301	-0,031	0,326	0,443	**1**	
Average Min. Temp.	-0,251	-0,195	-0,415	0,106	-0,356	-0,034	0,164	0,112	0,089	0,082	0,571	0,747	0,818	**1**

Table 5.20: Spearman's correlation matrix for site X3H015 on the Sabie River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,469	**1**												
Calcium	0,853	0,411	**1**											
Chloride	0,650	0,277	0,471	**1**										
Magnesium	0,862	0,417	0,901	0,531	**1**									
Sodium	0,724	0,331	0,545	0,790	0,573	**1**								
Phosphate	0,133	0,052	0,225	0,228	0,177	0,288	**1**							
Sulphate	0,356	0,134	0,433	0,189	0,341	0,334	0,414	**1**						
Ammonia	-0,131	-0,179	-0,065	-0,071	-0,020	-0,080	0,163	0,019	**1**					
Nitrate	-0,104	-0,125	-0,113	0,161	-0,165	0,216	0,400	0,286	0,248	**1**				
Water flow	-0,186	-0,181	-0,380	0,164	-0,429	0,199	0,056	0,023	-0,125	0,408	**1**			
Average Rainfall	-0,049	-0,132	-0,160	0,086	-0,217	0,106	0,015	0,074	-0,122	0,206	0,633	**1**		
Average Max. Temp.	0,006	0,015	-0,035	0,103	-0,030	0,120	0,159	0,062	0,017	0,157	0,301	0,464	**1**	
Average Min. Temp.	-0,061	-0,068	-0,159	0,089	-0,198	0,089	0,084	0,079	-0,076	0,193	0,561	0,759	0,816	**1**

The coefficients of correlation for the Spearman's correlation analysis completed for *E. coli* at site "Sabie Microbial - Calcutta" and the corresponding water flow and climate sites (Table 5.21) indicated significant associations between microbial water quality, water flow and climate variability.

Table 5.21: Spearman's correlation matrix for site "Sabie Microbial - Calcutta" on the Sabie River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	0,341	**1**			
Average Rainfall	0,205	0,530	**1**		
Average Max. Temp.	0,078	0,305	0,437	**1**	
Average Min. Temp.	0,221	0,493	0,679	0,788	**1**

In the light of the moderate positive correlation, variations in the *E. coli* counts at this site could be associated with variations in water flow. Thus, as the water flow increased or decreased at this site, so did the *E. coli* counts. As mentioned, Hyer (2007) and Dwivedi et al. (2013) confirmed these findings in previous research. This correlation matrix (Table 5.21) exhibited results that were similar to those recorded in the following correlation matrix for site "Sabie Microbial - Samora Camp" (Table 5.22).

Table 5.22: Spearman's correlation matrix for site "Sabie Microbial - Samora Camp" on the Sabie River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	0,351	**1**			
Average Rainfall	0,141	0,619	**1**		
Average Max. Temp.	-0,189	0,038	0,504	**1**	
Average Min. Temp.	0,046	0,398	0,801	0,761	**1**

The results of the Spearman's correlation analysis indicated significant correlations between *E. coli* and variations in water flow. A moderate positive correlation between water flow and *E. coli*, as described by Hyer (2007) and Dwivedi et al. (2013), was evident.

5.4.1.3. *Synthesis: Water Quality and Climate Impacts for the Sabie River*

The three physicochemical water quality datasets contributed to an in-depth spatial analysis of the Sabie River. Because the three sites were near one another, it was possible to easily evaluate water quality characteristics of the river as it flowed into the KNP. Overall, the physicochemical quality of the water in the Sabie River was virtually ideal. Although several water quality parameters fluctuated between acceptable and tolerable standards, most of the parameters remained within the ideal standards for domestic use, irrigation, and aquatic ecosystems. Overall, the microbial quality of the water in the Sabie River over the observed time period was substantially degraded, with the *E. coli* counts at both sites over the observed time period mostly of an unacceptable standard for all uses.

Spatially, the water quality parameters exhibited large variations between sites on the Sabie River. The mean values of the water quality parameters were significantly different between sites X3H001, X3H012 and X3H015, with the physicochemical quality of the water deteriorating progressively downstream and into the KNP. However, ammonia and nitrate, both of which are ingredients in commercial fertilisers, exhibited larger concentrations upstream which may have been due to that portion of the catchment being dominated by plantations (du Plessis, 2019). The microbial quality of the water also differed between the sites, improving as the river approached the KNP.

Temporal trends in water quality were similar for the respective sites. Analyses revealed that the Sabie River remains one of South Africa's most pristine rivers (van Vuuren, 2017b; Riddell et al., 2019a). However, the physicochemical water quality parameters at all sites mostly indicated increasing trends in the concentration levels of EC, pH, calcium, magnesium, sodium, and phosphate over the observed time periods. Despite the quality of the water at site X3H001 being at its best overall, the MK analyses indicated that the concentration levels of all the parameters at this site were increasing, which indicates deterioration in the quality of the water. Site X3H012 had several parameters with increasing trends, as did site X3H015. These findings show that the historically good quality of the river water is under potential threat, and if not monitored and managed correctly, this could have severe implications for the wildlife in the KNP that depend on the river as a water source. The microbial quality of the water in the Sabie River did not reveal any spatial trends and remained highly degraded at both monitoring sites. The main water quality parameters of concern for this river are those indicating increasing ionic loads, specifically chloride and *E. coli*, as well as higher pH levels.

The correlation analyses conducted for sites on the Sabie River indicated that climate variability influences the quality of the water. Overall, the physicochemical quality of the water exhibited various moderate to strong negative and positive correlations with water flow, average rainfall, and average minimum temperature. These parameters presented with monotic inverse relationships, varying in the opposite direction to water flow and average minimum and maximum temperature. In terms of microbial water quality, the moderate positive correlations indicated that the variations in the *E. coli* counts could be associated with variations in water flow at both sites.

The research findings show that the historically pristine water quality of the Sabie River has in recent years come under threat of increasing pollution and a changing climate. The gradual decline in water quality at the three analysed sites on the river suggests that the KNP can expect to experience long-term changes to the health of the aquatic and terrestrial ecosystems in the park that are supported by the Sabie River. The microbial quality of the water remains problematical and the sources from which *E. coli* issues need to be identified and addressed. Both the physicochemical and the microbial quality of the river water are widely affected by climate variability, a finding that should be taken into consideration for future research, monitoring, and management.

A discussion of the water quality trends, pollution hot spots, high risk areas and the relationships between water quality, water flow and climate variability for sites on the Crocodile River now follows.

5.4.2. The Crocodile River

The physicochemical quality of the water in the Crocodile River was analysed at three sites, namely, X2H016 (1977 - 2018), X2H046 (1987 - 2018) and X2H048 (1987 - 2019), while its microbial quality was analysed at two sites, namely “Crocodile Microbial - Karino Bridge” (2006 - 2021) and “Crocodile Microbial - Kanyamazane Downstream” (2006 - 2021). The water quality data for the Crocodile River were all non-normally distributed.

The locations of the three physicochemical water quality monitoring sites were near one another (Figure 5.22) and provided the researcher with an opportunity to gain a deeper understanding of the spatial trends of the river as it flows downstream, with due consideration being given to its dilution factor and the addition of various pollutants. A more detailed spatio-temporal analysis was possible, beginning with site X3H048, proceeding to site X2H046, approximately 12 km downstream, and then to site X2H016, approximately 65 km downstream. Site X2H016 is located inside the boundary of the KNP and is one of the primary water sources in the park.

The distribution of data for each of the respective water quality parameters was similar for sites X2H016, X2H046 and X2H048, with both similarities and differences in water quality overall occurring between the respective sites in terms of the mean concentrations of the various parameters. Box plots indicated that the mean values of EC and the calcium, chloride, magnesium, and sodium concentrations were generally lowest at site X2H048 (upstream and outside the KNP) and highest at site X2H016 (downstream and within the borders of the KNP), which indicate that the physicochemical quality of the water in terms of these parameters deteriorates downstream as the river flows into and across the KNP.

Box plots for *E. coli* indicated that mean microbial water quality was similar for the three sites. However, the microbial quality of the water declined slightly between the “Crocodile Microbial - Karino Bridge” and “Crocodile Microbial - Downstream Kanyamazane” sites. The results obtained through the time series trend and the correlation analyses indicate the aforementioned trends. These are discussed in depth in the following sections.

5.4.2.1. Time Series Trend Analysis for Sites on the Crocodile River

The results of the MK analyses for the physicochemical water quality parameters at site X2H016 on the Crocodile River mostly indicated a deterioration in the water quality (Figure 5.28). The computed *p*-values for all parameters, except ammonia, at this site were lower than the significance level of *a=0.05;* thus, *Ha* was accepted. Large positive *S* values revealed strong upward trends for EC and pH, and the calcium, chloride, magnesium, sodium, phosphate, and sulphate concentrations. Long-term increases in these parameters could therefore indicate possible domestic, mining, and industrial influences on the quality of the water and should be monitored carefully for further changes (Table 3.1). A large negative *S* value indicated that nitrate pollution at this site had declined over time.

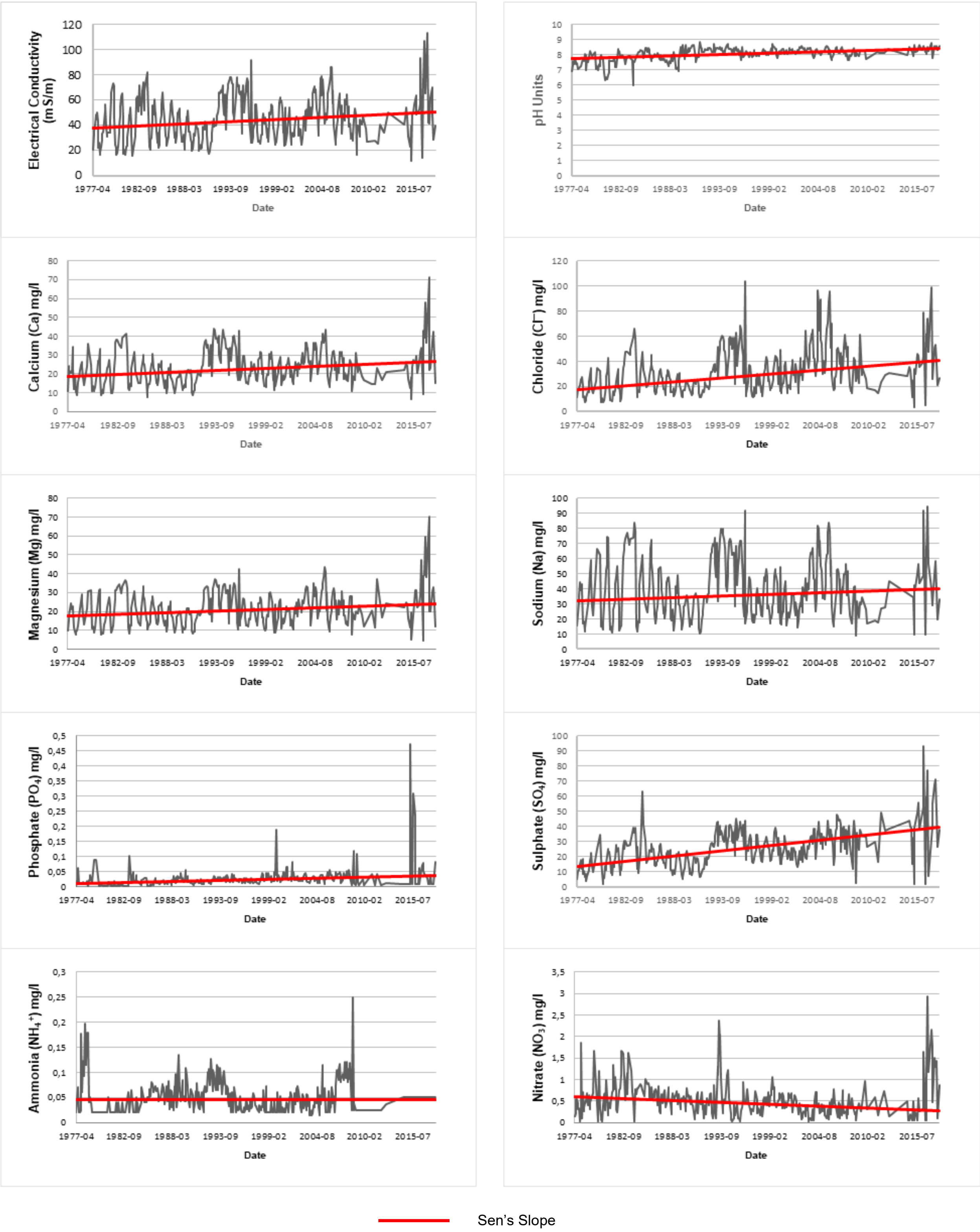

Figure 5.28: MK analyses for the physicochemical water quality at site X2H016 on the Crocodile River for the analysed time period.

In terms of domestic use, none of the water quality parameters had values that exceeded ideal and acceptable levels except for magnesium. Magnesium reached tolerable levels for domestic use at times. For irrigation use, all parameters, aside from EC and pH complied with ideal standards. EC and pH fluctuated to tolerable levels for irrigation use.

For aquatic ecosystems, the phosphate concentrations were of an ideal standard. Furthermore, the ammonia concentrations were within ideal to acceptable levels and the nitrate concentrations within ideal to tolerable levels. On the other hand, the chloride concentrations remained within the unacceptable range for the analysed time period.

The completed MK analyses at site X2H046 on the Crocodile River returned varying results (Figure 5.29). The computed *p*-values for all parameters, apart from ammonia and nitrate, indicated a trend. As shown by the large positive *S* values, there were strong upward trends in all these parameters, which revealed increasing physicochemical pollution. The computed *p*-values for ammonia and nitrate were greater than the significance level of $a=0.05$; thus, $H0$ was accepted. For this site and the observed time period, there was no evidence of any trend for these parameters. The MK analysis results were similar to those for site X2H016, which is downstream from the current site, thus indicating that pollution in terms of these water quality parameters was increasing on this stretch of the Crocodile River.

Overall, however, the water quality at this site appeared to be marginally better than that at site X2H016. For domestic use, all parameters met either ideal or acceptable standards. In comparison, site X2H016, had fewer parameters that met the ideal standard, meaning that the water quality downstream from X2H046 deteriorated slightly.

For irrigation use, the chloride, sodium, ammonia, and nitrate concentrations were within the ideal range; EC fluctuated between ideal and acceptable ranges; and the pH levels between ideal and tolerable ranges.

For aquatic systems, the phosphate and ammonia concentrations were of an ideal standard, while the nitrate concentrations were within ideal to acceptable ranges. Once again, the chloride concentrations were highlighted as a parameter of concern on account of their unacceptable levels for aquatic ecosystems.

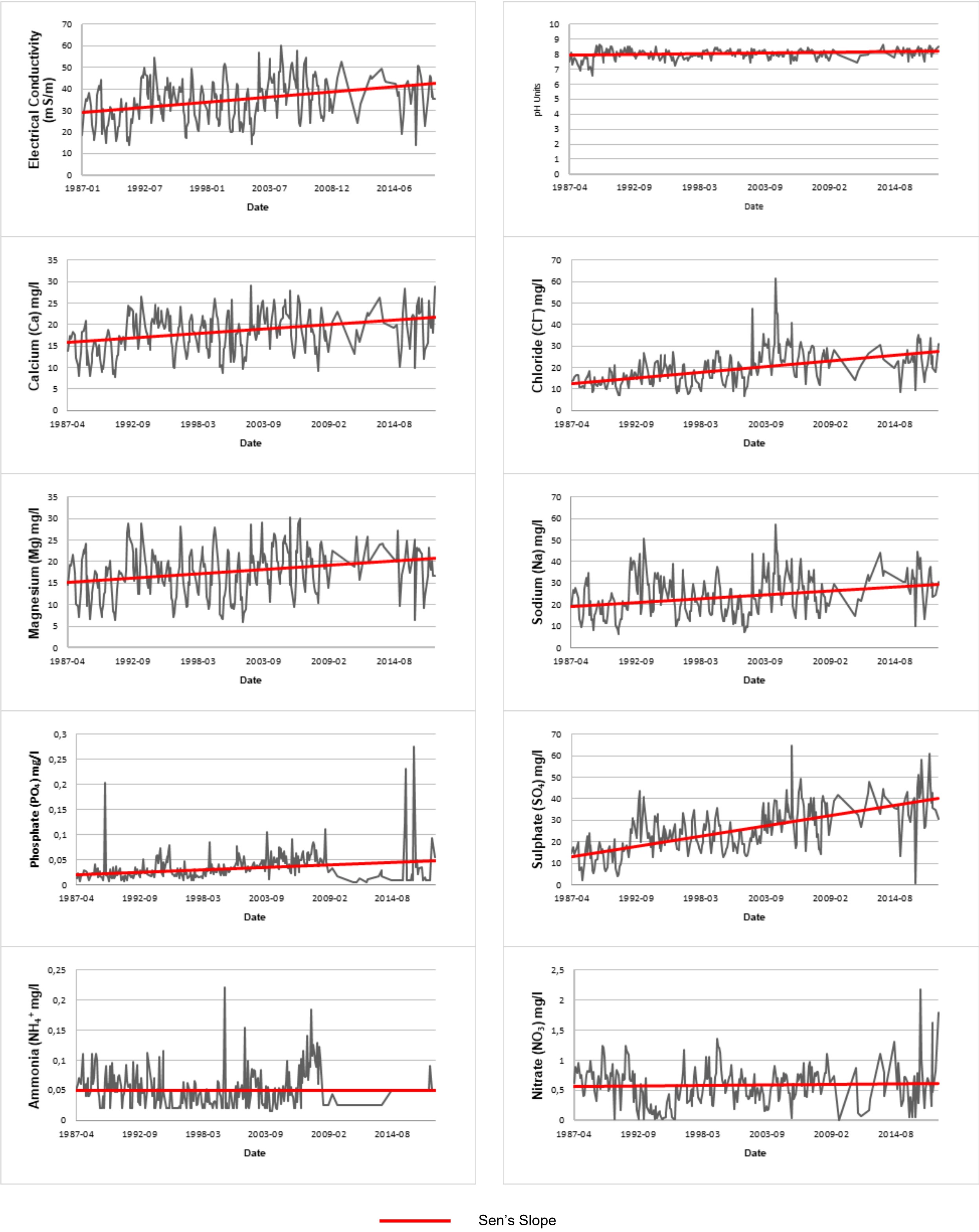

Figure 5.29: MK analyses for physicochemical water quality at site X2H046 on the Crocodile River for the analysed time period.

The results of the MK analyses for the physicochemical water quality parameters at site X2H048[3] returned varied findings (Figure 5.30). The computed *p*-values for EC, calcium, chloride, sodium, phosphate, and sulphate were lower than the significance level of *a=0.05;* thus, *Ha* was accepted. Large positive *S* values revealed strong upward trends for all these parameters, thus indicating increasing concentrations over the observed time period. No significant trends were observable from the computed *p*-values for pH, magnesium, ammonia, and nitrate.

The quality of the water at this site appeared to be similar to that at site X2H016 but was slightly worse than that recorded at X2H046. Only the sulphate concentrations were of an ideal standard for domestic use. The nitrate concentrations were mostly within the ideal range; however, one elevated concentration declined to a tolerable level in 2010. Chloride concentrations were mostly of an ideal standard, but several observations showed that the concentrations had risen to acceptable levels. EC and the calcium, magnesium, and sodium concentrations all fluctuated between ideal and acceptable levels for domestic use. However, one observation showed that magnesium had elevated to a tolerable level in 2006. The pH levels fluctuated between ideal and acceptable, with only two observations showing increases to tolerable levels in 2008 and 2011, respectively. The ammonia concentrations were mostly within the ideal range over the observed time period, with some observations showing elevations to acceptable and tolerable levels.

In terms of irrigation use, nitrate concentrations were mostly ideal, with one observation showing elevations to the tolerable level in 2010. EC, pH, chloride and sodium were within ideal to acceptable ranges. The ammonia concentrations were mostly at an ideal level, with some observations showing increased levels and thus reaching acceptable and tolerable standards.

In terms of the aquatic ecosystem TWQRs, the results were more varied than those for the previous sites. The ammonia concentrations were mostly of an ideal standard; however, there were some observations of tolerable levels. Approximately seven percent (7%) of nitrate observations met the tolerable standard; with 61% and 32% at an acceptable to ideal level respectively. In terms of the aquatic ecosystem standards, the phosphate concentrations were within the ideal level of < 0.5 mg/ℓ. Approximately five percent (5%) of the observations of phosphate concentrations at this site surpassed

[3] The furthest upstream site on the Crocodile River

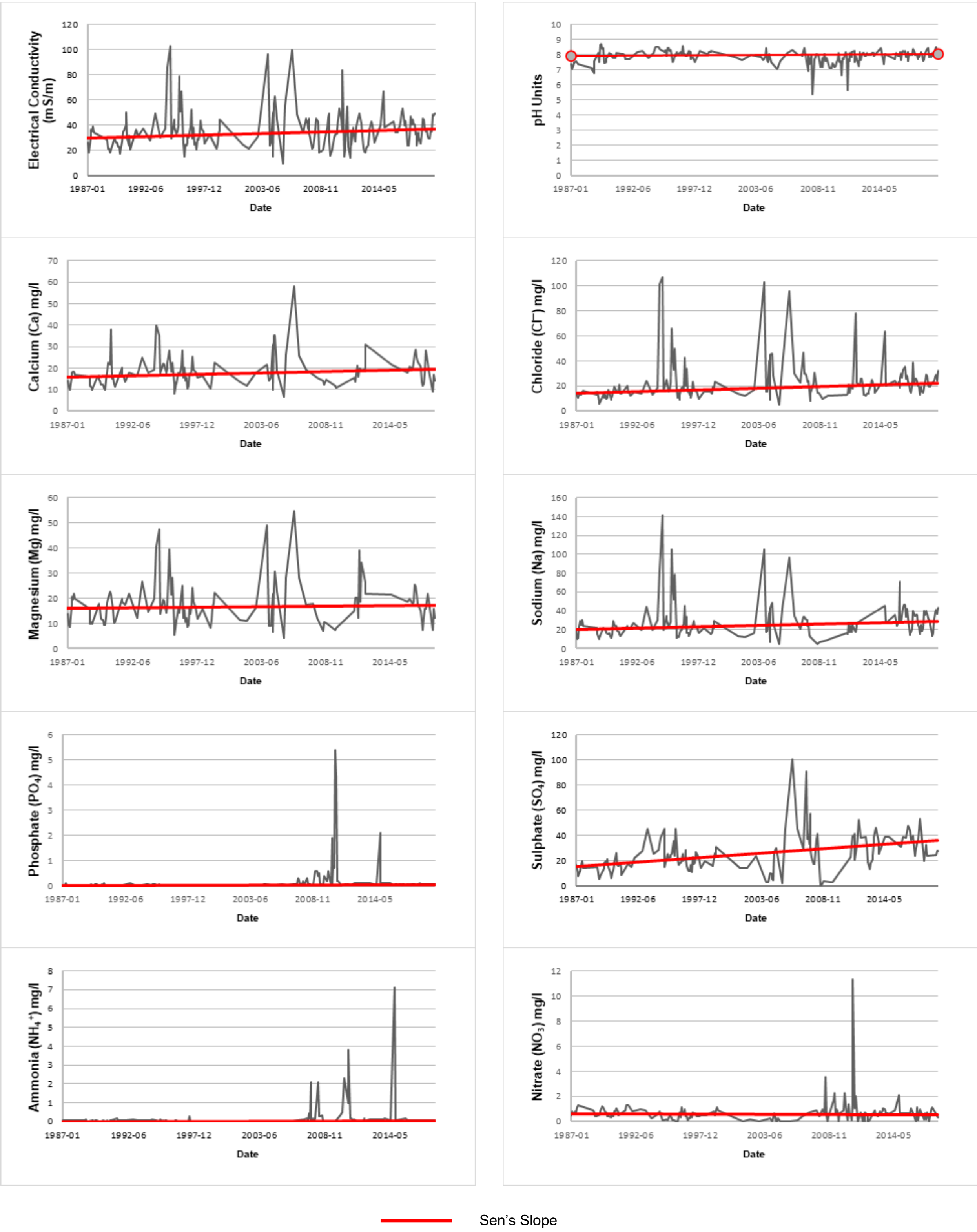

Figure 5.30: MK analyses for physicochemical water quality at site X2H048 on the Crocodile River for the analysed time period.

this guideline, particularly from 2010 onwards. This supports the results issuing from the completed MK analysis that indicate a gradually increasing trend in phosphate concentrations at this site. Owing to the potentially significant impacts of phosphate on the balance of freshwater systems, the monitoring of this water quality parameter should of necessity increase to assist in the identification of potential pollution issues in a proactive manner. Increased concentrations of phosphorus can cause excessive plankton growth, which in turn cycles large amounts of organic material into the waterbody, thus resulting in a lower DO. Lowered DO concentrations result in stress for the aquatic biota that require oxygen for respiration. Few organisms can survive in anoxic (deoxygenised) conditions (du Plessis, 2019).

The MK analysis at site "Crocodile Microbial - Karino Bridge" for *E. coli* on the Crocodile River (Figure 5.31) determined a computed *p*-value greater than the significance level of *a=0.05* and no significant trend was evident.

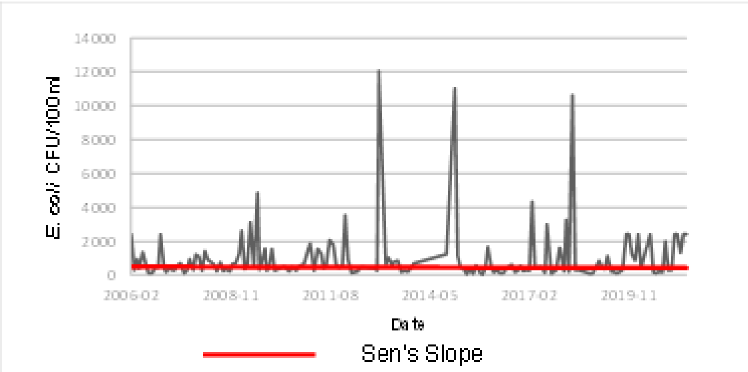

Figure 5.31: MK analysis for site "Crocodile Microbial - Karino Bridge" for the analysed time period.

In terms of domestic water use standards, the *E. coli* counts were of an unacceptable standard for 99% of all recordings that were made over the observed time period. For irrigation use, on the other hand, 25% of the observations showed levels of an unacceptable standard, while the other 75% were within the tolerable range for irrigation use.

Although this site is located upstream of the large Kanyamazane WWTWs, microbial pollution is still severe, while on the other hand, remedial action is of a critically low standard. There are no WWTWs located nearby and/ or upstream which could explain the unacceptably high microbial pollution levels. However, this does show that the water quality downstream of the Kanyamazane WWTWs is not the sole contributor to the unacceptable *E. coli* counts recorded at the “Crocodile Microbial - Kanyamazane Downstream” site (Figure 5.32). Several observations at the “Crocodile Microbial - Karino Bridge” site reached CFU/100 ml levels of more than 10 000. The site should therefore be flagged as high risk for current and future pollution events as such conditions could significantly affect human health, as well as the effective functioning of the ecosystems in the region.

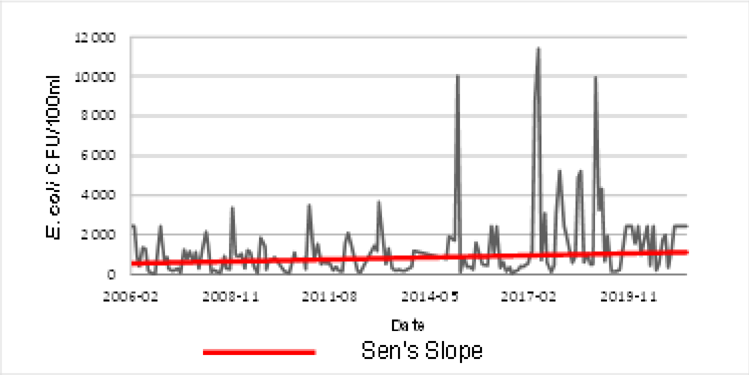

Figure 5.32: MK analysis for site “Crocodile Microbial - Kanyamazane Downstream” for the analysed time period.

The results of the MK analysis for *E. coli* at site “Crocodile Microbial - Kanyamazane Downstream” on the Crocodile River determined a computed *p*-value lower than the significance level of *a=0.05;* thus, *Ha* was accepted (Figure 5.32). A large positive *S* value revealed an upward trend indicating increasing *E. coli* counts over the observed time period. In terms of domestic use, the *E. coli* counts for 99% of the observations were of an unacceptable standard. For irrigation use, 42% of the observations were within the unacceptable range, and the other 58% of a tolerable standard.

Some observations showed *E. coli* counts in excess of 10 000 CFU/100 ml, with most of the observations for the more recent years, from 2015 onwards, supporting the MK analysis results, which show an increasing trend. It should be noted that the site is located approximately 2.5 km downstream of the Kanyamazane WWTWs. This explains the excessive *E. coli* counts in the river at this site. The site should be flagged as high risk for current and future pollution events and monitored more vigorously for regular pollution events. The Kanyamazane WWTWs should also be critically evaluated in terms of its compliance to the prevailing standards, while suitable interventions should be identified and implemented to reduce or minimise the increasing *E. coli* counts, which are associated with human health risks and degrading ecosystems.

5.4.2.2. Correlation Analysis Results for Sites on the Crocodile River

The established coefficients of correlation for the Spearman's correlation analysis for site X2H016 and the selected water flow and climate sites on the Crocodile River indicated moderate to strong positive and negative correlations between water quality, water flow and the respective climate parameters (Table 5.23). The most influential parameters affecting water quality were water flow, followed by average rainfall and average minimum temperature.

The correlation matrix indicated moderate to strong positive correlations between EC, pH, calcium, chloride, magnesium, sodium, and sulphate. Significant correlations were established between water flow and EC, calcium, magnesium, and sodium as well as moderate negative correlations with pH, chloride, and sulphate. Seasonal variations in pH in response to a changing hydrological cycle are typical of most freshwater sources (DWAF, 1996d). The mobilisation of sulphate through climate change related processes is indirect and varies between regions (Zak et al., 2021). However, severely acidic waters compromise the ability of fish to take up oxygen, while increased sulphate concentrations have additional negative implications for freshwater ecosystems. The latter case is due to the effects of a declining pH level, which is instrumental in mobilising heavy metals and other nutrients. Additionally, elevated sulphate concentrations might also alter the cycling of nitrogen and phosphorus and cause an imbalance in the nitrogen-phosphorus ratio (Zak et al., 2021).

As previously mentioned, high chloride concentrations can interfere with osmoregulation and are thus harmful to aquatic species in that they hinder their survival, growth, and reproduction (Hunt et al., 2012). The combination of elevated chloride and sulphate concentrations - in their turn influenced by variations in water flow - and their effects on pH could have profound negative consequences for freshwater ecosystems. Since water flow is inversely correlated, to varying degrees, with the aforementioned water quality parameters, it was observed that as the water flow decreased at site X2H016, so the conductivity and concentrations of these parameters increased, resulting in more severe cases of alkalinity/acidity.

Average rainfall and average minimum temperature presented moderate negative correlations with EC, calcium, and magnesium. Variations in these climate parameters

Table 5.23: Spearman's correlation matrix for site X2H016 on the Crocodile River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,492	**1**												
Calcium	0,887	0,543	**1**											
Chloride	0,848	0,579	0,907	**1**										
Magnesium	0,874	0,520	0,946	0,873	**1**									
Sodium	0,876	0,493	0,936	0,879	0,947	**1**								
Phosphate	0,076	0,209	0,061	0,176	-0,013	-0,041	**1**							
Sulphate	0,683	0,527	0,732	0,793	0,706	0,702	0,181	**1**						
Ammonia	0,062	0,134	0,063	0,065	0,049	0,081	0,149	0,033	**1**					
Nitrate	-0,022	-0,126	-0,001	-0,041	0,003	0,016	-0,010	-0,066	0,072	**1**				
Water flow	-0,702	-0,300	-0,611	-0,486	-0,643	-0,643	0,052	-0,340	-0,110	0,047	**1**			
Average Rainfall	-0,353	-0,255	-0,325	-0,206	-0,348	-0,286	0,063	-0,119	-0,074	-0,038	0,564	**1**		
Average Max. Temp.	-0,187	-0,059	-0,164	-0,082	-0,193	-0,153	0,092	-0,026	0,039	-0,272	0,279	0,471	**1**	
Average Min. Temp.	-0,353	-0,202	-0,319	-0,209	-0,361	-0,298	0,074	-0,153	-0,031	-0,132	0,523	0,754	0,836	**1**

inversely affected the concentrations of these water quality parameters. Since calcium and magnesium are usually analysed together (DWAF, 1996a) and contribute to the EC of a freshwater river/body, the influence of climate on both these parameters is significant. Magnesium influences biological processes in freshwater organisms and when present in large quantities, and in conjunction with calcium, it can cause a state of toxic eutrophication (van Dam et al., 2010; Kimambo et al., 2019; Salman et al., 2023). These mentioned water quality parameters should, therefore, be recognised as potential parameters of concern owing to their significantly negative impact on the functioning of aquatic ecosystems, on the health of aquatic organisms and/ or animals, as well as on possible human health risks.

At site X2H046 (Table 5.24), the results of the Spearman's correlation analysis are similar to those pertaining to site X2H016. Moderate to strong positive and negative correlations occurred between the same water quality, water flow and climate parameters, with the most influential parameters being water flow, followed by average minimum temperature and average rainfall.

The correlation matrix indicated moderate to strong positive correlations between EC, pH, calcium, chloride, magnesium, sodium, and sulphate. Thus, increases in any one of these parameters could be associated with increases in another. As with site X2H016, water flow had strong negative correlations with EC, calcium, magnesium, and sodium. Water flow also had moderate negative correlations with pH, chloride, and sulphate. As mentioned previously, pH is naturally responsive to variations in the hydrological cycle (DWAF, 1996d), and pH levels are influenced by high concentrations of chloride and sulphate (Hunt et al., 2012; Zak et al., 2021). The potential influence of climate change on those parameters that affect pH can cause significant harm to aquatic species and should therefore be highlighted as water quality parameters potentially of concern.

Average rainfall had moderate negative correlations with EC, calcium, magnesium, and sodium. Variations in rainfall inversely affected the concentrations of these water quality parameters. Thus, increased rainfall contributed to the dilution capacity of the river at this site, resulting in reduced concentrations of these parameters. However, during low rainfall and low-flow periods, a reduced dilution capacity causes the concentrations of ions to increase (Keller et al., 2014). At this site, this may then have resulted in negative impacts such as salinisation, which interferes with osmoregulation in aquatic species in the freshwater ecosystem. This in turn causes disturbances in biotic communities and results in reduced biodiversity (Weber-Scannell & Duffy, 2007; Singh et al., 2019).

Table 5.24: Spearman's correlation matrix for site X2H046 on the Crocodile River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	**1**													
pH	0,423	**1**												
Calcium	0,920	0,417	**1**											
Chloride	0,843	0,413	0,792	**1**										
Magnesium	0,932	0,435	0,858	0,747	**1**									
Sodium	0,934	0,405	0,876	0,799	0,895	**1**								
Phosphate	0,233	0,127	0,236	0,401	0,153	0,170	**1**							
Sulphate	0,799	0,345	0,755	0,813	0,741	0,759	0,264	**1**						
Ammonia	0,087	0,088	0,043	0,066	0,120	0,087	0,139	0,021	**1**					
Nitrate	0,131	0,258	0,090	0,162	0,220	0,091	0,074	0,156	0,230	**1**				
Water flow	-0,671	-0,347	-0,643	-0,481	-0,708	-0,670	-0,079	-0,440	-0,071	0,045	**1**			
Average Rainfall	-0,406	-0,279	-0,409	-0,250	-0,490	-0,390	0,037	-0,256	-0,140	-0,132	0,642	**1**		
Average Max. Temp.	-0,225	-0,175	-0,219	-0,121	-0,275	-0,194	0,025	-0,129	-0,023	-0,242	0,323	0,440	**1**	
Average Min. Temp.	-0,465	-0,306	-0,438	-0,319	-0,538	-0,426	0,034	-0,351	-0,113	-0,241	0,606	0,745	0,813	**1**

Average minimum temperature exhibited a strong negative correlation with magnesium and moderate negative correlations with EC, pH, calcium, chloride, and sodium. Significant variations in the minimum temperature at this site therefore inversely affected the concentrations of these water quality parameters.

The established coefficients of correlation derived from the completed Spearman's correlation analysis for site X2H048 (Table 5.25) on the Crocodile River showed results that were similar to those for sites X2H016 and X2H046. Moderate to strong positive and negative correlations occurred. The correlation matrix indicated moderate to strong positive correlations between EC, pH, calcium, chloride, magnesium, sodium, and sulphate. Thus, increases in any one of these water quality parameters could be associated with increases in another. It was established that the overall relationships were moderate, with only a few of the physicochemical water quality parameters exhibiting a response to changes. The most influential parameters were water flow, followed by the climate parameters of average rainfall and average minimum temperature.

Water flow at this site had a strong negative correlation with EC and moderate negative correlations with calcium, chloride, magnesium, sodium, and sulphate. Thus, as water flow decreased, so the concentrations of these water quality parameters increased. The latter includes several of the major ions responsible for the EC of a freshwater body, in conjunction with one another, they influence the salinity levels of freshwater bodies. Increased salinity in freshwater bodies alters the composition of ions, with the resultant toxicity possibly causing disruptions to the more sensitive aquatic species in the affected aquatic ecosystems (Weber-Scannell & Duffy, 2007; Singh et al., 2019).

The combination of calcium and magnesium, in high concentrations, could have significant negative impacts on aquatic toxicity and the proliferation of *Chlorophyll*, which is responsible for eutrophication (van Dam et al., 2010; Kimambo et al., 2019; Salman et al., 2023). Owing to their significant negative impact on the functioning of aquatic ecosystems, the health of aquatic organisms and/ or animals, as well as the possible risks that they pose to human health, these mentioned water quality parameters should also be considered as issues of concern.

Table 5.25: Spearman's correlation matrix for site X2H048 on the Crocodile River.

Parameters	EC	pH	Calcium	Chloride	Magnesium	Sodium	Phosphate	Sulphate	Ammonia	Nitrate	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
EC	1													
pH	0,310	1												
Calcium	0,527	0,403	1											
Chloride	0,680	0,433	0,625	1										
Magnesium	0,530	0,391	0,872	0,598	1									
Sodium	0,591	0,486	0,763	0,744	0,804	1								
Phosphate	0,173	-0,110	0,060	0,013	-0,011	0,083	1							
Sulphate	0,486	0,396	0,609	0,721	0,636	0,675	0,037	1						
Ammonia	0,137	-0,081	0,100	0,047	0,106	0,069	0,481	0,135	1					
Nitrate	-0,080	-0,104	-0,124	-0,197	-0,065	-0,124	0,277	-0,064	0,345	1				
Water flow	-0,612	-0,267	-0,349	-0,475	-0,365	-0,430	0,031	-0,380	-0,074	0,062	1			
Average Rainfall	-0,397	-0,179	-0,169	-0,216	-0,143	-0,137	0,004	-0,177	-0,079	-0,058	0,670	1		
Average Max. Temp.	-0,251	-0,134	-0,216	-0,151	-0,178	-0,159	0,131	-0,154	0,051	-0,137	0,351	0,409	1	
Average Min. Temp.	-0,425	-0,191	-0,302	-0,281	-0,303	-0,266	0,031	-0,310	-0,094	-0,106	0,582	0,712	0,780	1

The established coefficients of correlation for the Spearman's correlation analysis completed for *E. coli* at site "Crocodile Microbial - Karino Bridge" and the selected water flow and climate sites indicated significant positive correlations (Table 5.26).

Table 5.26: Spearman's correlation matrix for site "Crocodile Microbial - Karino Bridge" on the Crocodile River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	0,420	**1**			
Average Rainfall	0,311	0,731	**1**		
Average Max. Temp.	0,064	0,418	0,550	**1**	
Average Min. Temp.	0,212	0,677	0,773	0,870	**1**

Positive correlations between *E. coli* and water flow, as well as average rainfall, were evident. Thus, as rainfall and water flow increased or decreased at this site, there was an associated increase or decrease in the *E. coli* count. Hyer (2007), Dwivedi et al. (2013) and du Plessis (2014) confirmed these associations in their previous research.

The established coefficients of correlation for the Spearman's correlation analysis for *E. coli* at site "Crocodile Microbial - Kanyamazane Downstream" and the selected water flow and climate sites (Table 5.27) yielded results that were similar to those for the previous site. Significant positive correlations between *E. coli* and several climate parameters were evident. The correlation matrix indicated that variations in *E. coli* at this site could be associated with variations in average rainfall and average minimum temperature. In such instances, moderate positive correlations were indicated. Thus, as rainfall and average minimum temperature increased or decreased, so did the *E. coli* count at this site. Rainfall could therefore be determined to be a transportation agent of *Faecal coliforms* which may increase because of increased runoff into the surrounding water bodies at both microbial sites on the Crocodile River.

Table 5.27: Spearman's correlation matrix for site "Crocodile Microbial - Kanyamazane Downstream" on the Crocodile River.

Parameters	*E. coli*	Water flow	Average Rainfall	Average Max. Temp.	Average Min. Temp.
E. coli	**1**				
Water flow	0,291	**1**			
Average Rainfall	0,402	0,734	**1**		
Average Max. Temp.	0,246	0,448	0,554	**1**	
Average Min. Temp.	0,362	0,699	0,775	0,870	**1**

5.4.2.3. Synthesis: Water Quality and Climate Impacts for the Crocodile River

Owing to the application of three physicochemical water quality datasets, an in-depth spatial analysis enabled the researcher to determine the quality of the water in the Crocodile River. The three sites were located within proximity of one another; thus, the possible dilution and/ or buffering capacity of the river as it flowed into the KNP could easily be evaluated. The physicochemical quality of the Crocodile River over the observed time period was of an acceptable standard. Although several of the water quality parameters fluctuated to tolerable levels, most remained within the acceptable range for domestic use, irrigation, and aquatic ecosystems, as stipulated by the TWQRs. Because the spatio-temporal nature of *E. coli* counts were of an unacceptable standard for all uses, the microbial quality of the water in the Crocodile River can be described overall as substantially degraded and of critical significance.

Spatially, in terms of the water quality sites on the Crocodile River, the water quality in this river varied considerably. The mean values and the sample distribution of the water quality parameters differed significantly for sites X2H048, X2H046 and X2H016, with the physicochemical quality of the water appearing to deteriorate downstream and closer to the KNP (nearest site X2H016). However, the time series trend analyses indicated contradictory results. While the box plots indicated that water quality declines downstream, when compared to the TWQRs, X2H048, the furthest upstream site, presented with most of its observations falling within the tolerable range. In terms of the TWQRs, however, the quality of the water at X2H016 (the site the furthest downstream), exhibited no significant improvements on that of the upstream sites. The microbial quality of the water also differed between the sites; in that it declined in a downstream direction.

The water quality trends were similar for the three sites. Analyses revealed that the Crocodile River exhibited a mostly increasing trend in the concentration levels of the water quality parameters over the observed time period. Historically, the Crocodile River was one of the most biologically diverse rivers in the country. However, the results of the trend analyses suggest that its good quality water is potentially threatened. An improved monitoring system should therefore be an essential intervention to upgrade the water management practices, thereby avoiding a decline in the river's pristine status. If left unattended, the decline in water quality will have severe implications for the river itself, as well as for the wild animals in the KNP that depend on the Crocodile River as a source of water.

The trends in the microbial quality of the water in the Crocodile River also varied between the respective sites. While no trend was present upstream at the "Crocodile Microbial - Karino Bridge" site, the "Crocodile Microbial - Kanyamazane Downstream" site located downstream, indicated that microbial water quality deteriorated from upstream to downstream. The main water quality parameters in the Crocodile River which are cause for concern are EC, pH, chloride, magnesium, and nitrate, as well as *E. coli*.

The correlation analyses conducted for sites on the Crocodile River indicated relationships between water quality, water flow and climate parameters that varied in intensity. Overall, however, the physicochemical quality of water in the Crocodile River exhibited moderate to strong correlations with water flow and the respective climatic parameters. Correlation analyses indicated that several parameters, especially EC, calcium, magnesium, sodium, and chloride, could be associated with variations in the water flow of the river, average rainfall, and average minimum temperature. These parameters presented with monotic inverse relationships. In terms of the microbial quality of the water, the correlation analyses indicated that *E. coli* could be associated with variations in water flow, average rainfall, and minimum average temperature. Moderate positive correlations between these parameters were also evident.

It can be deduced that the quality of the water in the Crocodile River varies significantly - both spatially and temporally. Historically, the quality of the river water is good. However, it is not clear whether its quality truly deteriorates downstream, closer to the KNP, as the results from the various analyses are conflicting. Nevertheless, the quality of the river water shows predominantly increasing trends for most of the water quality parameters, such that ongoing monitoring and management are required to ensure that it does not deteriorate further. The microbial quality of the water remains problematic and the sources from which the *Faecal coliforms* issue need to be identified and their effects mitigated. The physicochemical and microbial aspects of the quality of the river water are widely affected by water flow and climate variability, a finding which should be considered in future research, and in the monitoring and management of freshwater bodies.

5.4.3. Water Quality Compliance for the Inkomati-Usuthu WMA

The compliance graphs for the Inkomati-Usuthu WMA (Figure 5.33) indicate that the temporal trends in water quality remained stable over both the long and the short-term. The percentages for ideal, acceptable, tolerable, or unacceptable measurements taken for domestic use or aquatic ecosystems were examined for the full study period, as well as for the five most recent years. They revealed that, apart from *E. coli,* the water quality complied mostly with ideal to acceptable standards. Historically, this WMA is regarded as one where the quality of the water has been modified the least and with the greatest biodiversity in South Africa. Both these aspects are reflected in the time series trend analyses, as well as in the compliance graphs (van Vuuren, 2017b; Riddell et al., 2019a; Shikwambana et al., 2021).

A tremendous 98% and 99% of all *E. coli* counts reached unacceptable standards for the full study period and the five most recent years, respectively. Of all the WMAs, the Inkomati-Usuthu has been impacted the most by microbial pollution, which appears to have worsened in the more recent years despite the previously pristine state of this WMA. Apart from nitrate and ammonia, which shifted by one percent (1%) from ideal/acceptable to tolerable levels, most of the other parameters remained the same in respect of the long and short-term comparisons that were made. Magnesium shifted from acceptable to tolerable, while calcium improved by two percent (2%), by shifting from an acceptable to an ideal level.

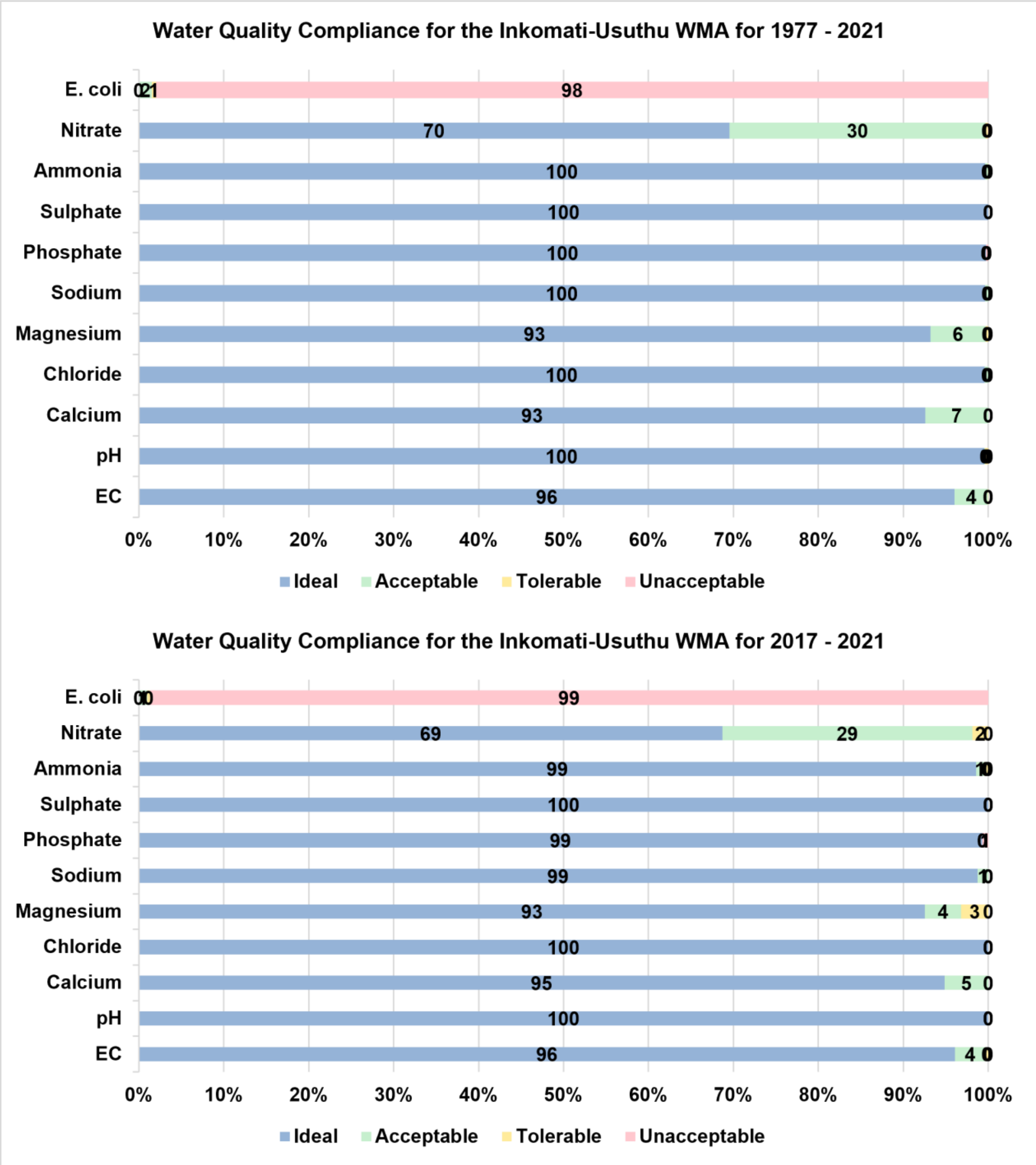

Figure 5.33: Percentage of compliance of national in-stream water quality guidelines at selected monitoring sites in the Inkomati-Usuthu WMA.

A summary of the results obtained and discussed from the various time series trend, correlation and compliance analyses in this chapter now follows and serves to conclude the chapter.

5.5. Conclusion

This chapter focused on providing an in-depth interpretation and assessment of the results obtained from the various data analyses that were conducted. Moreover, an evaluation regarding the potential negative implications of declining water quality on the various water use sectors, human health, and the functioning of ecosystems was carried out. It was based on the established water quality trends and water quality parameters identified as worthy of concern. The research aimed to establish the spatio-temporal trends in water quality and its suitability in respect of the aquatic ecosystems and wildlife of the KNP that rely on the major rivers of this region for their survival. Furthermore, the research also determined the possible impacts of water flow and climatic variability on the selected water quality parameters of these major rivers by assessing the relationships between each parameter. The objectives of this research were primarily attained through the application of time series trend and correlation analyses.

Basic statistics were collected, and the normality of the distribution was determined prior to the execution of the main statistical analyses. It was concluded that most of the distributions in the datasets were highly varied in terms of the parameters and sites and that the datasets were moderately to highly skewed, with a high level of kurtosis. Thus, most datasets revealed non-normally distributed data, therefore non-parametric testing methods could be applied.

MK time series trend analyses were carried out on each of the water quality parameters at each site, and a Sen's Slope (*S*) estimator was applied. These analyses revealed that most physicochemical water quality parameters had a strong increasing trend, while only a few had a decreasing trend (Table 5.28). Overall, it was determined that the quality of the water at the sites closest to the park was declining. The poor quality of water in the study area was primarily driven by the increasing levels of microbial (*E. coli*) pollution as well as salinity. Furthermore, the parameters indicative of nutrient enrichment and acidification also increased over the observed time period.

Monotic trends were detected in 75% of the physicochemical water quality parameters, 77,5% of which were increasing and 22,5% decreasing. These figures concur with the findings of previous research which indicate deteriorating water quality in the three WMAs (Ashton & Dabrowski, 2011; Fouché & Vlok, 2012; Monyai et al., 2016; Biggs et al., 2017; Marr et al., 2017a; Enoch, 2018; Baker & Greenfield, 2019; du Plessis, 2019). Monotic trends were present in only 18% of the microbial water quality datasets. Despite the lack of trends, the *E. coli* counts at all the microbial sites reached unacceptable ranges for domestic and irrigation use, thus indicating that microbial pollution is an issue of particular concern at the selected monitoring sites.

Table 5.28: Summary results of the MK time series trend analyses of water quality parameters at sites on rivers of the KNP.

Physicochemical Water Quality Sites	**Physicochemical Water Quality Parameters**									
	EC	***pH***	***Calcium***	***Chloride***	***Magnesium***	***Sodium***	***Phosphate***	***Sulphate***	***Ammonia***	***Nitrate***
Limpopo A5H006	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	No Trend	Increasing	Increasing	No Trend
Limpopo A7H008	No Trend	No Trend	No Trend	No Trend	No Trend	No Trend	No Trend	No Trend	Increasing	No Trend
Luvuvhu A9H011	Increasing	Increasing	Increasing	No Trend	Increasing	No Trend	Decreasing	Decreasing	Decreasing	Decreasing
Luvuvhu A9H012	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Decreasing	Decreasing	Increasing	No Trend
Shingwedzi B9H002	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	No Trend	Increasing	Decreasing	Decreasing
Shingwedzi B9H003	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	No Trend	Increasing	Decreasing	Decreasing
Letaba B8H008	No Trend	Increasing	No Trend	Increasing	No Trend	No Trend	No Trend	Increasing	Decreasing	Decreasing
Letaba B8H009	Increasing	Increasing	Increasing	Increasing	No Trend	Increasing	No Trend	Decreasing	No Trend	No Trend
Olifants B7H007	No Trend	Increasing	Increasing	No Trend	Increasing	Decreasing	Increasing	Increasing	No Trend	Increasing
Olifants B7H015	Decreasing	Increasing	Decreasing	Decreasing	Decreasing	Decreasing	Decreasing	Decreasing	Decreasing	Decreasing
Sabie X3H001	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing
Sabie X3H012	Increasing	Increasing	Increasing	No Trend	Increasing	Increasing	No Trend	Decreasing	No Trend	Decreasing
Sabie X3H015	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	No Trend	Decreasing	No Trend
Crocodile X2H016	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	No Trend	Decreasing
Crocodile X2H046	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	Increasing	No Trend	No Trend
Crocodile X2H048	Increasing	No Trend	Increasing	Increasing	No Trend	Increasing	Increasing	Increasing	No Trend	No Trend

Microbial Sites	**Microbial Water Quality Parameters: *E. coli***
A5H006 Microbial - Groblersbrug Border Post	No Trend
A7H008 Microbial - Downstream of Beit Bridge	No Trend
A9H030 Microbial - Nandoni Dam downstream	No Trend
Letaba Microbial - Downstream Giyani	Decreasing
Letaba Microbial - Giyani Upstream STW	No Trend
Olifants Microbial - L12 Olifants River	No Trend
Olifants Microbial - KNP Rest Camp	Decreasing
Sabie Microbial - Samora Camp	No Trend
Sabie Microbial - Calcutta	No Trend
Crocodile Microbial - Karino Bridge	No Trend
Crocodile Microbial - Kanyamazane Downstream	Increasing

Overall, only a few trends were evident in the microbial quality of the water over the observed time periods. This can be attributed to the fact that microbial water quality datasets usually indicate the periodic addition of wastewater from WWTWs as opposed to consistent pollution loads. A general upward trend was determined for EC and pH, and the calcium, and chloride concentrations at most of the sites selected for this research. These water quality parameters included several major ions that affected the EC of the freshwater bodies and, in conjunction with one another, their salinity. Thus, elevated EC levels could lead to increased salinity in affected freshwater bodies which is a matter of concern, particularly in the context of those freshwater bodies supplying conservation areas. The impact of increasing salinity levels on aquatic organisms is explained by Griffin et al. (2014), who also draw attention to the fact that the rate of change in salinity is just as critical as the total concentrations of salinity-causing ions such as chloride and sodium. Given enough time, species can often physiologically adapt or acclimatise to higher salinity levels, but only up to a point. Other toxicants may interact, either antagonistically or synergistically, with individual species that in themselves also impact on salinity. Salinity alters the ionic composition of the waterbody, thus affecting its toxicity, and ultimately results in shifts in the components of aquatic ecosystems (Weber-Scannell & Duffy, 2007; Singh et al., 2019).

The results of the MK analyses were compared with the TWQRs for domestic use, irrigation, and aquatic ecosystems in South Africa. The quality of the water was within ideal to tolerable ranges for most parameters and rarely exceeded tolerable levels for the observed time period. Only a few of the observations in respect of most of the parameters reached unacceptable levels with any frequency. The two exceptions were chloride[4] and *E. coli,* both of which persistently showed a tendency to be at unacceptable levels. Hunt et al. (2012) state that chlorides[5] occur naturally in both freshwater and salt water and are important for supporting aquatic life. According to the guideline by Hunt et al. (2012), none of the observations for chloride surpassed an acceptable level.

The microbial water quality sites located downstream from the WWTWs were generally more degraded than the upstream sites. This was due to the discharge of partially treated and untreated effluent into the rivers. All microbial water quality sites fell within

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[4] The TWQR for aquatic ecosystems is < 0.0002 mg/ℓ.
[5] According to Hunt et al. (2012), chloride concentrations of 1 to 100 parts per million (PPM) are normal in freshwater. PPM is directly equivalent to mg/ℓ, which is the measurement used in South Africa.

the unacceptable range in terms of the TWQRs for the entire or part of the observed time period. Thus, the microbial quality of the water in the three WMAs of the KNP was of an unacceptable standard and could, therefore, significantly degrade ecosystems and cause severe risks to human health.

Du Plessis (2019) discusses the prevalence of microbial water pollution in South Africa as follows. Owing to the poor functioning and limited capacity of WWTWs, approximately 50,000 litres of raw sewage is discharged into rivers each second. Apart from the human health problems caused by such high concentrations of coliforms in waterbodies, microbial pollution is extremely harmful to aquatic life (du Plessis, 2019). The microbial quality of the water in the WMAs therefore remains problematic. Thus, the point and diffuse sources of *E. coli* need to be identified and addressed to deal with the challenge of the critical levels of *E. coli* in the respective WMAs.

Compliance graphs were compiled for each of the WMAs in the study area and for the entire study period, as well as for the five most recent years. They also included each water quality monitoring site (Figure 5.34). According to these analyses, the quality of the water in the Limpopo WMA has deteriorated in the five most recent years, while that in the Olifants WMA has improved. A comparison of both time periods showed that the water quality in the Inkomati-Usuthu WMA remained stable. In terms of the total study area, most of the parameters indicated only a minor shift when long-term observations were compared with the short-term five-year observations. The *E. coli* counts were mostly of an unacceptable standard and shifted minimally within the unacceptable range from 93% to 94%. Only nitrate and calcium indicated deteriorating water quality standards when time period comparisons were made. This leads to the conclusion that water of a poor microbial quality is the most impactful parameter on ecosystems that support or are part of the KNP and its surrounding areas. This is most probably due to the poor management and maintenance services of the WWTWs, which are consistently operating above capacity and discharging partially and untreated wastewater into the rivers.

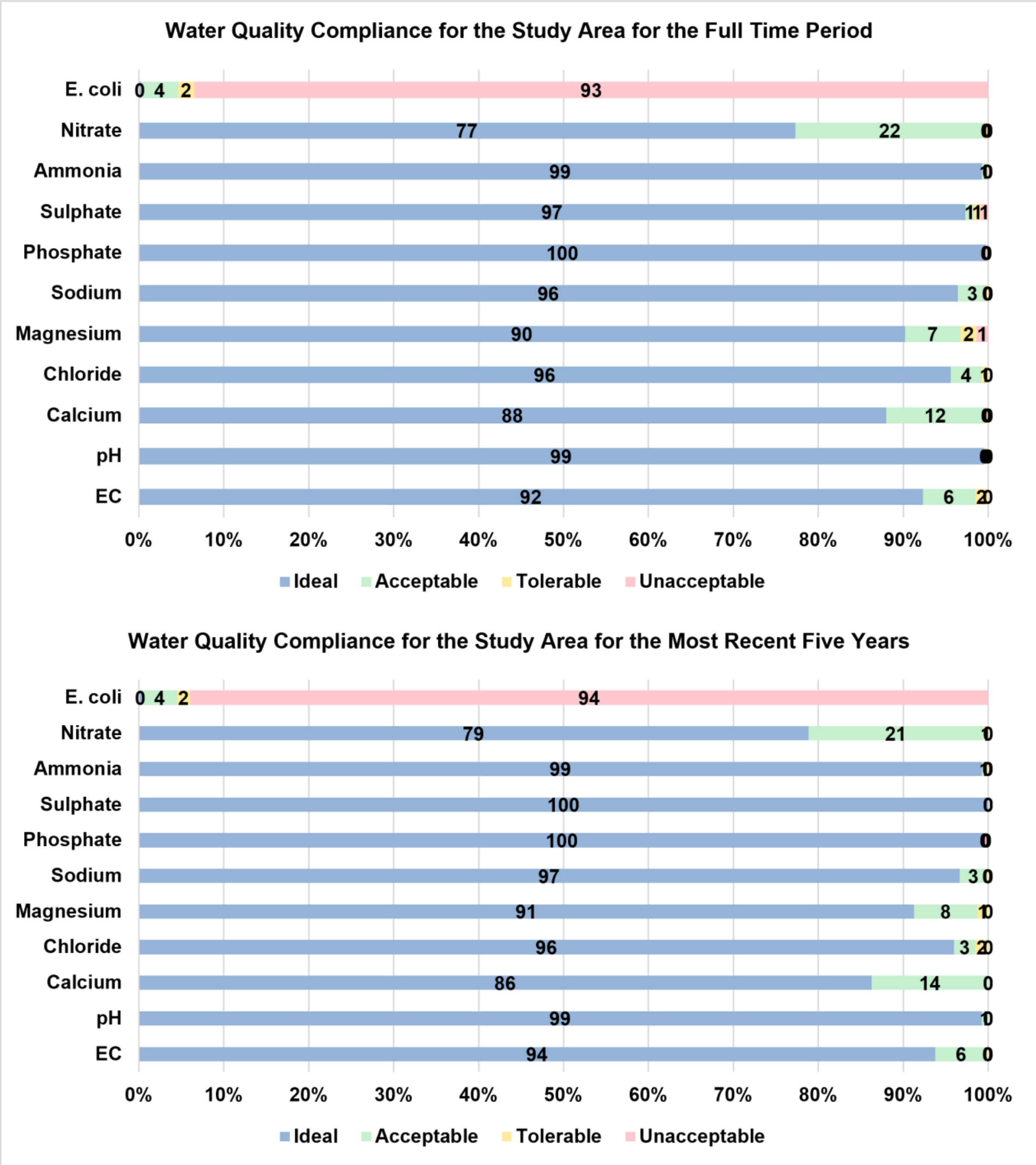

Figure 5.34: Percentage of compliance of national in-stream water quality guidelines at all sites in the study area.

The possible effects of climate variability on the quality of the water in various rivers were subsequently investigated with the aid of Spearman's correlation matrices, which calculated the value of the coefficient (R_S) for each correlation between the relevant two parameters. When R_S was greater than 0.5 (positive) or less than -0.5 (negative), a correlation was determined to be significant. When R_S was between 0.3 and 0.5 (positive) or between -0.3 and -0.5 (negative), a correlation was determined to be moderate. Evidence regarding the impacts of climatic variability on the quality of the water in the rivers of the KNP varied greatly. Overall, water quality in the Limpopo WMA exhibited the greatest resilience to variations in the local climate and displayed only weak relationships with several parameters; therefore, influences on water quality tend to be more readily associated with the specific characteristics of the region, the surrounding land cover, as well as the anthropogenic activities performed there. Climatic variability became more of an influencing factor in the Olifants WMA, with several water quality parameters exhibiting relationships with certain climate parameters. However, the influence of climate variability was most evident in the Inkomati-Usuthu WMA, which provides passage to two of the historically most pristine river systems in South Africa. The water quality sites in this WMA showed the greatest response to variations in climate in that overall, the correlation values were more significant than the others for the respective parameter datasets.

It was evident from the various time series trend analyses, as well as from the correlation matrices, that the salinisation of fresh surface water near the KNP is of primary concern for the management of the rivers in the study area. The analyses indicated that the physicochemical parameters responsible for salinity (calcium, chloride, magnesium, sodium, nitrate, and sulphate) have been increasing in concentration at most of the sites for several decades. Furthermore, the correlation matrices revealed that these parameters are most strongly influenced by changes in the flow regimes of the rivers, as well as by variations in the climatic conditions. The increasing salinity levels resulting from the decreased dilution factor during dry/drought periods are well documented (Weber-Scannell & Duffy, 2007; Dabrowski et al., 2014; Griffin et al., 2014; Keller et al., 2014). For instance, Tanner et al. (2022) studied the impacts of climate change on riverine ecosystems in the Western Cape Province. These authors predicted that salinity is likely to become more variable and to show seasonal increases that would in turn result in water stress and reduce the amount of water available for abstraction. Anthropogenic salinisation originates from several sources, including, but not limited to, poorly treated or untreated domestic effluent, industrial and mining effluents, irrigation runoff and tree felling. Salinisation impacts on both industry and agriculture, as well as on the ecology (Griffin et al., 2014). In South Africa, a semi-arid country, increasing salinity levels, coupled with increased risks of drought and low-flow periods, pose a serious threat to aquatic ecosystems and biodiversity in the rivers and the park, respectively (Weber-Scannell & Duffy, 2007; Singh et al., 2019).

Average water flow was determined to be the primary parameter to affect variations in the quality of the water in the selected study area. The relationships between the parameters varied according to the spatial characteristics of the region. However, where a relationship existed between water flow and a specific water quality parameter, the correlation would always be negative, thus indicating that water flow inversely affected the responsive water quality parameters at a given site. This observation was confirmed by significant negative correlations between water flow and EC, as well as by the relatively high concentration levels of calcium, chloride, magnesium, sodium, nitrate, and sulphate. No significant relationships could, however, be determined between water flow and the phosphate and ammonia concentrations. The findings of this research concur with the findings of du Plessis (2014), who studied the relationships between water flow and selected water quality parameters at various sites in the Upper Vaal WMA. This author observed that variations in water flow could be associated with variations in the concentration levels of calcium, chloride, magnesium, sodium, sulphate, and nitrate, as well as in C*hlorophyll a,* and *Faecal coliforms,* but could also find no correlations between water flow and phosphate and ammonia concentrations.

Thus, an increase in water flow could be associated with an overall decline in the concentration levels of certain water quality parameters, namely, calcium, chloride, magnesium, sodium, nitrate, and sulphate, that can predominantly be attributed to the dilution of these compounds in the waterbody. However, when the opposite, specifically an increase in concentrations, occurs, especially in terms of the *E. coli* counts, and such hazardous conditions are not addressed, freshwater ecosystems could be threatened. An increase in the concentrations of water pollutants owing to reduced flow negatively affects the functioning of aquatic life in various ways, usually in that the toxins within a waterbody increase, while the ability of aquatic species to take up oxygen through the water is reduced (Tanner et al., 2022). A reduction in water flow will thus have cascading effects for biodiversity, the ecological balance, and the health of ecosystems within South Africa's primary conservation area. Riddell et al. (2019b) previously highlighted the importance of maintaining water flow at the Ecological Reserve, to enable the proper management and functioning of the aquatic and terrestrial ecosystems within the park. Tanner et al. (2022) state that maintaining the KNP as an Ecological Reserve with due consideration given to the risks posed by climate change is of utmost importance in ensuring long-term water security and the sustainable management thereof, and thus containing degradation.

The influence of average rainfall on water quality varied between the sites. In cases where a relationship existed, the correlation between average rainfall and a selected water quality parameter would always prove to be negative and of moderate strength. A decrease in the rainfall within a region would thus be accompanied by elevated concentrations of the associated water quality parameters owing to the decreased dilution factor of the river. On the other hand, an increase in rainfall would be associated with dilutions in the concentrations of the associated water quality parameters. Rainfall could therefore be determined to be an agent for transporting certain minerals and compounds, which in their turn might elevate the concentrations of certain water quality parameters through runoff into the surrounding waterbodies or through the dilution of pollutants (du Plessis, 2014).

Minimum and maximum temperatures occasionally influenced the quality of the water in the study area. Previous research established that the temperature of water is particularly important for chemical reactions between some water quality parameters in aquatic ecosystems. For instance, pH and temperature are essential determinants of toxicity in freshwater bodies that is brought on by high concentrations of ammonia (DWAF, 1996a; DWAF, 1996d). Where a relationship existed between water quality and minimum or maximum temperatures, the association would usually be a moderate negative one, indicating that variations in temperature in the study area inversely affected water quality.

The relationships between *E. coli* and the selected climate parameters were more vague and more varied in comparison to the relationships between the climate parameters and the physicochemical water quality parameters. The responses of *E. coli* in freshwater rivers in the study area were highly localised and differed substantially among the WMAs, as well as within the WMAs of the analysed major rivers, and among the sites. Most of the microbial water quality monitoring sites exhibited weak correlations or no correlation at all with the climate parameters over the observed time period.

The influence of the climate parameters was more evident at sites on the Olifants, Sabie, and Crocodile Rivers that are in the lower portion of the study area. Where a relationship existed, water flow, followed by average rainfall and/ or minimum temperature, was the dominant parameter.

Although the impacts of climate variability on the rivers of the KNP ultimately differed among and within the WMAs, it is evident that at least, to some degree, the KNP authorities can expect that variations in the climate will have negative consequences for the park's aquatic and terrestrial ecosystems. Even a small variation in the hydrological characteristics of its primary rivers may trigger a compounding sequence of impacts, followed by long-term changes to the aquatic ecosystems and their functioning. The Inkomati-Usuthu WMA was the least resilient to climate variability. Since this region accommodates some of the most biologically diverse aquatic ecosystems in South Africa, the knowledge gained from this analysis is of critical importance for planning purposes in the short, medium, and long-term. This research can assist in developing improved management strategies and appropriate interventions to ensure that good water management practices are in place for the rivers to limit or reduce the predicted effects of an intensifying variability in the climatic conditions on water quality and to ensure that the associated aquatic and terrestrial ecosystems are protected and preserved.

Effectively managing water quality and water flow and meeting the associated requirements for the KNP within the current complexities brought on by increased climate variability are of utmost importance. It is essential that such measures be attained to ensure the long-term sustainable management of the park's resources, to limit the threat of increased human health risks, and to limit, contain, and rehabilitate already degraded or compromised ecosystems. Lastly, measures to limit the predicted increase in degradation (both spatially and in terms of its intensity/magnitude) must be put in place in the KNP to ensure water security for the human and animal populations, continued socio-economic growth, and lastly, of utmost importance, the conservation, protection, and sustainability of the park, which contributes immensely not only to the economic sector of the country, but also towards human livelihoods.

Based on the research results, a discussion of the most suitable interventions and/ or actions to take to address the identified risks, the prioritisation of the proposed short, medium, and long-term interventions and/ or actions to address the current degradation of the various rivers and the predicted impacts of climate variability on the quality of their water now follows. An overall synthesis of the significant results emanating from this research, recommendations and/ or actions for future studies/research, and suggestions for an overall way forward are also included as a conclusion to the chapter and to this dissertation.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. Introduction

The importance of good quality freshwater that meets ecological flow requirements has been highlighted for several years in policies and planning through concepts such as the Ecological Reserve (Pollard & du Toit, 2011). Access to clean freshwater is an essential requirement for societies and ecosystems to remain sustainable, functional, productive, and healthy (Gain et al., 2016). However, since the development of irrigation some 7 000 years ago, freshwater ecosystems have been modified and degraded on increasingly greater scales and at exponential rates; most of the degradation has taken place in recent decades alongside continued population growth, increased rural-urban migration, and accelerated economic growth (Schmutz & Sendzimir, 2018).

The demand for water globally has seen a 600% increase over the past century. Thus, despite the abundant attention given to water resources and the management thereof, projections predominantly show that the availability of water to most countries will decline dramatically by the year 2050 (Boretti & Rosa, 2019). Larger quantities of water will be required to meet urban growth demands, generate electricity, and support mining and industry. On the other hand, the demand for food, in tandem with the need for additional agricultural irrigation, which already accounts for 70% of global water use (DWA, 2010a; Boretti & Rosa, 2019), will grow by 60% in the next two decades. The availability of water is largely determined by its quality (van der Merwe-Botha, 2009; du Plessis, 2019). This is because polluted water cannot be used for domestic, agricultural, industrial or conservation purposes if it is not of a suitable quality. Under such conditions, it would then pose potential human health risks and put the natural environment at risk (UNEP, 2016). This growing pressure on water resources will be exacerbated by recurrent floods, prolonged droughts, and the predicted long-term effects of inescapable changes in the global climate (DWA, 2010a; DWA, 2010b; Turton, 2012; du Plessis, 2019). Since South Africa is an arid to semi-arid country, characterised by limited natural resources and widespread water stress, the impacts of climate change are expected to be more severe. As such, localised studies are required to understand the consequences of climate change for freshwater reserves (Saraiva-Okello et al., 2015; WWF, 2016; Enoch, 2018; Dallas et al., 2019; du Plessis, 2019; van Vuuren, 2020).

The KNP, one of South Africa's largest and most economically important nature-based tourism destinations (Nhamo & Dube, 2019), lies in the far eastern lowveld of the country and is beleaguered by polluted and degraded rivers that for the most part receive untreated or partially treated effluents along their reaches before entering the conservation area (Peterson et al., 2014; Riddell et al., 2019a). The KNP rivers are exposed to multiple types of land use, and as they flow from west to east, are subjected to the varying influences of different climatic conditions and biomes. As such, they are subject to an array of impacts on the quality of the water that they provide to the KNP (Petersen et al., 2014).

Along with the variability of the climate in the region, the quality of the river water has been a source of increased concern (Petersen et al., 2015). As such, it was deemed essential to take account of the historical and current quality of the water and its response to a changing climate to ensure proactive governance and the management of this vital resource. Further degradation of the country's water resources will result in widespread negative consequences on the social, environmental, and economic fronts (du Plessis, 2019). Thus, to avoid increased water scarcity and stress, improvements in the conservation of water resources must be treated as a matter of national priority, and in so doing, achieve water security. This research was thus initiated with due consideration given to the severe challenges associated with South Africa's freshwater resources. A critical evaluation of the quality of the water and the quantification of the responses of water quality to the variability of the climatic and water flow parameters over time contributed to an historical overview of the water quality in the KNP. These aspects also provided a glimpse into potential future impacts that may be further quantified and thereby mitigated. A summary of the literature, research objectives, and the various analyses and findings of the current research now follow.

6.2. Summary of Previous Research and the Current Findings

Apart from the substantial research that has already been completed, specifically the examination and prediction of the possible impacts of climate change on water resources in terms of quantity and flow, little has been reported on the possible effects of climate change on water quality in South African rivers. It should be noted, however, that earlier research has highlighted the short and long-term impacts of climate change on the quality of surface water.

Another aspect that should also be noted is that the resulting changes in the biochemical composition of freshwater ecosystems through pollution, etc., compromise the functioning of various organisms, and in fact, the entire ecological system. While these impacts are difficult to quantify, a series of cascading effects can be expected in such ecosystems and would also be reflected in changes in their biodiversity (Dallas et al., 2019). The predicted increase in the intensity and frequency of hydrological events - as in the case of floods and droughts - may, because of their ability to alter the dilution capacity of a water body, be the largest climatic determinants of water quality. In low rainfall and river flow scenarios, the dilution capacity and DO of a river are predicted to be at low levels and thus to inhibit the functioning of most freshwater ecosystems and their associated organisms (Delpha et al., 2009; IPCC, 2014; IPCC, 2022). Conversely, during periods of heavy rainfall, water quality is usually negatively impacted by the flushing of organic matter into rivers, increased effluent runoff from urban and agricultural areas, and the transportation of solid materials into rivers, to mention just a few (Delpha et al., 2009; Xai et al., 2014). Furthermore, more extreme and/ or higher than expected temperatures may alter the biochemical reaction rate of pollutants and thus increase their toxicity in the water system (DWAF, 1996a; Xai et al., 2014). Additionally, increasing water temperatures can also cause DO to deplete at a faster rate (IPCC, 2014; IPCC, 2022). Several studies indicate that higher water temperatures and reduced water flow rates during the summer months may lead to a greater impact by pollutants on rivers because of the decreased buffering capacity of the already stressed water resources (Delpha et al., 2009; van Vliet & Zwolsman, 2008; Hosseini et al., 2017).

Nhamo and Dube (2019) noted that climate change has profound impacts on protected areas and the tourism economy that they support. Other studies point specifically to climate change as one of the most significant challenges for freshwater resources in the immediate future (Lipsett, 2017; MacFayden et al., 2018; Udall, 2018). In 2015, freshwater system degradation and global climate change were listed by SANParks as the two environmental threats of greatest concern to the KNP (Petersen et al., 2014; Petersen et al., 2015; Nhamo & Dube, 2019). The progressive deterioration in the quality and flow of water received by the park, along with the growing impacts of increased climate variability, has been problematic for years (Pollard et al., 2011; Petersen et al., 2014; Gerber et al., 2015; Biggs et al., 2017). In fact, the KNP has a long history of water quality and river flow issues which can be traced as far back as a century ago (de Villiers & Mkwelo, 2009; Riddell et al., 2019a). O'Keeffe and Davies (1991), and Pienaar et al. (1997) highlighted multiple incidents of pollution which the KNP's perennial rivers have sporadically been subjected to as early as the 1920s, as well as increasing siltation, as early as the mid-1940s.

The cumulative effects of altered water quality and flow regimes over many decades are evident from the degradation and loss of aquatic ecosystems and other related biodiversity in the KNP. Heavy pollution and invasive alien species have severely plagued the rivers in the KNP and the associated catchment areas over the past three decades (Pollard et al., 2011). The continued and unchecked degradation of the water quality in this region will reduce the availability of freshwater and have widespread negative social, economic, and environmental consequences for the region (du Plessis, 2019). Additionally, the increased frequency of extreme weather events in South Africa, as well as the location of the KNP in a semi-arid region, makes the KNP particularly vulnerable to climate change (Nhamo & Dube, 2019). The increasingly significant impact that climate change related weather events has had on the hydrological system and freshwater infrastructure has been evident in numerous events that have taken place recently. Some of these include flooding in the KNP in 2000 and 2012, in the eastern region of South Africa in April 2022, and the more recent flooding in the KNP in February 2023 (Lipsett, 2017; Shikwambana et al., 2021; Pinto et al., 2022; Henning, 2023). Floodings of this magnitude disproportionately affect the marginalised communities in the region, often taking lives, ruining livelihoods and certainly, through additional pollution loads, leaving lasting impacts on freshwater ecosystems (Xai et al., 2014; Riddell et al. 2019; Pinto et al., 2022). Thus, research into these various processes and the established interactions and relationships between climate change and water quality has the potential to provide a deeper understanding, and by extension, the formulation of proactive adaptation strategies and appropriate mitigation measures.

Since climate change poses a serious threat to protected areas, an understanding of the spatio-temporal effects of climate change on water resources, the life force of a protected area is essential to managing and conserving its ecosystems and biodiversity in an informed and sustainable manner (MacFayden et al., 2018). However, owing to insufficient research, this understanding is still limited within the context of South Africa. Furthermore, only a few empirical studies have been conducted; despite increasing evidence of the near-future impacts of climate change in the region, as well as the ongoing calls by government, civil society, and academics to close or reduce these existing knowledge gaps (Nhamo & Dube, 2019). Research focused on climate change, specifically as it relates to water quality and flow, is becoming increasingly important and that which models and projects its possible impacts under various scenarios will prove invaluable for future water resource planning and management (Lipsett, 2017). This research was initiated considering the severe water quality and river flow issues afflicting the freshwater resources in the WMAs of the KNP (Riddell et al., 2019a).

This research aimed to examine, critically evaluate, and discuss the historical spatio-temporal trends in water quality within the Limpopo, Olifants and Inkomati-Usuthu WMAs at those monitoring sites nearest to/ bordering on the KNP, as well as their respective responses to local climate and water flow variability over the observed time periods. Furthermore, this research set out to establish the suitability of water quality at the various sites according to the South African Water Quality Guidelines for domestic use, irrigation, and aquatic ecosystems; and to identify pollution hotspots requiring remedial action. To achieve the set aim and objectives, time series trend analyses and Spearman's Rank Correlation Analyses were conducted for each of the 27 water quality monitoring sites. The water quality parameters that were assessed included EC, pH, calcium, chloride, magnesium, sodium, phosphate, sulphate, ammonia, nitrate and *E. coli*. Water quality and water flow data were obtained from the DWS, and climate data were acquired from the SAWS. These selected parameters were used to compile a water quality compliance graph for each WMA, as well as the study area in its entirety. These subsequent analyses of the data enabled the researcher to establish the following major conclusions and priorities in respect of the study area.

Water quality in the study area is of a heterogenous nature, differing in terms of the variables constituting its composition, the monitoring sites from which samples are taken, the rivers, and the catchments. The physicochemical quality of the water at most sites was of an ideal to acceptable standard, while the microbial quality of the water at all sites was mostly of an unacceptable standard. Seventy-five percent (75%) of the time series trend analyses indicated that either an increasing or decreasing trend for physicochemical water quality parameters prevailed. Of those parameters exhibiting a distinctive trend over the observed time period, 77,5% were increasing in concentration and 22,5% decreasing. This indicates that most of the monitoring sites experienced (and continue to experience) deteriorating water quality over the observed time periods, and that immediate action would be required to improve the conditions influencing these water resources.

Only 18% of the microbial water quality datasets exhibited an increasing or decreasing trend. However, *E. coli* counts at all microbial sites reached tolerable to unacceptable standards for domestic and irrigation use. This suggests that microbial pollution has been an unabating and problematic influence on water quality in the region, to such an extent in fact that critical interventions are needed with immediate effect. These findings confirm earlier research results which have raised ongoing concerns for water quality in the region of the KNP which is rapidly declining. Furthermore, its remediation will require committed and concerted long-term management plans and actions from government and other role players to improve and maintain an ecologically appropriate water quality standard (Ashton & Dabrowski, 2011; Fouché & Vlok, 2012; Monyai et al., 2016; Biggs et al., 2017; Marr et al., 2017a; Enoch, 2018; Baker & Greenfield, 2019; du Plessis, 2019).

It was noteworthy that the water quality at the monitoring sites closest to the KNP declined the most. However, each of these sites, and the rivers concerned, exhibited different water quality characteristics, and faced contrasting water quality challenges. The primary threats to water quality that were observed from the analyses were microbial pollution and increasing salinisation, although acidity also affected some sites. In terms of the physicochemical quality of the water, the monitoring sites for the Limpopo, Luvuvhu, Shingwedzi, and Olifants Rivers were predominantly characterised by increasing salinity, which was indicated by elevated EC levels and chloride, sodium, and magnesium concentrations (Riddell et al., 2019a).

DWS (DWAF, 1996a) states that when present in elevated concentrations, these parameters should be analysed together as they control biological processes in freshwater organisms that are associated with protein synthesis, enzyme activation, energy transfer, and cellular homeostasis. When present in large quantities and in freshwater ecosystems, they may reach concentrations which are toxic to aquatic organisms (van Dam et al., 2010) and may thus affect the adaptation of individual species, the structure of their communities, and disrupt microbial and ecological processes (du Plessis, 2014). Owing to anthropogenic pollution in the form of salts, fertilisers, as well as industrial and domestic chemicals, the concentrations of these parameters often increase further downstream (DWAF, 1996a; Enoch, 2018). In their research, Cañedo-Argüelles et al. (2013) state that the salinisation of rivers is an urgent ecological issue which is amplified by climate change, leading ultimately to a reduction in aquatic biodiversity and compromising the ecosystem services that a river can provide. Thus, if left unchecked and unmanaged, the implications of climate change for water quality in and around the KNP are dire, potentially leading to not only reduced access to potable water for the surrounding communities and reduced potential for abstraction in the agricultural and mining sectors, but also to a decline in the functioning of ecosystems and in the biodiversity within these freshwater ecosystems.

The decline in the water quality of the Letaba, Sabie and Crocodile Rivers is largely driven by acidification and nutrient enrichment, reaching (at times) tolerable to unacceptable levels of nitrate, chloride and ammonia, and tolerable pH levels. River acidification results from excessive nutrient loads, AMD, and contamination by heavy metals and acid rain (UNEP, 2016; Oberholster et al., 2017). Acidification adversely affects aquatic ecosystems in terms of their structure and ability to function naturally, and young organisms are affected more severely (Barker, 2006; du Plessis, 2014; Oberholster et al., 2017). As such, the contamination of the KNP rivers cannot be allowed to continue. Inaction and failing to put appropriate measures in place will cause these rivers to become sterile, devoid of biodiversity, and unable to function effectively as viable ecosystems for supporting wildlife in the KNP.

All the selected microbial water quality monitoring sites were highly impacted by *E. coli*, which is generally used as an indicator of eutrophication, as well as of sewage pollution. Owing to their ability to cause nutrient enrichment and the growth of algae and other nuisance plants, aquatic ecosystems are sensitive to the impacts of *Faecal coliforms*. These plants then use up all the oxygen in the water, causing fish in the aquatic ecosystem to die (du Plessis, 2014). Long-term eutrophication ultimately results in a barren freshwater ecosystem devoid of biodiversity (du Plessis, 2019).

In terms of the impacts of climate variability on water quality in the three WMAs, varying results were obtained. The Limpopo and Luvuvhu monitoring sites showed very little response to changes in the local climate, while the Shingwedzi and Letaba sites showed moderate responses. Sites on the Olifants, Sabie and Crocodile Rivers were most strongly receptive to oscillations in the local climatic conditions. The Spearman's Rank Correlation Analyses showed a significant southward trend, in that the relationship between climate variability and water quality became stronger from north to south, with the weakest influences on the Limpopo River and the strongest on the Crocodile River. This north-to-south increase in the climatic impact on water quality is possibly due to a decline in aridity and an increase in the average annual rainfall further south. Being divided into two distinct climatic zones, the southern portion of the KNP is wetter and more humid than the northern region (Petersen, 2012).

Rainfall influences the ability of a river to buffer certain pollutants (the dilution factor) owing to increased freshwater flows that mitigate the effects of pollutants. Thus, it can be concluded that this parameter would impact water quality more strongly in the southern regions. Furthermore, in the northern region of the study area, it was observed that water flow, and not the climatic parameters, was the most influential parameter affecting water quality (Xai et al., 2014). This could be attributed to the seasonality of the rivers, some of which are no longer perennial as a result of over-abstraction in the upper portions of the catchment (van Vuuren, 2017b). Therefore, rather than the primary agent of change, rainfall can be seen as a contributing factor to changes in water quality in the northern regions (du Plessis, 2014).

The parameters most susceptible to climate variability included the major ions of calcium, chloride, magnesium, and sodium, as well as the physical parameters, namely, EC and pH, while the influence of climate variability on sulphate was found to be minimal. Since these parameters are primarily responsible (to a lesser degree) for salinity and acidification, it can be concluded that the variability of the climatic conditions in the study area, followed by fluctuating acidity, is the most likely to have the greatest impact on salinity.

Few of the microbial sites exhibited a response to variations in the climate. Where a relationship was present, water flow, followed by rainfall, was the most influential parameter. As previously mentioned, this observation may be due to the relationship between water quality and the dilution capacity of a given river. The impact of the increased variability of climatic conditions on water quality is largely due to the dilution capacity of the surface water, which is influenced by water flow and rainfall (Antonopoulos et al., 2001). As a result of a lower average rainfall, the dilution factor, being the ratio between the volume of freshwater and the quantity of the physicochemical or microbial parameters being measured, is higher than under high rainfall conditions, when it is lower. As such, the more arid regions have lower dilution factors (Keller et al., 2014). A reduction in water flow also impacts the dilution factor of rivers, often resulting in higher pollution loads (Enoch, 2018). Thus, over-abstraction and a significantly low or high average rainfall will impact river water flow by increasing effluent runoff, which causes the influx or increased concentration of microbial pollutants, such as pathogens and bacteria, into the surrounding water bodies (du Plessis, 2019).

Lastly, compliance graphs were compiled for each of the WMAs and the study area in its entirety. The graphs indicate that over the research study period, *E. coli*, being of an unacceptable standard for most of the the observed research stages, proved to be a primary threat and the largest risk factor impacting on water quality in the region. EC, chloride, magnesium, sulphate and nitrate also impacted the rivers, their standards at times being tolerable to unacceptable. However, in accordance with the TWQRs, the physicochemical quality of the water mostly appeared to be mostly of an ideal to acceptable standard, albeit, as previously observed through the time series trend analyses, presenting with a trend toward declining water quality.

Thus, it is clear from the deteriorating quality of the water observed within each of the selected WMAs that water quality monitoring and management in South Africa is failing the country's important conservation areas and threatening the overall functioning of its natural ecosystems. Water quality managers have been unable to properly and fully implement the appropriate legislation, policies, strategies, and actions to uphold or enforce the existing water quality standards, leaving the country at high risk in terms of water scarcity and stress under significantly variable climatic conditions (van der Merwe-Botha, 2009). As such, the final objective for this research included the presentation of recommendations for future research, policies, planning, and management strategies that will contribute to informed decision-making and improve the quality of the water flowing into the KNP.

This analysis of the quality of the water and its relationship to climate variability within the KNP area allowed for recommendations to be established for the future cost-effective and sustainable treatment of wastewater and the management of water resources for the benefit of South Africa's prime conservation and tourism area. Through these recommendations, it will be possible to maintain and improve the water resource sustainability of the WMAs and ensure the delivery of exceptional quality water to the KNP and water users further to the east. These recommendations now follow.

6.3. Recommendations for Policy, Improved Planning and Proactive Water Management

It has been well noted in this research that, being indicators of raw sewage pollution and increased physicochemical pollution, salinisation, acidification, eutrophication and microbial pollution should be the primary drivers of increased water quality concerns and would, therefore, require immediate attention. Short-term interventions are required to halt and/ or alter the course of water quality degradation, to ultimately maintain and improve the access of the public and institutions to water of an acceptable standard, and despite the dams being full, to address the lack of service delivery, causing water shortages or at the worst, no supplies at all. Water of a suitable quality is required and as set out by the country's commendable legislative framework, reliable water supplies to the communities surrounding the KNP and the KNP itself should be guaranteed. Further medium and long-term actions are required to prevent the current and future degradation of the quality of the water in the study area and maintain its integrity once its quality has been restored.

The water quality measured at the selected monitoring sites showed continued major pollution by both point and diffuse-sourced pollutants. Notably, the most probable reasons for pollutants identified by this research included inadequate to no maintenance, intermittent functioning, and the incapacity of WWTWs across South Africa, resulting in the discharge of raw and untreated effluent - risking both human and environmental health. Other major sources of pollution or increased water stress include the over-abstraction of water for irrigation purposes on farms, agricultural runoff containing fertilisers and pesticides, runoff containing organic matter, industrial effluents, domestic wastewater containing chemicals, AMD, as well as other emerging contaminants. As a result of the expansion of urban areas and attempts to maintain food security for a growing population, the area of land under cultivation is increasing and intensifying. According to the established trends in this research, the above-mentioned pollutants are thus on course to increase, as they accumulate in waterways and impact negatively on the functioning of aquatic ecosystems, and by extension, negatively affect fauna and flora in protected areas such as the KNP. Thus, there is an urgent and immediate need to address these pollutants at their source, as well as along the rivers in which they occur before they enter the KNP. As such, rather than rectify these issues in a reactive manner, they should be addressed proactively. A detailed description, including recommended short, medium and long-term interventions based on the primary results of this research and prioritised according to the gravity of the identified issues (i.e., from high to low priority) now follows.

6.3.1. Flagging Pollution Hotspots

Those selected monitoring sites observed during this research which exhibited declining trends in the quality of their water (i.e., of a tolerable to unacceptable standard), were flagged as pollution hotspots/ high risk areas. These sites should therefore be provided with dedicated means for frequent monitoring in the short-term as a step in the process to rectify ongoing contamination (Ashton & Dabrowski, 2011). Maps of these sites should be superimposed on land use maps so that the various pollution impacts can be determined. Thus, stock can be taken of the most recent water quality situation and programmes be developed to promote and inform proactive management interventions to address and/ or improve water quality (MTPA, 2012). It is further recommended that investments be made in the associated monitoring instruments to measure microbial variables/parameters, especially *Faecal coliforms* (*E. coli*) and that they be placed at strategic locations within the WMAs to determine the current state of sewage and/ or microbial pollution and to facilitate the real-time identification of environmental and human health risks in a proactive manner (du Plessis, 2014).

6.3.2. Maintaining, Restoring and/ or Upgrading WWTWS

Of major and immediate concern is that most of the WWTWs in the study area do not, as per the prescribed guidelines in the 2023 Green Drop Watch Report, meet the minimum effluent discharge requirements to release properly treated wastewater directly into the rivers. The Green Drop Watch Report attributed the dilapidated state of the WWTWs to the following (DWS, 2023a; DWS, 2023b):

- The amount of wastewater far exceeds the capabilities/ design capacity of the existing WWTWs.
- Dysfunctional processes lead to the inability of the WWTWs to meet the required discharge standards.
- The frequent malfunctioning of equipment is due to non-maintenance and neglect.

Wastewater originates mainly from domestic sources and generally includes household chemicals and sewage. The unacceptable quality of the wastewater being discharged directly into rivers may have severe human health and ecological ramifications, as well as other water-related risks, such as, but not limited to eutrophication and microbial pollution.

Thus, it is recommended that the treatment of wastewater be improved upon with immediate effect through the upgrading and optimisation of the existing WWTWs within the study area (DWA, 2012). Policy states that WWTWs which have failed to achieve the minimum Green Drop compliance target of 31% should be placed under regulatory focus and be required to submit a corrective action plan within 60 days of this enactment. To meet the compliance stipulations, many of these WWTWs will require additional government funding to upgrade the existing facilities. Once these upgrades have taken place, the effluent discharged from these WWTWs should be monitored daily and such corrective actions should be continuously monitored and evaluated to uphold a good standard in its treatment (DWS, 2023a; DWS, 2023b).

6.3.3. Management of River Salinisation

Owing to the high cost of treating salinised water, which cannot be used for agricultural and industrial purposes, the salinisation of rivers has resulted in the loss of millions of Rands annually. Salinisation also has a severe impact on the goods and services that rivers provide, posing health risks to society and affecting the surrounding environment. The two main strategies usually adopted to manage the salinisation of rivers worldwide include, firstly, those aimed at preventing further salinisation and reducing the discharge of salts, and secondly, those aimed at reducing the prevailing salinity of the river water and minimising the consequences thereof for the affected ecosystems.

Cañedo-Argüelles et al. (2013) suggest that both approaches be integrated as follows. The prevention of salinity should be prioritised and weighed up against the economic cost of minimising those activities which contribute to the discharge of saline wastewater. Where such discharges cannot be prevented, techniques such as integrated wastewater control systems using plate dolomite for ion exchange should be implemented to reduce the salinity of the wastewater effluent before it enters a water body (Cañedo-Argüelles et al., 2013). Furthermore, these authors suggest that the opportunities for non-river disposal, such as the use of evaporation ponds at a point-source pollutant site, be maximised. It is also recommended that, without exception, measures such as these, that are specific to saline wastewater, should be written into the existing legislation and be mandatory. In so doing, the mentioned mandatory guidelines and/ or prescribed standards set for wastewater should be implemented, enforced, and applied to water users across all sectors as a medium-term solution to reducing the salinisation of water resources within the KNP area.

6.3.4. Limiting Harmful Developments

Owing to the continued overexploitation of South Africa's freshwater river resources, and the limited attention given to their degradation, resulting therefore in the intensification of water scarcity and threatening the overall challenge of water insecurity, the country is currently facing a water deficit. According to the National Water and Sanitation Master Plan (DWS, 2018), South Africa's water use is roughly divided as follows: approximately five percent (5%) is consumed through afforestation, five percent (5%) through mining, 17% through domestic use, 18% through industry and 55% through agriculture (Mnguni, 2020). Agriculture, the largest water use sector, contributes the most in terms of non-point source pollution or runoff, leading to nutrient enrichment and salinisation (du Plessis, 2022). The agricultural sector, followed by forestry, subsistence farming, and mining, have been cited as the leading land use practices in the Limpopo, Olifants and Inkomati-Usuthu WMAs (Barker, 2006; Pollard & du Toit, 2011; Fouché & Vlok, 2012; Odiyo et al., 2014; Jury, 2016; Biggs et al., 2017; Roux et al., 2018; du Plessis, 2019; DWS, 2019).

As a result of population growth and the associated increase in the demand for food, agricultural intensification and expansion in these areas will be rampant in the years to come. To achieve food security, this condition will then encourage the extensive use of harmful fertilisers and pesticides. Pollutants resulting from increased volumes of agricultural return flows into surface water will further exacerbate the processes of salinisation and nutrient enrichment and lead to poor quality water that is harmful to both human and environmental health (du Plessis, 2022). Furthermore, persistent urbanisation and the growth of the economy through industrialisation and mining will continue to threaten these scarce freshwater resources. It is a fact that mining operations near the KNP are prolific and ongoing. If unmitigated, their social and hydrological impacts will severely threaten water supplies and sanitation, as mining is notoriously water intensive and often leads to spills or other events that result in contaminated water resources (Schoderer et al., 2020). Therefore, as a medium to long-term response to declining water quality in the three WMAs surrounding the KNP, it is highly recommended that local government/s should limit the amount of development permitted in the agricultural and mining sectors in such areas within the WMAs that are closest to the KNP. Another essential consideration is that mines approaching the end of their operations should have the appropriate end-of-life environmental policies in place for closure and restoration in terms of wastewater storage and disposal (Ashton et al., 2001).

Of major concern is that only 16% of South Africa's water, already scarce, is formally protected within conservation areas. Thus, it is recommended that the areas surrounding the monitoring sites that this research has flagged as pollution hotspots and high risk areas should, where possible, be strategically set aside for conservation purposes, be protected, secured, and well-managed to ensure long-term water security (du Plessis, 2019). For South Africa to improve the quality and availability of its freshwater resources, an overall improvement in water governance and management approaches is needed, especially in terms of water quality and the management of the consequent effects of land use change on the surrounding and/ or affected water bodies. Current calculations for the country's future water use and demand do not consider the amount of water that is required by the subsistence farming sector and rural communities. This is indeed a shortcoming in that these amounts could increase the overall demand for water by 20 - 30% (by volume), which is well above the original estimate. As such, it should, be factored into the medium and long-term development plans for water (du Plessis, 2019).

6.3.5. Nature-based Solutions

Existing buffer zones surrounding the lower reaches of the KNP need to be defined. These buffer zones should be secured and well protected to minimise further water degradation and perhaps control the major contaminants (e.g.: agricultural runoff, poorly treated wastewater, sewage pollution and AMD) from entering water bodies, specifically the rivers flowing into the KNP. Natural and man-made wetland systems may be effective in increasing the buffering capacity of the rivers but only as long as the pollution sources are properly investigated and addressed with a clear action plan showing short, medium, and long-term plan. Experts, as well as the relevant role players or interested parties, can assist by assessing the extent to which these passive water treatment systems could be effective in improving water quality. They should consider the implications of climate change in the context of the addition of pollutants to these systems, and thus as factors negatively affecting their functioning (Ashton & Dabrowski, 2011).

In addition, the commercial agricultural industry must also become less dependent on chemical fertilisers and pesticides, and instead favour eco-friendly or 'green' fertilisers and compost to reduce the runoff contributing to eutrophication and salinisation in the event of the over-abstraction of water resources. Pest control can be undertaken by applying biological control methods rather than chemical pesticides. Natural pest control usually entails the use of the natural enemy of the pest to remove the latter from an affected crop (Ncube, 2015). These methods can be phased in as medium-term solutions to reduce pollutants and evolve as part of a longer-term strategy to maintain water quality once it has been re-established.

6.3.6. Actual Enforcement and Implementation of Legislation and Strategies

South Africa is well-known for its exceptional policies and legislative frameworks around water. However, owing to a lack of political will and continued economic constraints, to name but a few, the implementation of guidelines and standards, and even their enforcement, has been found wanting over the past three decades (Mirzabaev et al., 2019). It is imperative over the long-term that the appropriate tools and legislations are not only in place but also enforced to improve overall water governance, especially in terms of governing/ monitoring to maximum efficiency the discharge of pollution/ untreated wastewater (the extent of which is often unknown) from both point sources and diffuse sources (Griffin et al., 2014). For instance, Ashton and Dabrowski (2011) note that all institutions, such as commercial farms, industry and WWTWs that have been granted a water use license and/ or an effluent discharge license must submit regular reports to DWS on the quantity of water used and the quantity and quality of effluent or wastewater being discharged into the surrounding water bodies. Going forward, these reports could enable diligent monitoring of both point and diffuse-sourced pollutants, identifying and promptly prioritising areas for remedial action, and eliminating some of the poor quality return flows received by the KNP (Ashton & Dabrowski, 2011). Failure to comply with these stringent requirements should result in the issuing of a directive, the withdrawal of a license, and prosecution as a final measure (Griffin et al., 2014). Over time, this would ensure that the most cost-effective water management policy - namely preventing pollution before it takes place - is upheld and enforced.

Furthermore, it is recommended that by 2025, a comprehensive water quality management and monitoring plan be compiled firstly for the lower reaches of each of the rivers entering the KNP, and then for other large conservation areas across South Africa. These management plans will in time complement the integrated water resource management plans of the DWS for the various national catchment areas (Ashton & Dabrowski, 2011). Simultaneously, coordination between the various role players is urgently required for water governance to be most efficient and effective. The government, private sector, non-governmental organisations, communities, as well as individuals must participate in the process, and as a collective, and hold one another accountable (du Plessis, 2019; du Plessis, 2022).

6.3.7. Improving Water Quality Objectives and Water Quality Monitoring

In terms of water quality objectives and water quality monitoring, legal provision was made for the protection of water resources through the South African National Water Act (No. 36 of 1998). The measures contained within the legislation are termed “Resource-directed Measures” (RDM) and include the setting of water quality objectives at the national level (Griffin et al., 2014). Physicochemical and microbial water quality monitoring has thus been the backbone of water quality monitoring in South Africa for decades (Fouché & Vlok, 2012; Griffin et al., 2014). However, the evaluations that were made during this research highlighted several well-known shortcomings of this monitoring programme. These, as well as the suggested actions for immediate effect, now follow.

Long-term, accurate and consistent data relating to water quality, water flow, and climate monitoring are important resources for managers to use in large, protected areas such as the KNP (Griffin et al., 2014; MacFayden et al., 2018). The approach taken in this research was to identify long-term trends and relationships from a range of sites and parameters. However, the monitoring of current river water quality across South Africa is in a dire state: it is inadequate and presents a major limitation for current water research (Marr et al., 2017a). In many cases, monitoring sites have been rejected as a result of the scarcity of data or gaps in the data and in the sampling, that are too large and/ or too many. Even monitoring sites with ample data frequently include multiple years of very few records. A common observation regarding the quality of the data that was made through this research compared well with observations made by other research studies and are listed as follows:

- Interruptions in monitoring for sequential years have resulted from malfunctioning equipment. Owing to lengthy repairs to equipment, many datasets contained missing data for the years 2012 - 2015 (du Plessis, 2019).
- The frequency of monitoring varies both spatially and temporally and has over the more recent years decreased and become highly irregular (Griffin et al. 2014). Moreover, in some cases, there has been a significant time lapse (often

more than a month) between sequential samples, making it difficult to properly interpret changes in water quality and to determine remedial actions (Ashton & Dabrowski, 2011).

Furthermore, this research also observed that large proportions of the samples taken over the respective research periods were marked by unreliable analyses. A similar observation by Ashton and Dabrowski (2011) highlighted the effects of a relatively large proportion of samples based on untrustworthy analyses and on data that could not, therefore, be used for research purposes, thus, presenting a significant waste of time, funding, and human resources.

Griffin et al. (2014) also emphasises the lack of follow-up monitoring after the completion of research studies, as well as the collection of insufficient data covering turbidity, metal content, organic pollutants and oxygen levels. Thus, this research recommends a review of the efficiency and effectiveness of the National Monitoring Programme (NMP), which should be followed up by remedial action to ensure the ongoing and regular collection, processing and recording of data to facilitate research. This investment in reliable data concerning water quality, water flow and climate will go a long way to contribute to future research on the development of urban areas, industry, and most importantly, strategic agricultural areas (Clark et al., 2022). Training in data collection, improvements in the data infrastructure, innovative and new ways of collecting data and exploiting the sources from which the data can be collected, and sufficient funding are urgently required to improve the availability and integrity of water quality data in South Africa, as well as in the study areas of this research (du Plessis, 2022).

Furthermore, even though regulatory tools for water quality management have been developed and are available, there is a need to clarify and refine such tools (e.g., the TWQRs) that are used for monitoring aquatic ecosystems. During this research, it was noted in Volume 7 (Aquatic Systems) of the South African Water Quality Guidelines, (DWAF, 1996d) that there are no guidelines for EC, pH, calcium, magnesium, sodium, sulphate, and *Faecal coliforms*. A revision of the full set of outdated TWQRs (three decades old) is required, as also the development of stringent guidelines for the relevant parameters affecting amongst others, aquatic ecosystems. In fact, the lack of TWQRs for such parameters has presented a serious limitation to this research and has up to now, owing to the ambiguity of their role, contributed little to the overall improvement of water quality in South Africa. In many instances, actual compliance with these guidelines could not be fully and/ or accurately determined as TWQRs for domestic use are also used alternatively to determine the possible impacts of water quality on aquatic ecosystems. Thus, as part of strengthening the NMP, this identified shortcoming (and the concern surrounding it) should be addressed by extending these guidelines, specifically those underlying the determination and monitoring of the quality of water dedicated to conservation areas (Griffin et al., 2014), as well as the relevant parameters (Marr et al., 2017a).

6.3.8. Large-scale Upskilling of Water Management Personnel

South Africa faces many serious challenges regarding water resource management, all of which are exacerbated by the overall shortage of management expertise, as well as capacity at all levels. It is specifically the local municipalities, also in a dire state, that are contributing to water degradation. There appears to be a lack of structure and skills required to proactively manage the water of the country and eliminate the questionably reactive decision-making processes to address water quality issues (Nkhonjera, 2017; du Plessis, 2019; (Mirzabaev et al., 2019). One of the predominant reasons for the inability of approximately 70% of the South African local municipalities to appropriately manage their water reticulation systems is due to the lack of experienced experts and the general skills shortage (DWS, 2018; SAICE, 2022). In addition, residual skills have also been neglected for quite some time (du Plessis, 2019). It is thus recommended that government should urgently and immediately invest in the relevant upskilling of water resource management personnel to address capacity issues and bridge the skills gap, specifically within the Limpopo, Olifants and Inkomati-Usuthu WMAs.

6.3.9. Limiting Climate-Altering Emissions

Water is one of the most vulnerable elements in terms of climate change (Dallas et al., 2019). As indicated previously, climate change affects rainfall, temperatures, and evaporation rates, all of which are predicted to become more erratic in the years to come. An approximate 10% reduction in rainfall can be expected for South Africa by 2025, resulting in an overall decrease in surface runoff of up to 75% (du Plessis, 2019). Through this research, climate change has been noted to have already played a role in affecting the diluting and buffering capacity of rivers in the study area. Climate change was determined to be most impactful on the rivers located in the southern region of the KNP which includes the Sabie and Crocodile Rivers, with water, some of which is of the most pristine quality, and an abundance of aquatic life (van Vuuren, 2017b; Roux et al., 2018; Riddell et al., 2019a). To ignore the potential impacts of intensifying climate variability and/ or change on these rivers could result in an ecological cataclysm. Increasing temperatures, that alter the composition of freshwater bodies, or floods and droughts, that impact on the dilution capacity of a river, are some of the factors that would cause such a dire situation.

Given these findings, and as long as decision-making around suitable projects and their implementation by South African water and infrastructure managers, in conjunction with all levels of government, are lacking, preparations for significant long-term changes in the KNP rivers that could negatively affect the region should be made. Policy makers and spatial/ town planners should refrain from poorly conceived actions that may amplify the risk of undesired outcomes (e.g., increasing the demand for already over-allocated water resources and contributing further to climate change through excessive air pollution - that already exceeds emission standards, unsustainable development, poor land use, and allocation strategies (Udall, 2018; UN Water, 2018). Since South Africa is warming up at double the rate of the rest of the world (WWF, 2016), it would be ill-advised to continue with the current emission trajectory, and even more so, to increase emissions (Udall, 2018). The challenge faced by the water sector will thus be to balance the allocation of the already stressed water resources to accommodate a wide variety of needs, while implementing emission reduction strategies (e.g., alternative power generation) and integrating climate considerations into future water planning for all economic sectors (Dallas et al., 2019).

Thus, addressing the root causes of climate change through both policy and action are of utmost importance, and should preferably be in line with the United Nations Sustainable Development Goals and the associated timeline to reduce emissions/ to achieve net zero. Additionally, and to complement water quality monitoring data systems, the collection and recording of real time, accurate climate monitoring data will be essential for further research on the effects of the increased variability of climatic conditions on water resources. Nkhonjera (2017) argues that South Africa lacks a robust national monitoring system for climatic data that provides extensive data at both the spatial and temporal levels. The most recent quality-controlled climatic data on a national-scale date back to 2000. In the light of this serious limitation, urgent consideration and action are required (Nkhonjera, 2017).

In summary, without an overhaul of the wastewater treatment works and consideration being given to other aspects obstructing improvements to the existing systems, a radical transformation of water quality monitoring; revised and more stringent water quality guidelines; their enforcement; and restorative water management practices which challenge a rapidly changing climate, there is little hope for the life-giving rivers of the KNP. To preserve and enhance one of South Africa's prime conservation and tourism hotspots, namely, the KNP, political will, as well as swift and firm action, must, as described in this section, be taken. Future research may aid in these endeavours and a discussion of them now follows.

6.4. Recommendations for Future Research

Studies which attempt to determine the broad relationship between water quality, water flow, and climate variability, as well as its impacts on a conservation area, still require more in-depth research to develop appropriate adaptation strategies and contextually relevant mitigation measures to reduce the effects of increased climate variability in South Africa. To the best knowledge of the researcher, this research is one of the first to study the susceptibility of the quality of the water in the KNP rivers to variations in the local climate. This research has proved invaluable in establishing possible trends and patterns and in identifying priority water quality issues and major areas of concern which in some cases require immediate interventions. Thus, it is recommended that this research be extended further to investigate the following.

Additional opportunities exist for research to occur on different scales, namely, on larger and more detailed scales and/ or on smaller scales, which would include larger land areas and, therefore, other conservation destinations. Localised case studies have been highlighted as a matter of concern to establish the responses of individual rivers, catchments, and conservation areas relative to climate variability in the respective regions (Nkhonjera, 2017). Observations of climate variability, water quality relationships and trends should be carried out in more detail for each of the rivers of the KNP and be extrapolated to include protected areas such as the IAi-IAis/ Richtersveld Transfrontier Park. Focusing on the impacts of one river and/ or protected area provides the opportunity for in-depth evaluations as to how rainfall and temperature affect a specific river system or biome and determines the extent to which climate variability interacts with the unique pollution impacts a river might be subjected to (Lipsett, 2017). Furthermore, the current research selected and analysed a range of physicochemical parameters and a single microbial parameter to obtain a broad overview of the quality of the water in the study area. The research did not take heavy metals, *Chlorophyll a*, DO, in situ temperatures, and SASS5 (most of which are currently unavailable from the monitoring programmes) into account. Consequently, future research could extend to a larger suite of parameters and use a similar methodology (Marr et al., 2017a).

Most historical water research on the KNP has focused on in-stream flow requirements (O'Keeffe & Davies, 1991; O'Keeffe & Coetzee, 1996) and water availability to support wildlife in the KNP. However, little has been done to determine the in-stream water quality guidelines of water for each of the rivers that flow through the KNP. The KNP Rivers Research Programme (KNPRRP) was established in the early 1990s to provide information on water quality and to quantity the requirements to sustain the natural environment of the KNP and predict the response of rivers to a changing landscape (O'Keeffe & Coetzee, 1996). The programme concluded in 1999 and helped to establish in-stream flow requirements for the KNP and water allocations. The programme identified the impacts of various sources of pollution; generated knowledge of the components of the various systems of the riverine environment, including fish and invertebrates, and based on the obtained results, ultimately enabled SANParks to build relationships with upstream neighbours (van Vuuren, 2017a) in an attempt to address or minimise continued pollution.

Thus, this research recommends the revival and rejuvenation of the KNPRRP to specifically develop in-stream water quality guidelines for the KNP rivers which can be coupled with the existing in-stream flow guidelines, and as such, assist in maintaining good water quality and possibly reduce and/ or minimise the continued degradation of the environment. Currently, the KNP applies the DWS (DWAF) domestic use (drinking water) TWQRs as Thresholds of Potential Concern since most of the rivers are also used for potable water (SANParks, nd).

6.5. Conclusions

South Africa's freshwater resources are under threat. Owing to ongoing overconsumption, persistent contamination, and the looming impacts of climate change, water insecurity is becoming a greater risk to the functioning of society and the natural environment with each passing year. Our freshwater reserves that give life to protected areas are particularly at risk of drying up or becoming unusable. Freshwater is a key ecosystem component that services the KNP, the surrounding protected areas, and the local human settlements, which also rely on the KNP for their livelihoods. In recent years, the KNP management highlighted freshwater system degradation and global climate change as the greatest risk factors associated with the longevity of the KNP.

While the quality of freshwater for many of the KNP rivers has been assessed to varying degrees over the years, research covering the KNP rivers as an entire ecosystem and which considers the impacts of climate change on water quality, has been lacking.

By focusing on the quality characteristics of the river water in the study area in relation to variations in water flow, rainfall and temperature in the region, this research has provided a wealth of detail on the spatio-temporal trends in water quality and the oscillations in response to a changing climate. There are clear indications that in terms of both the physicochemical and microbial quality of the water, the general quality of the water has progressively declined over some 20 to 30 years, and in some cases exponentially. This is the result of insufficient political action and the continued state of neglect that encompasses the region.

This research established the following primary concerns pertaining to several important rivers that are essential to the proper functioning of the KNP ecosystems. Through this research, it was confirmed that the KNP has been subjected, historically, to the inflow of poor quality water, that has steadily been deteriorating. Time series trend analyses indicated that the physicochemical quality of the water in the Limpopo, Luvuvhu, Shingwedzi, Letaba, Olifants, Sabie and Crocodile Rivers has predominantly regressed over the long-term and will remain on that trajectory without appropriate interventions. While most of the parameters remain at an ideal to tolerable level, they could potentially exceed the threshold and reach an intolerable condition - a likely scenario for the future.

It is evident that the water resources required to support and sustain conservation practices in the rivers of the KNP are over-extended and under immense pressure in terms of flow, quality, and their susceptibility to climate-related impacts. Impacts on water quality are spatio-temporally heterogenous and widespread, with the main issues being those of increasing salinisation, acidification and microbial contamination, and all possibly resulting in eutrophication. The salinisation, acidification, and eutrophication of these rivers will likely have a series of cascading effects on the functioning of the aquatic ecosystems. Combining the different parameters that were selected for this research may cause them to become toxic to aquatic life, to affect the biological functioning of the ecosystem, and/ or to alter the structures of communities, ultimately leading to a loss of biodiversity, as well as to a lack of ecosystem services to the KNP. Within the study area, there is in fact an array of source sites from which these pollutants emanate. These include poor functioning WWTWs, agricultural land supporting the runoff of fertilisers, effluents, etc., into the rivers, and industries and mines from which wastewater is discharged.

Furthermore, multiple studies have noted that climate change will have profound impacts on protected areas, with some pointing specifically to climate change as one of the most significant challenges to freshwater resources. In terms of the KNP, the pressure that climate variability has already put on the already scarce and stressed water resources was found to increase from north to south and to coincide with the increased rainfall in the more southerly regions of the KNP. On account of the dilution factor, rainfall influences the ability of a river to assimilate the impacts of pollution. When rivers are flowing at a low level because of a limited rainfall, the water quality parameters may measure at a higher level than when the river receives an influx of freshwater. This is not always the case, however, as the addition of freshwater runoff from surrounding areas may also contribute pollutants to a river. However, considering the response of the Sabie and Crocodile Rivers to climatic variability, it appears that rainfall and water flow are the main factors influencing the quality of the water in these rivers, which are the most susceptible in the study area to climate variations.

Each river is subject to starkly different challenges in terms of pollution and the spatial response among the respective rivers to climate change varies greatly. Furthermore, there is a large and continuously growing dependency on the freshwater river resources of the KNP. As such, management must be careful and meticulous, and to avoid water insecurity, take the near-future impacts of climate change into account. For South Africa to fulfil its predicted future water consumption needs, to avoid impending water stress and scarcity, and to continue to preserve essential protected areas such as the KNP, action, accountability, and transparency must prevail. If the country is to restore its neglected water resources and struggling water sector, well planned action plans are needed. Action plans alone are inadequate, however, unless they are supported by meaningful acts of implementation, supervision, and management. The KNP is a valuable asset and of huge ecological and economic significance to the surrounding communities in that it offers some of their members a form of livelihood. It is thus imperative as per the above recommendations that the minimum water quality and flow standards be met to preserve the socioeconomic and environmental benefits that the park offers.

This final chapter made recommendations for current remedial and mitigating measures to be put in place to address the aforementioned issues of pollution and climate change, as well as future strategic planning, development and actions required to maintain and conserve water quality for the KNP once it has been restored. Multiple previous studies have called for an urgent response to water quality challenges, such as microbial pollution and salinisation, and this research has added to that narrative. It should be noted that South Africa can no longer afford to have policies in place without committed action. Polluters have been allowed, and even enabled, to unrestrictedly contaminate freshwater resources. This research calls for immediate interventions to halt degradation and improve the physicochemical and microbial quality of the water, as well as to support medium and long-term action plans, and to coordinate action plans among the various sectors to drastically improve the quality of the water in the country.

Some of these recommendations include the flagging and management of pollution hotspots in order to restore the quality of the river water at these sites; to maintain and/ or upgrade the WWTWs currently discharging untreated effluent into freshwater bodies/rivers; to manage salinisation, which is one of the leading issues around the quality of river water established in this research; to limit further harmful developments in terms of agriculture, urban expansion, industry and mining; to make use of nature-based solutions (e.g., organic fertilisers and biological pest control); to ensure the enforcement of legislation that protects river water quality; to improve the objectives and monitoring of water to determine its quality; to upskill the water resource management personnel; and to reduce and limit future emissions contributing to air pollution and climate change. Lastly, recommendations for future research were made, including the replication and expansion of the methodologies employed in this research. Additional water quality parameters and monitoring sites can be considered, and the research can be further extended to other protected areas.

Since the KNP is mandated to preserve biodiversity and an array of interlinked ecosystems, it is especially important that government officials, managers, policy makers, and other relevant stakeholders have a current, accurate and informed view of the potential trends and impacts that can be expected in the future conservation of the rivers delivering water to the KNP and ultimately to Mozambique, and outward to the Indian Ocean. Through the analyses of long-term water quality trends and the relationships among water quality, water flow and climate parameters within and outside the KNP, this research developed a deeper understanding of the susceptibility of water quality to changes in the local climate and determined these impacts on one of South Africa's largest tourist destinations, namely the KNP. It is hoped that the approach to this research may prove useful in providing insights to other researchers, water resource managers and government, and assist in paving the way forward to the informed and proactive management of the rivers of the KNP.

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APPENDIX I: SOUTH AFRICAN WEATHER SERVICES DISCLOSURE STATEMENT

FORM: DISCLOSURE STATEMENT

The provision of the data is subject to the User providing the South African Weather Service (SAWS) with a detailed and complete disclosure, in writing and in line with the requirements of clauses 1.1 to 2.4 (below), of the purpose for which the specified data is to be used.

1. **Should the User intend using the specified data for commercial gain then the disclosure should include the following**:
   - 1.1. the commercial nature of the project/funded research project in connection with which the User intends to use the specified data;
   - 1.2. the names and fields of expertise of any participants in the project/funded research project for which the specified data is intended; and
   - 1.3. the projected commercial gains to the User as a result of the intended use of the specified data for the project/funded research project.

2. **Should the User intend using the specified data for the purposes of conducting research, then the disclosure should include the following**:
   - 2.1. the title of the research paper or project for which the specified data is to be used;
   - 2.2. the details of the institution and supervisory body or person(s) under the auspices of which the research is to be undertaken;
   - 2.3. an undertaking to supply SAWS with a copy of the final results of the research in printed and/ or electronic format; and
   - 2.4. the assurance that no commercial gain will be received from the outcome from the research.

If the specified data is used in research with disclosure being provided in accordance with paragraph 2 and the User is given the opportunity to receive financial benefit from the research following the publication of the results, then additional disclosure in terms of paragraph 1 is required.

The condition of this disclosure statement is applicable to the purpose and data requirements of the transaction recorded in Schedule 1 below.

SCHEDULE 1

Please note: The South African Weather Service will only act upon customer requirements noted on this disclosure statement and not from any other correspondence.

FULL PERSONAL DETAILS OF USER

Full Names	Nicole Carys Christie (Married: Ras)
University/school/organisation	University of South Africa

Student Number (if applicable)	56082886
Email address	niki.christie818@gmail.com / 56082886@mylife.unisa.ac.za
Cellphone	073 478 8576
Supervisor	Dr Anja du Plessis
Project/Thesis Title	Working title: The influence of climate variability on water availability and quality of rivers in the Kruger National Park from July 2009 to June 2019
Current registered degree (e.g. BSc)	MSc Geography
Expected finalization date (MMYYYY)	28/02/2023

FORM: DISCLOSURE STATEMENT

The South African Weather Service reserves the right to request, at any time, from the student proof of registration for the Degree at the University.

THE PURPOSE (*Please indicate a detailed description of the purpose for which the data will be used)*

The data will be correlated with water quality and hydrological trends in order to investigate the impacts of climate change and variability on the flow and quality of water of seven major rivers that traverse the Kruger National Park. The water quality and flow data will be obtained from the DWS open access database

DATA REQUIRED *(Indicate weather elements (e.g., rain, temp), place/s, time period and resolution (e.g., daily, hourly)*

Climate data is required for in the Kruger National Park (and/ or nearby surrounding areas) for the period 1955 to 2021

Rainfall: Monthly
Min & Max Temperature: Monthly

For the following monitoring stations:
Phalaborwa gate
Hoedspruit
Komatidraai
Nelspruit
Bourkesluck

Please also provide coordinates for the following stations:
station [0596179 3] - SKUKUZA
station [0639474 9] - SATARA
station [0639504 6] - SATARA
station [0682141 8] - LETABA
station [0682141A2] - LETABA
station [0725756 3] - SHINGWEDZI
station [0725756A8] - SHINGWEDZI
station [0768011 3] - PUNDA MARIA
station [0768011A8] - PUNDA MARIA
station [0768382 0] - SHINGWEDZI VLAKTEPLAAS

I hereby accept that:

- SAWS will be acknowledged in the resulting thesis/project or when published, for the data it provided.
- SAWS will be provided with a copy of the final results in printed or electronic format.
- The data received shall not be provided to any third party.

Signature of the User:  Date: 16/11/2021

Public Document Document Reference: WCS-CLS-FRM-004.1 Page 2 of 3

FORM: DISCLOSURE STATEMENT
(*Please sign the document and do not type your name in as this is a legal document and requires a signature*.)

PROTECTION OF PERSONAL INFORMATION ACT (POPIA)

SAWS value its customer's privacy and strives to continuously ensure compliance with POPIA, to protect and safeguard against unauthorised use of personal information.

The Customer hereby accepts that:

- He/she has read and understood the customer processing POPIA notice found on https://www.weathersa.co.za/home/popia

Signature of the User: Date: 16/11/2021

(*Please sign the document and do not type your name in as this is a legal document and requires a signature*.)

APPENDIX II: SANPARKS DATA USER AGREEMENT

SANPARKS Scientific Services Spatial Data User Agreement

DISCLOSURE STATEMENT

The provision of the data is subject to the User providing South African National Parks (SANParks) Scientific Services, Kruger National Park (KNP) with a detailed and complete disclosure, in writing and in line with the requirements of clauses 1.1 to 2.3 (below), of the purpose for which the specified data is to be used. The statement is to be attached to this document as Schedule 1.

1. Should the User intend using the specified data for commercial gain then the disclosure should include the following:

   1.1 - the commercial nature of the project/funded research project in connection with which the User intends to use the specified data;

   1.2 - the projected commercial gains to the User as a result of the intended use of the specified data for the project/funded research project.

2. Should the User intend using the specified data for the purposes of conducting research, then the disclosure should include the following:

   2.1 – if the data is required for a SANParks registered project the project registration details are to be provided

   2.2 – for research that does not form part of a SANParks registered project the following need to be provided

      2.2.a - title of the research paper or project for which the specified data is to be used;

      2.2.b - the details of the institution and supervisory body or person(s)/ organisation under the auspices of which the research is to be undertaken;

   2.3 - the assurance that no commercial gain will be received from the outcome from the research.

If the specified data is used in research with disclosure being provided in accordance with paragraph 2 and the User is given the opportunity to receive financial benefit from the research following the publication of the results, then additional disclosure in terms of paragraph 1 is required.

The condition of this disclosure statement is applicable to the purpose and data requirements of the transaction recorded in Schedule 1.

SCHEDULE 1

User Details

Name: Nicole Carys Christie

Telephone number(s): 073 478 8576

Fax: NA

E-mail: 56082886@mylife.unisa.ac.za / niki.christie818@gmail.com

Postal address: NA

University / Organisation: University of South Africa (UNISA)

SANParks Registered researcher: ~~Yes~~ / **No**?
If **YES** - Researcher / project number:

If **NO** – Registered Course (where applicable): 98004: MSc (Geography) – Dissertation (DFGGR91)

Project/Thesis Title: *Possible influence of climate variability on water quality and flow in rivers of the Kruger National Park from July 2009 to June 2019*

Supervisor: Dr. Anja du Plessis

The Purpose

(Please include a detailed description of the purpose for which the data will be used. Clearly state if the data will be used for research or commercial purposes.)

The data is required for the completion of a Master of Science (Geography) Dissertation at UNISA. The research will conduct temporal and spatial data analyses in order to determine the correlation / association between water quality, hydrology and climatic variables over a 10-year period, and to establish the nature of the relationship between these variables, as well as to highlight priority / risk areas.

Data Required

(Please include a detailed description of the individual datasets (e.g. main rivers rather than the generic term hydrology) and area / time period if applicable. Information on the available data and their designated categories can be obtained from the SANParks Data Repository - http://dataknp.sanparks.org/sanparks/.)

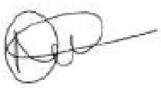
I spoke to Dr Riddell who previously indicated that SANParks (KNP) monitors water quality in the park on an ad-hoc basis and that this data can provided (although SANParks is primarily dependent on the National Chemical Monitoring Program, there may be some additional data). Dr Riddell further indicated that the Inkomati-Usuthu Catchment Management Agency has also provided monthly data which could be of use.

Consequently, I would like to request the following data:

- Daily / Monthly water flow data
- Monthly water quality data for the following parameters:
  - EC, pH, Calcium, Chloride/Chlorine, Magnesium, Sodium, Ammonia, Nitrate/Nitrite, Sulphate, Orthophosphate, *Faecal Coliform* (E. coli), Chlorophyll *A*, DOC.
- For the following rivers at stations located inside the park and / or just outside of the park's western boundaries
  - Limpopo, Luvuvhu, Shingwedzi, Letaba, Olifants, Sabie, Crocodile.
- For the period 2008 to present.

I, ……Nicole Carys Christie….., understand the Data User Agreement and agree to abide by its terms.

Signed:



……………………………………	…………………………………………
Data user	*SANParks data provider*
Name: Nicole Christie	Name:
Date: 27 / 07 /2021	Date:

The Spatial Data User Agreement is to be completed and signed by the data user and emailed to the GIS Lab: gisuser@sanparks.org.

Terms of Agreement

Liability

Digital and non-digital data and metadata belonging to the Kruger National Park Scientific Services are provided to researchers on an "as-is" basis with no guarantee as to data quality. Neither the staff nor South African National Parks (SANParks) may be held liable for any loss of any sort resulting from use of data and/metadata provided by Scientific Services.

Data Access and Ownership

The Scientific Services data are intended for use by registered researchers only and the database administrator (DBA) has the right to withhold data from any person or body in accordance with the SA *Promotion of Access to Information Act, 2000*. SANParks reserves the right to withhold data intended for commercial purposes.
All data collected and captured by SANParks registered researchers and staff belong jointly to the researcher and to SANParks. SANParks reserves the right to demand that the data user returns the data to SANParks and destroys all other copies.

Acknowledgement

SANParks Scientific Services should be acknowledged in the resulting thesis/project or when published, for the data it provided.

Data Categories

Data provided by Scientific Services fall into one or more of the categories below:

1. **Copyright data**;
2. **Lead-time protected data**;
3. **Sensitive data**;
4. **Protected data**;
5. **Open data**;
6. **Other data**;
7. **SA Weather Services data**.

Data derived from other data (whether by the user or as provided by the DBA) is categorized according to the most restrictive combination of their source data categories. For example, if copyright data is combined with open data to produce another dataset, then that derived dataset is categorized as copyright data.

Conditions of Use

1. **Copyright data** may be used for non-profit research only.

2. **LTP data** may be distributed only with written consent of the registered researcher, even though SANParks is a co-owner of the data. SANParks is also prohibited from using the data without permission from the registered researcher until the LTP period has expired (whereafter the data are to be reclassified into a different Data Category.) During the LTP period, the registered researcher is encouraged to allow access to a summarized version of the data.

3. **Sensitive data** will be distributed at the discretion of the database administrator, subject to local and international laws. This data may be used for non-profit collaboration and registered research only.

4. **Protected data** may be distributed with permission from the data owner only.

5. **Open data** will be distributed at the discretion of the database administrator. SANParks reserves the right to withhold data intended for commercial purposes.

6. **Other data** will be distributed according to the specific restrictions attached to the dataset.

7. **SAWS data** may be distributed only to registered researchers. SAWS must be acknowledged in any publications for which the data was used and a copy of these publications has to be submitted to SANParks for archiving. These publications will be made available to SAWS.

Recipients of data from Scientific Services are to destroy all copies of the data when they are finished using it except for archive and backup purposes. Furthermore, they shall not distribute the data themselves and shall ensure that they take reasonable precautions against the theft of the data.

Definitions:

1. A **data user** is any person or organization which has data that came from SANParks Scientific Services.
2. **Copyright data** are data which are subject to copyright laws and may not be reproduced without the owner's written consent.
3. **Lead-time protected data** (LTP data) are subject to intellectual property rights, usually protected for a period of up to three years to provide registered researchers adequate opportunity to publish their findings.
4. **Sensitive data** are data that may not be made public due to a perceived risk in doing so (e.g. locations of endangered species.)
5. **Protected data** are data that may not be made public due to their confidential nature (e.g. military and poaching information.)
6. **Open data** are data with no restrictions on use or distribution.
7. **Other data** are data subject to custom-defined use and distribution restrictions such as scientific data collected by and for a particular research program. The permissible uses and restrictions are to be clearly stated by the data owner in the metadata records and/or a customized addendum to the Data User Agreement.
8. **Non-profit research** is research which does not involve the trade of any data, product (including maps and scientific models), or service.
9. **Income-generating research** is research which does involve the trade of data, product (including maps and scientific models), or service.
10. **Non-profit nature conservation / environmental management** is the use of data for the purpose of nature conservation or environmental management, not necessarily through scientific research, by a person or organization which does not generate any revenue from this activity.
11. **Commercial nature conservation / environmental management** is the use of data for the purpose of nature conservation or environmental management, not necessarily through scientific research, by a person or organization which does generate revenue from this activity.
12. **South African Weather Service data** is all climate data as recorded by automatic weather stations owned by the South African Weather Service.

APPENDIX III: DWS / DWAF WATER QUALITY GUIDELINES AND TARGET WATER QUALITY RANGES

Table: Water Quality Ranges for Electrical Conductivity

Electrical Conductivity Water quality guidelines and standards (mS/m)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	0-70	70-150	150-450	>450
Aquatic Ecosystems	No guidelines			
Recreational Use	No guidelines			
Irrigation	40	40-90	90-540	>540

Table: Water Quality Ranges for pH

pH Water quality guidelines and standards (pH units)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	6-9	9-11	4-6	<4 and >11
Aquatic Ecosystems	No guideline			
Recreational Use	6.5-8.5	5.0-6.5 and 8.5-9.0	No guideline	0-5.0 and >9
Irrigation	6.5-8.4	No guideline	<6.5 and >8.4	No guideline

Table: Water Quality Ranges for Calcium

Calcium (Ca^{2+}) Water quality guidelines and standards (mg/ℓ)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	0-32	32-80	>80	No guideline
Aquatic Ecosystems	No guidelines			
Recreational Use	No guidelines			
Irrigation	No guidelines			

Table: Water Quality Ranges for Chloride

Chloride (Cl^{-}) Water quality guidelines and standards (mg/ℓ)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	0-100	100-200	200-1200	>1200
Aquatic Ecosystems	0.0002	No guideline	0.0035	0.005
Recreational Use	No guidelines			
Irrigation	100	<140	140-700	>700

Table: Water Quality Ranges for Magnesium

Magnesium (Mg^{2+}) Water quality guidelines and standards (mg/ℓ)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	0-30	30-50	50-100	>100
Aquatic Ecosystems	No guidelines			
Recreational Use	No guidelines			
Irrigation	No guidelines			

Table: Water Quality Ranges for Sodium

Sodium (Na^{+}) Water quality guidelines and standards (mg/ℓ)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	0-100	100-200	200-600	>600
Aquatic Ecosystems	No guidelines			
Recreational Use	No guidelines			
Irrigation	70	70-115	115-460	>460

Table: Water Quality Ranges for Phosphate

Phosphate (PO_4^{-2}) Water quality guidelines and standards (mg/ℓ)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	No guidelines			
Aquatic Ecosystems	<0.5			
Recreational Use	No guidelines			
Irrigation	No guidelines			

Table: Water Quality Ranges for Sulphate

Sulphate (SO_4^{-2}) Water quality guidelines and standards (mg/ℓ)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	0-200	200-400	400-600	>600
Aquatic Ecosystems	No guidelines			
Recreational Use	No guidelines			
Irrigation	No guidelines			

Table: Water Quality Ranges for Ammonia

Ammonia (NH_4^+) Water quality guidelines and standards (mg/ℓ)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	0-1	1-2	2-10	>10
Aquatic Ecosystems	<0.5	0.5-2.5	2.5-10	>10
Recreational Use	No guidelines			
Irrigation	5	No guideline	5-30	>30

Table: Water Quality Ranges for Nitrate

Nitrate (NO_3) Water quality guidelines and standards (mg/ℓ)				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	0-6	6-10	10-20	>20
Aquatic Ecosystems	<0.5	0.5-2.5	2.5-10	>10
Recreational Use	No guidelines			
Irrigation	5	No guideline	5-30	>30

Table: Water Quality Ranges for *Faecal Coliforms*

***Faecal Coliform*, *E. coli* Water quality guidelines and standards (counts/100 ml)**				
Water Use	Ideal	Acceptable	Tolerable	Unacceptable
Domestic Use	0	0-10	10-20	>20
Aquatic Ecosystems	No guideline			
Recreational Use	0-130	No guideline	600-2000	>2000
Irrigation	1	No guideline	1-1000	>1000

APPENDIX IV: RIVER WATER QUALITY MONITORING SITES ASSESSED AND INCLUDED IN THE ANALYSIS OF PHYSICOCHEMICAL PARAMETERS

WMA		River	Site Name	Site No.	Date Range	Years on Record	No. Samples	Latitude	Longitude	Source
A: Limpopo	1	Limpopo	Botswana Sterkloop on Limpopo River	A5H006	1980 - 2018	38	2088	-22,9350	28,0042	DWS
	2	Limpopo	Downstream of Beit Bridge on Limpopo River	A7H008	1993 - 2018	25	1319	-22,2256	29,9906	DWS
	3	Luvuvhu	Luvuvhu River at Pafuri/Kruger National Park	A9H011	1983 - 2017	34	4836	-22,4217	31,2111	DWS
	4	Luvuvhu	At Mhingas on Luvuvhu River	A9H012	1988 - 2018	30	4714	-22,7697	30,8869	DWS
B: Olifants	5	Shingwedzi	At Silvervis Dam/Kruger National Park on Shingwedzi	B9H002	1984 - 2018	34	2377	-23,2152	31,2200	DWS
	6	Shingwedzi	Shingwedzi River at Kanniedood Dam Kruger National Park	B9H003	1984 - 2018	34	2480	-23,1432	31,4626	DWS
	7	Letaba	At Letaba Ranch on Groot Letaba	B8H008	1977 - 2018	41	8315	-23,6581	31,0500	DWS
	8	Letaba	The Junction on Groot Letaba	B8H009	1975 - 2018	43	6784	-23,8803	30,3669	DWS
	9	Olifants	At Oxford on Olifants River	B7H007	1976 - 2018	42	8659	-24,1838	30,8238	DWS
	10	Olifants	Olifants River at Mamba/ Kruger National Park	B7H015	1983 - 2018; 2021	36	8277	-24,0589	31,2372	DWS
X: Inkomati-Usuthu	11	Sabie	Sabie River at Sabie	X3H001	1976 - 2018	42	4332	-25,0889	30,7779	DWS
	12	Sabie	Phabeni KNP / Sabie River ICMA	X3H012	1983 - 2018	35	3534	-25,0180	31,2497	SANParks
	13	Sabie	Sabie River at Lower Sabie Rest Camp/Kruger National Park	X3H015	1983 - 2020	37	9104	-25,1494	31,9406	DWS
	14	Crocodile	At Ten Bosch Kruger National Park on Crocodile River	X2H016	1977 - 2018	41	15124	-25,3622	31,9567	DWS
	15	Crocodile	Crocodile River at Riverside/ Kruger National Park	X2H046	1986 - 2018	32	7245	-25,3989	31,6106	DWS
	16	Crocodile	Malelane gate KNP	X2H048	1985 - 2021	36	4159	-25,4597	31,5356	SANParks

APPENDIX V: RIVER WATER QUALITY MONITORING SITES ASSESSED AND INCLUDED IN THE ANALYSIS OF MICROBIAL PARAMETERS

WMA		River	Site Name	Site Number	Date Range	Years on Record	No. Samples	Latitude	Longitude	Source
A: Limpopo	1	Limpopo	Groblersbrug Border Post to Botswana Klippan 25 LQ N11 Bridge on Limpopo River	A5H006	2008 - 2011; 2013 - 2017	8	43	-22,9979	27,9421	DWS
	2	Limpopo	Downstream of Beit Bridge on Limpopo River	A7H008	2010 - 2011; 2013 - 2017	7	37	-22,2256	29,9906	DWS
B: Olifants	3	Luvuvhu	Nandoni Dam Downstream of Dam Weir on Luvuvhu River	A9h030	2009 - 2011; 2014 - 2015	5	29	-22,9785	30,6010	DWS
	4	Letaba	Giyani Upstream of STW near R81 Adolf Mhinga Bridge on Klein Letaba River	-	2001 - 2015	14	299	-23,3127	30,6834	DWS
	5	Letaba	Downstream of Giyani Sewage Works at Irrigation Abstraction	-	2001 - 2009; 2011 - 2015	14	253	-23,3297	30,7064	DWS
	-	Shingwedzi	Shingwedzi Rest Camp KNP STW Final Effluent	-	This is the only site on the Shingwedzi River that has Microbial data, and it could not be included in the analysis due to there only being 3 measurements between 2008 - 2014.					
	6	Olifants	Olifants Rest Camp KNP Sewage Works Final Effluent Discharge	-	2007; 2009 - 2015	8	29	-24,0013	31,7449	DWS
	7	Olifants	L12 Olifants River Downstream of Confluence with Tswenyane River	-	2009 - 2011; 2013 - 2015	6	33	-24,4375	30,6195	DWS

X: Inkomati-Usuthu	8	Sabie	Sabie River at Samora Camp	-	2002 - 2004; 2006 - 2012; 2016	10	128	-24,9639	31,3149	DWS
	9	Sabie	Calcutta 294 KU Downstream of Hoxane Weir and Hoxane WWTW on Sabie River	-	2006 - 2008; 2010 - 2020	14	130	-25,0203	31,2181	DWS
	10	Crocodile	Kanyamazane Downstream at N4 Bridge on Crocodile River	-	2004; 2006 - 2021	16	255	-25,4995	31,1791	DWS
	11	Crocodile	Karino Bridge on Crocodile River	-	2004; 2006 - 2021	16	243	-25,4700	31,1006	DWS

APPENDIX VI: MONTHLY MAXIMUM RIVER WATER FLOW MONITORING SITES ASSESSED AND INCLUDED IN THE RESEARCH

WMA		River	Site Name	Site No.	Date Range	Years on Record	No. Samples	Latitude	Longitude
A: Limpopo	1	Limpopo	Limpopo River at Botswana	A5H006	1971 - 2021	50	547	-22,9348	28,0039
	2	Limpopo	Limpopo River at Beit Bridge	A7H008	1992 - 2021	29	331	-22,2272	29,9904
	3	Luvuvhu	Luvuvhu River at Nooitgedacht	A9H005	1947 - 2021	74	863	-23.0856	30.1753
	4	Luvuvhu	Luvuvhu River at Mahinga	A9H012	1987 - 2021	34	391	-22.76851	30.8893
	5	Mutale (Tributary of Luvuvhu)	Mutale River @ Kruger National Park	A9h013	1988 - 2021	33	313	-22.4377	31.0778
B: Olifants	6	Shingwedzi	Shingwedzi River at Silwervis Kruger National Park	B9H002	1983 - 2021	38	456	-23.2163	31.2235
	7	Shingwedzi	Shingwedzi River at Kanniedood Kruger National Park	B9H003	1985 - 2013	28	340	-23.1433	31.4626
	8	Letaba	Great Letaba River at Letaba Ranch	B8H008	1959 - 2021	61	664	-23.6584	31.0499
	9	Letaba	Great Letaba River at The Junction	B8H009	1960 - 2021	61	716	-23.8793	30.3674
	10	Letaba	Little Letaba River at Locatie van Tabaan	B8H033	1987 - 2021	34	368	-23.2810	30.5431
	11	Olifants	Olifants River at Oxford	B7H007	1967 - 2019	54	500	-24.1847	30.8229
	12	Olifants	Olifants River at Mamba Kruger National Park	B7H015	1987 - 2021	34	372	-24.0663	31.2429
X: Inkomati-Usuthu	13	Sabie	Sabie River at Sabie	X3H001	1948 - 2021	73	867	-25.0889	30.7779
	14	Sabie	Sabie River at Lower Sabie Rest Camp Kruger National Park	X3H015	1987 - 2021	34	389	-25.1495	31.9407
	15	Sabie	Sabie River at Kruger Gate Kruger National Park	X3H021	1990 - 2021	31	351	-24.9685	31.5154
	16	Crocodile	Krokodil River at Karino	X2H006	1930 - 2020	90	1093	-25.4698	31.0881
	17	Crocodile	Krokodil River at Tenbosch Kruger National Park	X2H016	1960 - 2020	60	683	-25.3639	31.9557
	18	Crocodile	Krokodil River at Riverside	X2H046	1985 - 2021	36	425	-25.3989	31.6106

APPENDIX VII: DETAILS OF THE CLIMATE MONITORING SITES IN AND ADJACENT TO THE KNP FOR WHICH DATA WERE OBTAINED AND USED IN THIS RESEARCH

WMA		Site Name	Rainfall Start/End Dates	Rainfall Years on Record	Temp Start/End Dates	Temp Years on Record	Latitude	Longitude
Limpopo	1	Punda Maria	1955 - 2021	66	1955 - 2021	66	-22,6800	31,0200
Olifants	2	Shingwedzi Vlakteplaas	1983 - 2021	38	-	-	-22,8669	31,2170
Inkomati-Ususthu	3	Graskop	1989 - 2020	31	1989 - 2020	31	-24,9351	30,8391
Inkomati-Ususthu	4	Skukuza	1955 - 2021	66	1955 - 2021	66	-24,9926	31,588
Inkomati-Ususthu	5	Nelspruit	1993 - 2021	27	1993 - 2021	27	-25,5031	30,9116

APPENDIX VIII: PHYSICOCHEMICAL AND MICROBIAL WATER QUALITY MONITORING SITES PAIRED WITH WATER FLOW AND CLIMATE MONITORING SITES INCLUDED IN THE RESEARCH

WMA	River	Site Name	Site No.	Site Type	Water Flow Site	Rainfall Site	Temperature Site
A: Limpopo	Limpopo	At Botswana Sterkloop on Limpopo River	A5H006	Physicochemical	A5H006	Punda Maria	Punda Maria
	Limpopo	Downstream of Beit Bridge on Limpopo River	A7H008	Physicochemical	A7h008	Punda Maria	Punda Maria
	Limpopo	Groblersbrug Borderpost to Botswana Klipppan 25 LG N11 Bridge on Limpopo River		Microbial	A5H006	Punda Maria	Punda Maria
	Limpopo	A7h008q01 Downstream of Beit Bridge on Limpopo River		Microbial	A7h008	Punda Maria	Punda Maria
	Luvuvhu	Luvuvhu River at Pafuri/Kruger National Park	A9H011	Physicochemical	A9H013 - Mutale River (Tributary)	Punda Maria	Punda Maria
	Luvuvhu	At Mahingas on Luvuvhu River	A9H012	Physicochemical	A9H012	Punda Maria	Punda Maria
	Luvuvhu	A9h030 Nandoni Dam Downstream of Dam Weir on Luvuvhu River		Microbial	A9H005	Shing - Vlak	Punda Maria
B: Olifants	Shingwedzi	At Silvervis Dam/Kruger National Park on Shingwidzi	B9H002	Physicochemical	B9H002	Shing - Vlak	Punda Maria
	Shingwedzi	Shingwidzi River @ Kanniedood Dam Kruger National Park	B9H003	Physicochemical	B9H003	Shing - Vlak	Punda Maria
	Letaba	At Letaba Ranch on Groot Letaba	B8H008	Physicochemical	B8H008	Punda Maria	Punda Maria
	Letaba	The Junction on Groot-Letaba	B8H009	Physicochemical	B8H009	Skukuza	Skukuza
	Letaba	Downstream of Giyani Sewage Works at Irrigation Abstraction		Microbial	B8H033	Shing - Vlak	Punda Maria
	Letaba	Giyani Upstream of Sewage Treatment Works near R81		Microbial	B8H033	Shing - Vlak	Punda Maria

		Adolf Mahinga Bridge on Klein Letaba River					
	Olifants	At Oxford on Olifants River	B7H007	Physicochemical	B7H007	Skukuza	Skukuza
	Olifants	Olifants River at Mamba/Kruger National Park	B7H015	Physicochemical	B7h015	Skukuza	Skukuza
	Olifants	Olifants River at Mamba Kruger National Park (L12)		Microbial	B7H007	Graskop	Graskop
	Olifants	Olifants Rest Camp KNP Sewage Works Final Effluent Discharge		Microbial	B7H015	Skukuza	Skukuza
X: Inkomati-Usuthu	Sabie	Sabie River at Sabie	X3H001	Physicochemical	X3H001	Skukuza	Skukuza
	Sabie	Phabeni KNP	X3H012	Physicochemical	X3H021	Skukuza	Skukuza
	Sabie	Sabie River at Lower Sabie Rest Camp/Kruger National Park	X3H015	Physicochemical	X3H015	Skukuza	Skukuza
	Sabie	Sabie River at Samora Camp		Microbial	X3H021	Skukuza	Skukuza
	Sabie	Calcutta 294 Ku - Downstream of Hoxane Weir and Hoxane Wastewater Treatment Works on Sabierivier		Microbial	X3H021	Skukuza	Skukuza
	Crocodile	At Ten Bosch Kruger National Park on Crocodile River	X2H016	Physicochemical	X2H016	Skukuza	Skukuza
	Crocodile	Crocodile River at Riverside/Kruger National Park	X2H046	Physicochemical	X2H046	Skukuza	Skukuza
	Crocodile	Malelane gate KNP	X2H048	Physicochemical	X2H046	Skukuza	Skukuza
	Crocodile	Kanyamazane D/S at N4 Bridge Krokodilpoort on Crocodile		Microbial	X2H006	Nelspruit	Nelspruit
	Crocodile	Karino Bridge in Crocodile River		Microbial	X2H006	Nelspruit	Nelspruit

APPENDIX IX: UNISA-CAES RESEARCH ETHICS APPROVAL

UNISA | university of south africa

UNISA-CAES HEALTH RESEARCH ETHICS COMMITTEE

Date: 12/02/2021

NHREC Registration # : REC-170616-051
REC Reference # : 2021/CAES_HREC/014
Name : Ms NC Christie
Student #: 56082886

Dear Ms Christie

Decision: Ethics Approval from 12/02/2021 to 31/01/2024

Researcher(s): Ms NC Christie
56082886@mylife.unisa.ac.za

Supervisor (s): Dr A Du Plessis
duplea@unisa.ac.za; 011-471-2877

Working title of research:

Possible influence of climate variability on water quality and flow in rivers of the Kruger National Park from July 2009 to June 2019

Qualification: MSc Geography

Thank you for the application for research ethics clearance by the Unisa-CAES Health Research Ethics Committee for the above mentioned research. Ethics approval is granted for three years, **subject to submission of the relevant permission letter and yearly progress reports. Failure to submit the progress report will lead to withdrawal of the ethics clearance until the report has been submitted.**

The researcher is cautioned to adhere to the Unisa protocols for research during Covid-19.

Due date for progress report: 31 January 2022

Please note the points below for further action:

1. The researcher must submit the permission letter from SanParks for the use of their data to the committee once obtained.

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The ***negligible risk application*** *was* ***expedited*** *by the UNISA-CAES Health Research Ethics Committee on 12 February 2021 in compliance with the Unisa Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment. It will serve at the next committee meeting of 04 March 2021 for ratification of the decision.*

The proposed research may now commence with the provisions that:

1. The researcher will ensure that the research project adheres to the relevant guidelines set out in the Unisa Covid-19 position statement on research ethics attached.
2. The researcher(s) will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.
3. Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study should be communicated in writing to the Committee.
4. The researcher(s) will conduct the study according to the methods and procedures set out in the approved application.
5. Any changes that can affect the study-related risks for the research participants, particularly in terms of assurances made with regards to the protection of participants' privacy and the confidentiality of the data, should be reported to the Committee in writing, accompanied by a progress report.
6. The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study. Adherence to the following South African legislation is important, if applicable: Protection of Personal Information Act, no 4 of 2013; Children's act no 38 of 2005 and the National Health Act, no 61 of 2003.
7. Only de-identified research data may be used for secondary research purposes in future on condition that the research objectives are similar to those of the original research. Secondary use of identifiable human research data require additional ethics clearance.
8. No field work activities may continue after the expiry date. Submission of a completed research ethics progress report will constitute an application for renewal of Ethics Research Committee approval.

Note:

The reference number ***2021/CAES_HREC/014*** *should be clearly indicated on all forms of communication with the intended research participants, as well as with the Committee.*

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Yours sincerely,

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APPENDIX X: CERTIFICATE CONFIRMING LANGUAGE EDITING

CERTIFICATE

This serves to confirm that I, Venessa de Boer, identity number 4607060025085, and residing at 59 Kelvin Road, Bramley, Johannesburg, was responsible for the language editing and proof reading of the dissertation

entitled

"ASSESSMENT OF THE POSSIBLE RELATIONSHIPS AND INFLUENCE OF CLIMATE VARIABILITY ON WATER QUALITY AND FLOW IN MAJOR RIVERS OF THE KRUGER NATIONAL PARK"

by

NICOLE CARYS CHRISTIE

Dissertation submitted in accordance with the requirements for the

degree

MASTER OF SCIENCE in **GEOGRAPHY**

at the

UNIVERSITY OF SOUTH AFRICA

Supervisor	: Prof. Anja du Plessis
Date	: 29 February 2024
Student Number	: 56082886
Signed on computer	: *V de Boer*

APPENDIX XI: PROOF OF JOURNAL ARTICLE SUBMISSION

South African Geographical Journal

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Review

Submission Confirmation

Print

Thank you for your submission

Submitted to
South African Geographical Journal

Manuscript ID
RSAG-2024-0017

Title
Possible influence of climate variability on water quality and the prevalence of physicochemical and microbial pollution in the Sabie and Crocodile Rivers

Authors
Christie, Nicole
du Plessis, A.

Date Submitted
25-Feb-2024

Author Dashboard

APPENDIX XII: TURNITIN SIMILARITY REPORT

ASSESSMENT OF THE POSSIBLE RELATIONSHIPS AND INFLUENCE OF CLIMATE VARIABILITY ON WATER QUALITY AND FLOW IN MAJOR RIVERS OF THE KRUGER NATIONAL PARK

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ASSESSMENT OF THE POSSIBLE RELATIONSHIPS AND INFLUENCE OF CLIMATE VARIABILITY ON WATER QUALITY AND FLOW IN MAJOR RIVERS OF THE KRUGER NATIONAL PARK

by N C CHRISTIE

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