ASSESSING IMPACTS OF CLIMATE CHANGE EXTREMES AND LAND USE/LAND COVER CHANGES ON SURFACE WATER QUALITY IN LETABA CATCHMENT, SOUTH AFRICA

By

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Dedication

This work is dedicated to my mom and dad, who have always been there for me with their love and support. I couldn't have done this without you. To all my dear friends and family, thank you for being a part of my journey and making the highs and lows more meaningful. This thesis is my way of saying thank you for being my rock and my cheerleaders.

Declaration

I **Grace Mohlala** declare that “**Assessing impacts of Climate Change Extremes and Land Use/Land Cover changes on surface water quality in Letaba catchment, South Africa**” 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 and that this work has not been submitted before for any other degree at any other institution.

.... **27/11/2023** ....

Signature Date

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Abstract

Water, a fundamental resource, plays a crucial role in human prosperity, and its relationship with climate dynamics and land use patterns is critical, particularly in semi-arid regions. This study assesses the impact of climate change and land-use/land-cover (LULC) changes on surface water quality within the Letaba Catchment. Remote sensing and GIS techniques provided valuable insights into land use changes, showcasing the effectiveness of the Random Forest classifier algorithm. The analysis of precipitation patterns over three key years (1986, 1994, and 2018) reveals substantial variations, uncovering the localised nature of rainfall influenced by geographical factors. The transition from 1986 to 1994 revealed noteworthy shifts, including an increase in forestry (6% to 13%) and built-up areas (11% to 12%), while water bodies experienced a significant reduction from 13% to 5%. The subsequent leap to 2018 continued this transformation, with further decreases in water bodies, forestry, and vegetation, and notable expansions in built-up areas, cultivated land, and barren land. This analysis showed the impacts of both natural processes and anthropogenic developments on the Letaba catchment's landscape. Examining surface water quality parameters, the study revealed a concerning decline in pH levels in 2018, indicating acidity and suggesting potential implications for aquatic life. Despite this, phosphorus, and Chemical Oxygen Demand (COD) levels adhered to acceptable standards, emphasizing the ecosystem's resilience to maintain nutrient balance. The analysis of the complex interaction between rainfall, LULC changes, and surface water quality parameters revelled intriguing insights. For the years 1986, 1994, and 2018, no significant connection was observed between electrical conductivity and rainfall. The examination of non-linear connections, crucial in understanding the impacts of LULC changes on the dynamics of surface water quality, highlighted the nuanced relationships captured through Spearman rank correlation. This study provides important analysis into the evolving surface water quality parameters of the Letaba Catchment, emphasising the impact of temporal dynamics, climate, and anthropogenic impacts on landscape and surface water quality.

Keywords: Climate extremes and land use changes; Surface water quality parameters; GEE; Random Forest classifier; Rainfall patterns; Pearson correlation coefficients; Spearman rank correlation.

Conference presentations

The research work has been formally presented at:

1. Scenario Building for future Water Resource Management in Limpopo workshop, **June 2023, CSIR International Convention Centre (CICC), Pretoria.**
2. 13th Faculty of Science and Agriculture (FSA) Postgraduate Research Day, **September 2023**, **Bolivia Lodge**, **Polokwane**.
3. Scenario Building for future Water Resource Management in Limpopo Feedback workshop, **November 2023**, **The Ranch Hotel and Resort**, **Polokwane.**

Table of Contents

List of Figures

List of Tables

List of Acronym

CART	Classification and Regression Tree
CDC	Centre for Disease Control
CMI	Climate Moisture Index
CMORPH	Climate Prediction Centre Morphing Technique Rainfall
COD	Chemical Oxygen Demand
DOM	Dissolved Organic Matter
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
GEE	Google Earth Engine
GIS	Geographical Information System
GLM	Generalised Linear Model
GSMaP	Global Satellite Mapping Precipitation
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resource Management
LULC	Land use and Landcover
Mg/l	Milligrams per Litter
ML	Machine Learning
MSDI	Multivariable Standardised Drought Index
NB	Naïve Bayes
NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Water Index
NPS	Non-Point Source
NTU	Nephelometric Turbidity Units

OA	Overall Accuracy
PA	Producer Accuracy
PS	Parametric System
RF	Random Forest algorithm
SAHS	South African Health Standard
SANS	South African National Standards
SANS 241	South African National Drinking Water Standard
SAWS	South African Weather Services
SDGs	Sustainable Development Goals
SPI	Standardised Precipitation Index
SRTM	Shuttle Radar Topography
SSA	Sub-Saharan Africa
SSI	Standardised Soil Moisture
SVMs	Support Vector Machines
SWBD	Surface Water Body Data
TRMM	Tropical Rainfall Measuring Mission
TSS	Total Suspended Solids
UA	User Accuracy
WHO	World Health Organisation
WIM	Water Indication Mask
WQR	Water Quality Risk
WSSI	Water Supply Stress Index
WSSIR	Water Supply Stress Index Ratio

CHAPTER ONE

INTRODUCTION

1.1. Background to the Study

Water, as a fundamental resource, stands at the core of human prosperity and societal well-being, serving as a key resource for various economic and social activities. The complex relationship between water resources, climate dynamics, and land use patterns is a sequence of greatest importance, especially in regions characterised by semi-arid conditions (Edokpayi, et al., 2022). In such areas, rainfall plays a crucial role in shaping the structure, composition, and functionality of vegetation communities. However, the looming Specter of global warming, a consequence of anthropogenic activities, introduces a precarious dimension to this delicate balance. Water resources encompass surface water bodies such as rivers, lakes, and reservoirs, as well as groundwater stored in aquifers beneath the Earth's surface (Molekoa et al., 2022).

The availability, distribution, and water quality resources are influenced by various factors, including climate, topography, land use, and human activities. Surface water consists of a significant portion of water resources and is crucial for various uses, including agriculture, industry, and domestic supply (Buenaobra, et al., 2021). The projections of future climate scenarios paint a disconcerting picture, indicating an increased likelihood of extreme precipitation events that could give rise to both droughts and floods (Dash & Maity, 2019). This climatic uncertainty poses a significant threat to agriculture, a sector intricately linked to the livelihoods of communities, particularly those in less developed countries. The Intergovernmental Panel on Climate Change (IPCC) warns that exceeding global warming levels of 1.5 °C above pre-industrial levels could have severe challenges, particularly for communities reliant on rain-fed agriculture (Ishtiaque et al., 2022).

Small-scale farmers, often the backbone of such agricultural economies, face heightened risks of crop yield reduction, soil erosion, and damage to critical infrastructure. The Letaba catchment, situated in South Africa, is not only a significant hydrological and ecological region but also a complex progression deeply impacted by various forces of changing climate extremes and land uses alterations (Djalante, 2019). These critical factors sophisticatedly interplay and wield considerable effect over the quality of surface water within this watershed. The compelling challenge arises from the undeniable impact of climate change extremes, evident through the rise in extreme weather events, which has brought about a paradigm shift in the region's climatic patterns (Zengenia, et al., 2016). Coupled with this, the dynamic changes in land use and land cover have further added layers of complexity to the hydrological and ecological dynamics in this area. The repercussions of these interconnected changes extend to the quality and sustainability of surface water, which forms a lifeline for various ecological, agricultural, and societal needs (Buenaobra, et al., 2021).

The discernible shift in climatic trends, such as increasing frequency and intensity of extreme weather events like floods or droughts, has had a significant influence on the water resources of the Letaba catchment. Simultaneously, challenges in land use practices, including deforestation, urban expansion, and agricultural modifications, significantly influence the land cover, subsequently affecting the hydrological processes and quality of surface water within the catchment (Gyamfi, et al., 2015). Human activities in the past two centuries have emerged as a predominant force in reshaping the environment, creating extraordinary magnitudes of change at a rapid pace and immense spatial scale.

Anthropogenic impacts, particularly those centred on the utilisation and exploitation of land-related resources and services, have culminated in extensive land clearing and consequential alterations in land cover and use patterns (Loukika, et al., 2021). The resultant modifications, notably in Letaba catchment, are emblematic of the extensive transformation of the landscape and environment. These radical shifts in land cover and land use, often driven by anthropogenic demands, emphasises the complexities of the interactions between human-induced alterations and the subsequent impact on the quality of surface water in this region (Molekoa, et al., 2022). As the land undergoes metamorphosis, the intricate network of streams within the catchment responds, reflecting the great interdependence of land and surface water quality.

Within the context of the Letaba catchment, the assessment of climate extremes and land use/land cover (LULC) changes on quality of water is further nuanced by the region's ecological diversity. The Letaba catchment, with its varying topography and ecosystems, introduces an additional layer of complexity to the study (Mello, et al., 2020). Unlike some other regions, this catchment encompasses a spectrum of landscapes, ranging from high-altitude areas to low-lying plains, each exhibiting distinct responses to climate dynamics and human interventions (Molekoa, et al., 2022). Furthermore, the study places a different emphasis on the implications of these environmental shifts on surface water quality within the Letaba catchment.

As climate patterns evolve and land cover transforms, the delicate balance of surface water resources is inevitably impacted (Dash & Maity, 2019). The impact on quality of water in rivers, lakes, and other water bodies within the catchment forms a critical aspect of understanding the broader consequences on the region's ecological integrity. In the pursuit of understanding and mitigating these impacts, the application of innovative technologies becomes crucial. Remote sensing, coupled with the capabilities of Google Earth Engine (GEE), emerges as a pivotal alternative tool, addressing the limitations associated with traditional ground-based methods (Dash & Maity, 2019; Djalante, 2019; Matarira et all, 2022; Mashala et al, 2023; Montoya et al, 2023).

The comprehensive and real-time data provided by remote sensing facilitates reliable analysis of large-scale environmental changes. GEE, with its cloud-based computing capabilities, enhances the efficiency of processing extensive datasets, enabling a more accurate and timely assessment of changing climate and LULC impacts on surface water quality (Matarira, et al., 2022). The abundance of data obtained through remote sensing not only provides an aerial perspective of vast landscapes but also allows for the detection of refined differences that conventional methods might overlook (Akter, et al., 2016). Located at the intersection of climate science, environmental monitoring, and technological innovation, this study initiates a comprehensive investigation into the impacts arising from climate change extremes and changes in LULC on surface water quality within the Letaba catchment.

By harnessing advanced technologies such as remote sensing and GEE, the study aims to go beyond traditional methodologies, providing an in-depth understanding of the evolving environmental dynamics (Markert, et al., 2018). In addition to remote sensing and GEE, emerging technologies such as machine learning algorithms for data analysis are being integrated into the study (Loukika, et al., 2021). These tools provide a more sophisticated understanding of the complex relationships between climate, land use, and surface water quality. By leveraging the advanced capabilities of remote sensing and GEE, this study aims to transcend conventional methodologies, providing a detailed comprehension of the evolving environmental landscape (Loukika, et al., 2021).

In the face of the Letaba catchment's challenges concerning sustainable water resource management, environmental preservation, and resilient development, this research aspires to illuminate the way forward. Through informed decision-making and a comprehensive understanding of the complex dynamics at play, this study seeks to contribute to shaping the future of this crucial South African catchments.

1.2. Problem statement

The Letaba catchment, a vital region for the sustenance of local communities, is confronted with a complex challenge arising from the confluence of climate change extremes and transformative shifts in land use/land cover (Visser et al., 2014). The escalating impacts of climate change manifest through erratic weather patterns and extreme events, intensifying existing water-related issues like shortages, contamination, and disrupted water supply within the catchment (Bhaga et al., 2020). The surge in atmospheric water vapor and the increased frequency of intense rainstorms contribute to heightened flood and drought risks, amplifying concerns about potential agricultural pollutant runoff (Kifanyi et al., 2019).

Furthermore, for ever-expanding local population's anthropogenic activities, predominantly centred around agriculture, contribute to climate change by releasing greenhouse gases (Gokool et al., 2019). This further influences the catchment's climate, leading to complex dynamics impacting surface water quality. Unsustainable agricultural practices, linked to the local dependence on farming, foster soil erosion and induce alterations in land use, resulting in the degradation of surface water quality through sedimentation (Ahmad et al., 2021). The landscape is further altered by physical developments such as road construction, industrial activities, and deforestation for agriculture, further complicating the intricate relationship between climate change, land use/land cover changes, and surface water quality in the Letaba catchment (Kanjira et al. 2014; Gokool et al., 2019; Kifanyi et al., 2019). In addressing these intricate challenges, a comprehensive assessment is imperative to unravel the complex interplay of climate change extremes and evolving land use/land cover patterns on surface water quality within the Letaba catchment. This study aspires not only to contribute to scientific knowledge but also to provide crucial insights necessary for informed decision-making towards the sustainable management of water resources in this significant South African watershed.

1.3. Rationale

Globally, surface water and marine habitats are essential to a country's economic stability, overall wellness, standard of living, and sustainable development (Murdoch et al., 2000). Extreme weather events associated with climate change, such as intense rainfall and prolonged droughts, contribute to irregular water supply, heightened water scarcity, and the contamination of water sources. As climate change, shifts in rainfall distribution, and alterations in resource utilisation become increasingly prevalent, the impact on surface water quality cannot be understated (Ahmad et al., 2021).

Insights drawn from long-term ecological observations and research facilities at the Letaba catchment, coupled with interpretive modelling simulations, emphasize the great effect of climatic variations on surface water quality (Murdoch et al., 2000; Visser et al., 2015; Rahman & Latch, 2015). Surface water quality degradation, triggered by extreme weather events such as storms, snowmelt, hot weather, or droughts, becomes a critical concern. Ongoing climate stress, leading to ecological thresholds being surpassed more easily, is anticipated to bring about severe changes in surface water quality (Thiru et al., 2020). The complex relationship among temperature shifts, oxygen level variations, and water quality regulation in ecosystems requires a comprehensive grasp of climate changes and their impact on surface water quality resources (Puchlik et al., 2022).

Land, as the fundamental source of resources for human progress and the arena for anthropogenic activities, undergoes dynamic changes driven by human-environment interactions (Tamm et al., 2018). Sustainable water resource management requires a comprehensive examination of the impact of changes in land use and land cover (LULC) on hydrology (Abuelaish & Olmedo, 2016). To address this, protecting, managing, and mitigating the diminishing freshwater resources is imperative for assessing the implications of changing climate, land use, and land cover on surface water quality (Obeidat et al., 2019).

The study aims to bridge these knowledge gaps by assessing the effects of climate change, land use, and land cover changes on surface water quality in the Letaba River catchment. Leveraging remotely sensed data with enhanced spectral and spatial resolutions, along with temporal and multiscale explanations, the research aims to establish a nuanced relationship between the associated changes in climate and LULC (Gintamo et al., 2021). A comprehensive land cover mapping spanning multiple years is crucial for understanding changes over time, evaluating past management decisions, and predicting the potential consequences of current decisions, thereby providing valuable insights for sustainable water resource management in the Letaba catchment.

1.4. Aim and objectives

i. Aim

The objectives of the study were to assess the impacts of Climate change extremes and Land Use/Land Cover changes on surface water quality in Letaba river catchment.

ii. Specific Objectives

The objectives of the study were to:

- Determine precipitation-based climate extremes in Letaba catchment.
- Analyse land use and landcover (LULC) change in Letaba catchment.
- Assess the state of water quality in Letaba catchment at different time scales.
- Assess the effects of climate extremes and LULC on surface water quality.

1.5. Significance of the study

Studying the impacts of changing climate extremes, land use, and land cover changes on surface water quality within the Letaba catchment holds crucial significance across various dimensions. Firstly, the catchment's ecosystem health directly ties to water quality, making it imperative to assess how these external effects affect its resilience to environmental stressors. Secondly, given the catchment's role in supporting water resources crucial for human consumption and agricultural activities, studying the connections between these factors and surface water quality becomes pivotal in guiding effective water resource management strategies. This knowledge helps ensure sustainable and adequate water supplies for local communities.

Thirdly, the implications for the local economy and agricultural sector are substantial, with changes in land use and land cover directly impacting agricultural practices and productivity. By understanding these effects on surface water quality, mitigation and adaptations in farming practices can be implemented to ensure a resilient agricultural sector. Additionally, changes in surface water quality due to climate and land use alterations can have significant impacts on biodiversity and the ecological balance of the region, guiding conservation and restoration efforts. Finally, the study holds essential significance for community health, where access to clean and safe water is fundamental. By understanding the impacts of climate extremes and land use on surface water quality, measures can be enacted to ensure safe water access and reduce health risks for local communities. Overall, studying these impacts is crucial for informed decision-making, policy formulation, and the sustainable management of this critical resource.

1.6. Description of the Study Area

The research area (Letaba River Catchment) is situated in the Mopani District of Limpopo province (23°39’29.0’’S, 31°03’00.0’’E) and covers around 13 400 km^2 of the area (Figure 1.1). The Groot Letaba River and its major tributaries, the Molototsi River, Middle Letaba, Klein Letaba, and Letsitele discharge the watershed (Department of Water and Forestry, 2006). The Letaba stream meanders through Kruger National Park from the convergence of the Groot Letaba and Klein rivers until it meets the Olifants river near the Mozambique border. In the Groot Letaba basin, more than 20 significant streambed dams and irrigation canals have been built (Kifanyi et al., 2019). The Letaba River catchment system is the primary source of freshwater for Tzaneen town's neighbouring settlements (and other towns such as Letsitele) and farming land. The region has an annual precipitation of 612 millimetres and average annual temperatures of 28 °C in the warmer season and 18 °C in the cold season (Golook et al., 2019). In the Letaba catchment, the mean annual runoff ranges from more than 10% of the mean annual rainfall in the moist mountainous zone to less than 2% in the dry regions of the catchment. The river basin's courses include steep bedrock and immovable boulder rapids, as well as cascades and the occasional waterfall (Gokool et al., 2017).

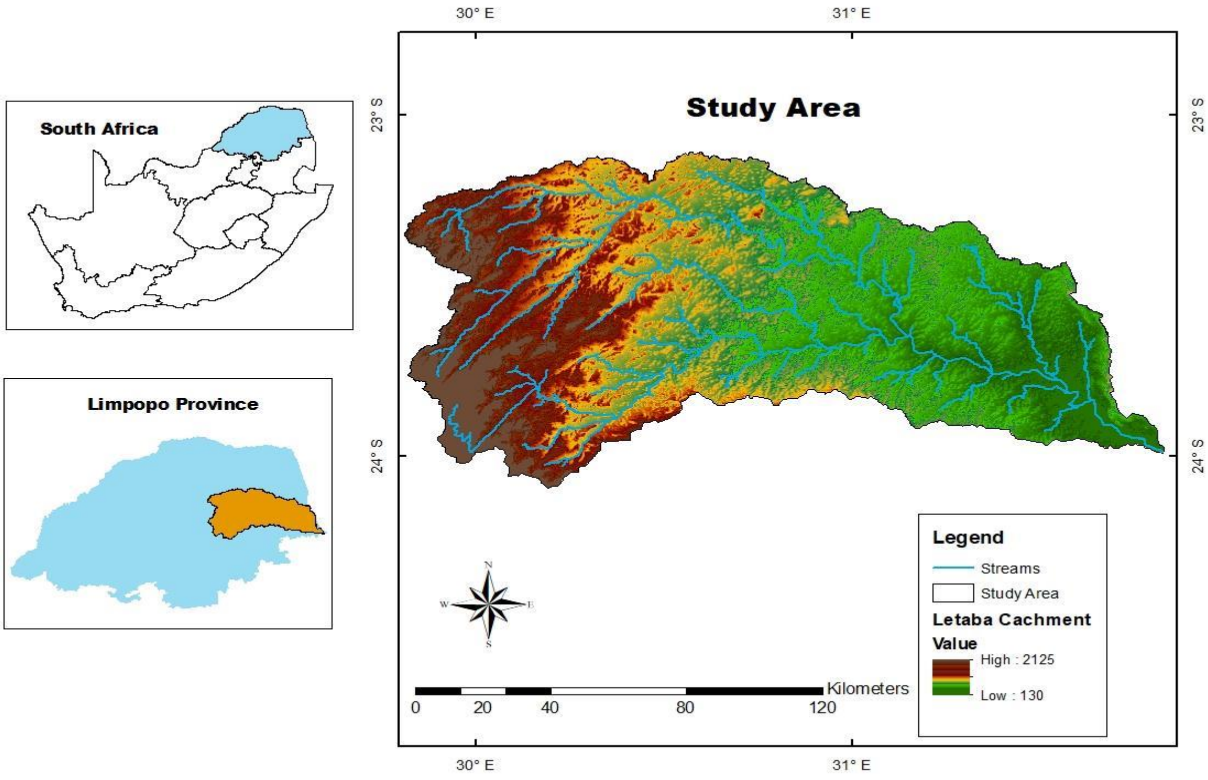


Figure 1.1: The Study Area.

1.7. Structure of the dissertation

The structure of the dissertation is structured into seven chapters, each addressing specific aspects related to the research study in the Letaba catchment:

Chapter 1: General Overview and Introduction

In this initial chapter, the study is introduced, providing a brief overview of the research's purpose, and setting the tone for the entire thesis. The chapter outlines the structure and objectives of the research, preparing the reader for the subsequent content.

Chapter 2: Literature Review

Chapter two is dedicated to an extensive literature review. It presents a synthesis of existing knowledge and research in the field of "Integrating Earth Observation and Geospatial Technologies for Assessing the Effects of Climate Extremes and Land Use/Land Cover Changes on Surface Water Quality." This chapter lays the theoretical foundation for the subsequent empirical investigations.

Chapter 3: Precipitation-Based Climate Extremes

Chapter three delves into the methodology and analysis of precipitation-based climate extremes within the Letaba Catchment. It provides an understanding of how extreme weather events are assessed and identified within the study area.

Chapter 4: Mapping Land Use and Land Cover (LULC)

This chapter is dedicated to the mapping of Land Use and Land Cover (LULC) within the Letaba catchment using remotely sensed Landsat time series data. It explains the process, data sources, and methodology employed to create these essential maps.

Chapter 5: Investigation of Surface Water Quality

Chapter five shifts the focus to the state of surface water quality in the Letaba Catchment. It explores the various parameters and qualities that define good water quality and investigates how these criteria are met or challenged in the region.

Chapter 6: Effects of Climate Extremes and LULC on Surface Water Quality

This chapter concentrates on assessing the effects of climate extremes and Land Use/Land Cover (LULC) changes on surface water quality within the Letaba catchment. It discusses the findings, interpretations, and implications of the research.

Chapter 7: Conclusion and Recommendations

The final chapter, Chapter seven, provides a synthesis of the entire research work. It presents the conclusions drawn from the study's findings and offers recommendations for future research or potential actions to address the identified issues. This chapter serves as the culmination of the thesis, summarizing the key insights and implications of the research.

The structure of the thesis ensures a logical and organized progression, starting with the introductory chapter, followed by a comprehensive literature review and then progressing through the empirical research phases. Each chapter is dedicated to a specific aspect of the study, including methodology, results, and discussion, leading to a coherent and well-rounded understanding of the research topic.

2. CHAPTER TWO

Literature Review on Integrating Earth Observation and Geospatial Technologies for Assessing Climate Extremes and Land Use/Land Cover Changes on Surface Water Quality

2.1. Introduction

Water is an important natural resource, an essential economic resource, and a socially shared resource (Mitra, et al., 2009). Water is the primary building block of the earth's ecosystem, although just 0.007% of the water resources in the globe are currently accessible to humans directly (Zhang, et al., 2023). The most significant impacts on water supplies have come from population expansion and environmental instability, and deterioration of river catchments through developments (such as agricultural activities, mining, urban developments) are no exception (Kajal, et al., 2023). One of the key concerns that affects human existence, and the growth of socioeconomic systems is compromised surface water quality.

Scholars from both local and foreign institutions are paying more attention to the problem of water contamination because of the growing deterioration of the natural ecosystem, growing industrialisation, not monitored agricultural methods, and other concerns (Akter, et al., 2016; Dash & Maity, 2019; Edokpayi, Nkhumeleni, Enitan-Folami, & Olaniyi, 2022; Taguchi, et al., 2023; Xie, et al., 2023). The quality of surface water can alter because of climatic changes, such as variations in the recurrence of extreme precipitation or droughts, through direct impacts like dilution, concentration, and physical forces like riverbank scour, as well as through indirect mechanisms like variations in the demand of water or the shift on how stormwater runoff interacts with organic substances on the surface (Sun, et al., 2005; Ryberg & Chanat, 2022).

The sixth proposed aim of the Sustainable Development Goals, provide access to water and sanitation for everyone and its sustainable management, is related to the quality of available freshwater resources (Usali & Ismail, 2010). Therefore, the contamination of the quality of water has emerged as a great environmental issue on a global scale, and it is constantly under pressure and more vulnerable due to climatic precipitation extremes, growing population, industrialisation, and changing LULC (Dlamini, et al., 2021; Han & Bu, 2023).

River catchment's surface water quality reflects the repercussions of a variety of human-caused factors, as well as natural processes such as variations in precipitation, temperature, erosion, and weathering of crustal materials (Zhang, et al., 2009; Phan, et al., 2020; Guo, et al., 202; & Vinayak, et al., 2021). Because it is required to implement a monitoring system that provides a representative and accurate estimation of the surface water quality. According to Cheng, et al. (2022), the main goal for successfully reviving the world's economy and achieving social sustainability is to improve our available water resources. Hence, numerous contributing factors including climate extremes, LULC, river morphology, and vegetation cover in areas of the catchment can contribute to the loss of the quality of these resources.

Anthropogenic developments such as river catchment policies, LULC of the environment, domestic wastewater, freshwater extraction methods, and others may alter the original river's flow and pollute the stream (Merga, et al., 2022). Dispersed water contamination is not a reflection of a discharging source that can be easily located and treated, but rather results from several interconnections between the hydrological cycle, a changing climate, and LULC patterns. For example, Zhang, et al. (2018) emphasised that Climate change and LULC are two of the most significant factors influencing hydrological changes. LULC can change the direct physiological and morphological characteristics of the landscape, as well as the soil and atmospheric boundary layer flow indirectly (Nasiri, et al., 2022).

It also has an impact on processes of hydrology through evapotranspiration, interception, infiltration, and surface runoff. Meanwhile, changes in precipitation and temperature brought on by climatic change can have a crucial influence on the hydrological conditions and spatiotemporal patterns of water resources (Zhang, et al., 2009; Frank, et al., 2015; Phan, et al., 2020; Vinayak, et al., 2021; & Han & Bu, 2023). According to Winkler, et al. (2021), nearly a third of the world's surface area has transformed in the last 60 years, and roughly 3/4 of the surface land has been impacted by humans. The biogeochemical cycle is directly impacted by the spatial distribution of water sources, which also controls the surface hydrothermal and mass balance and modifies the water, energy, and carbon cycles of the land and atmosphere, resulting in changing climate extremes (Mitra, et al., 2009).

The ecological processes, river runoff, and hydrological cycle are all crucially impacted by LULC change, which influences the safety of river water quality (Akter, et al., 2016). Therefore, considering anthropogenic land use activities is necessary for assessing surface water quality. Cheng et al. (2022) conducted a Web of Science database retrieval system using VOS Viewer 1.6.15 platform to analyse the titles and abstracts of various articles and got the keywords' network visualisation map in the scholars related to LULC and surface water quality. Studies have been predicting alterations in the quality of water due to climatic changes or reporting alterations for specific geographical areas for decades (Moore, et al., 1997; Murdoch, et al., 2000; Nearing, et al., 2004; Delpla, et al., 2009; Frank, et al., 2015; Ryberg & Chanat, 2022; Han & Bu, 2023).

In most of South Africa, higher rainfall intensities are predicted by climate predictions, with a greater percentage of precipitation occurring during extreme storm periods (Dlamini, et al., 2021). The morphology of rivers may vary as a result of altered stream power and, consequently, changing the sediment loads brought on by higher flows (Ryberg & Chanat, 2022). Modifications in suspended sediment can lead to alterations to the quality of water. Quality of the water is a direct concern for humanity, but it is also essential to preserving and promoting the ecological well-being and functioning of marine ecosystems, which are crucial for the provision of goods and services for the earth (Kajal, et al., 2023). Water quality monitoring in aquatic ecosystems is vital for effective utilisation of water resources and ensuring long-term use. For tackling the difficult challenge associated with ground-based techniques, remote sensing continues to be a crucial alternative tool (Markert, et al., 2018; Molekoa, et al., 2022; Saeid, 2022).

It offers an efficient, reliable, and comprehensive mapping approach that assesses the geographic extent and the state of surface water quality across small to large regions (Thamaga, et al., 2022). In addition to providing an inventory for monitoring and evaluating the impacts of climatic precipitation extremes and changes of LULC on water bodies, satellite remotely sensed imagery allows researchers to obtain the historical trends and current data required to assess water quality parameters (Usali & Ismail, 2010; Buenaobra, Alleto, & Manhuyod, 2021). Satellite mapping assists in gathering historical surface water quality data, essential for assessing threats, monitoring changes, and informing mitigation strategies (SUN, et al., 2005).

An expanding number of researchers are interested in developing innovative frameworks as well as reliable and spatially explicit techniques to evaluate the state of the water quality (Mitra, et al., 2009; Zhang & Shao, 2020; Shikwambana, et al., 2021; & Cheng, et al., 2022). The level of parameters that affect water quality measured at the ground and the transmittance of a water body are estimated by remotely sensed water quality data (Jin, 2022). Multi-spectral and hyperspectral remotely sensed satellite imagery, such as those taken by Landsat, MODIS, SPOT, and RapidEye, can be used to analyse how water bodies are distributed spatially through time (Thamaga, et al., 2022). As a result, there is a limited information of the factors influencing surface water quality because the acquired data on water quality lacks the necessary geographical and temporal representation.

2.2. Geographic dispersion of surface water bodies

Only a small percentage of the physical surface is covered by surface water bodies, including fresh and saltwater lakes, rivers, and reservoirs, even though they are crucial to both terrestrial ecosystems and human society (Messager, et al., 2016). Numerous agricultural, environmental, and ecological problems centre on how water is distributed spatially, and its alterations over time also play a significant role in the socioeconomic growth of people (Dlamini, et al., 2021). The management of adaptable and sustainable ecosystems as well as scientific research depend on understanding the distribution of water in space and time. Surface water bodies are vital to the global ecology and climate system because they play a significant role in the water cycle of the world (Feng, et al., 2016).

Understanding hydrological processes and managing water resources greatly depend on the geographical distribution of surface water bodies and the mapping of these bodies. In addition to being a significant global issue, a lack of water resources has significant implications for a nation's national livelihood and sustainable economic growth (Zhou, et al., 2023). South Africa is a country with severe water shortages, and the distribution of the nation's total water supplies among the provinces is uneven (Plessis, 2023). The dispersion of water resources over space and time must be studied, however the Letaba Catchment has hardly any studies that are pertinent to this topic. The water resources in Letaba Catchment feature properties such as concentrated annual dispersion of rainfall and river runoff, uneven regional and temporal patterns, and high annual variability. A non - parametric statistical technique is regularly used in hydrological trend analysis since hydrological time series typically do not follow a normal dispersion and exhibit fractal properties (Zengenia, et al., 2016). The capability of the collected data to give macroscopic, real-time, adaptive, and cost-effective information, which is significantly different from traditional in situ measurements, has led to remote sensing being a common approach for monitoring surface water bodies (Du, et al., 2016). The majority of global initiatives for mapping surface water have used coarse-resolution satellite data, such as that from the Moderate-resolution Imaging Spectroradiometer (MODIS) (Kenabatho, et al., 2017).

Surface water bodies' geometric properties, such as their land area, depth, amount of stored water, and coastline length, play a crucial part in the global hydrological cycles and biogeochemical cycles. Furthermore, the position of lakes and streams within the river network affects the velocity of water flow into and out of them, which in turn determines their hydrological retention time, or the average period of time water spends in a region (Usali & Ismail, 2010). The distribution of water is uneven practically throughout the world, hence, it must be managed and used effectively due to its ability to sustain life on Earth over a long period of time. Balasubramanian, (2017) highlighted that the earth's water content is estimated to be around 1.386 billion cubic kilometres, although 97% of that water is found in the form of saltwater-contained in seas and oceans.

Meanwhile, approximately 3% of the water resource currently available on Earth is clean water, and nearly 66.7% of it is frozen into ice caps and glaciers. (Vliet, et al., 2021) Underground water resources comprise about 30.1% of the total amount of the available water resource and only 0.3% of surface water is readily accessible on the land's surface, while the remaining 0.9% is present as water vapour and soil water . Lakes, wetlands, and flowing water such as rivers all share the 0.3% of surface water that is readily available, which leads to a limited percentage for biological water (Vliet, et al., 2021). In comparison to their population, many parts of the world, including much of northern Africa, receive extremely little water (Figure 2.1). The map displays the number of months in each location with low precipitation.

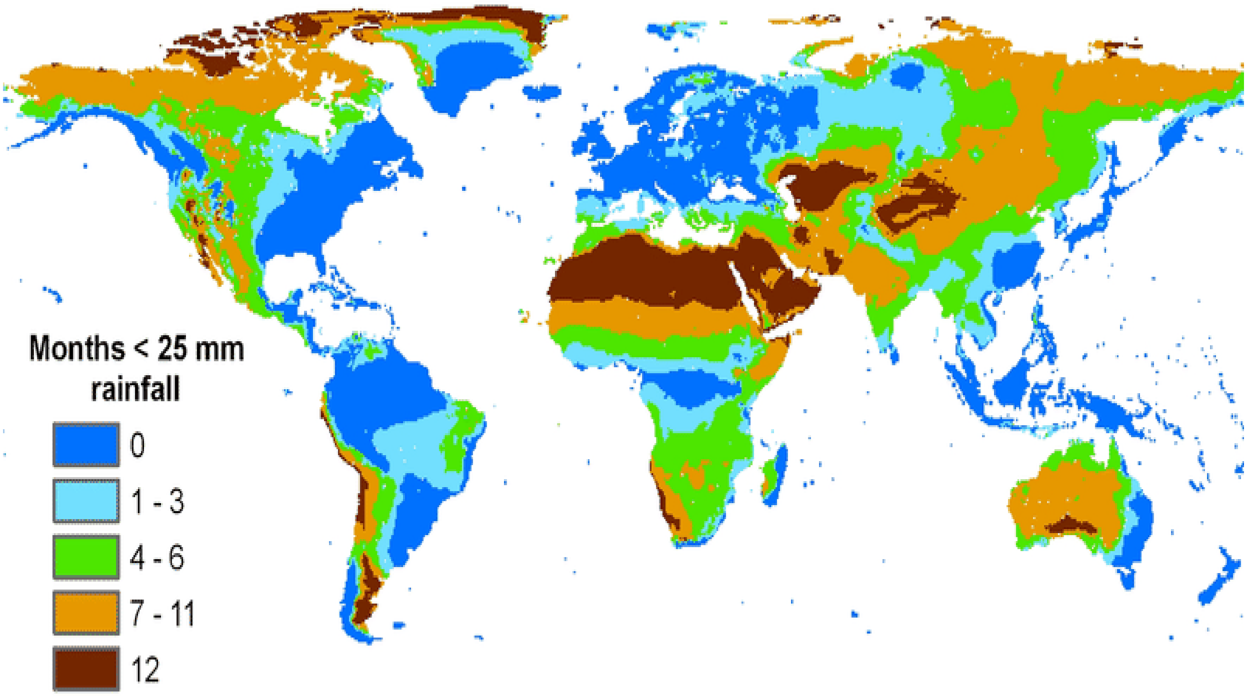


Figure 2.1: The number of months in each location with low precipitation (Hunter et al., 2010)

2.3. LULC and Climate change impacts on surface water quality

Global need for economic development (such as housing and food production) has expanded as a result of increasing population. A large portion of land has been artificially transformed into agriculture and buildings in order to provide humanity with shelter and food (Akter, et al., 2016). Humans employ large amounts of pesticides and fertilisers to maintain crop growth rates and yields in the setting of declining cultivated land and richness, which results in increasing intensity of farmland usage and adverse consequences on local water quality and environmental health (Mekonnen & Hoekstra, 2015). Urbanisation, population growth, socioeconomic needs for energy, and climatic changes all have an unprecedented impact on water supplies and the systems that support them.

In response to the global population boom, humans have built a broad array of dams and reservoirs to offer irrigation energy and water resources. However, in recent years, the rapid expansion of both light and large enterprises globally has absorbed large amounts of water resources (Mulamattathil, et al., 2015). It is anticipated that surface water quality will be impacted by hydrologic variabilities. The two main causes of surface water quality contamination have been recognized as the change in land use, Landcover and climate change.

The impact of changing climate extremes on surface water quality has, however, only been the subject of a low amount of studies (Midekisa, et al., 2017; Chotpantarata & Boonkaewwan, 2018; Mello, et al., 2020). Regional and international land use and landcover activities have expanded recently, including urban, agricultural, and grazing land uses, resulting in a considerable impact on the application of nutrients and other chemicals as well as the surface water quality of aquatic ecosystems. For example, the non-point source (NPS) pollution processes, which are intricate and reliant on seasonal and spatial scales, are influenced by patterns of land use and landcover (Matarira, et al., 2022). Most discharge from industrialised metropolitan areas typically contains significant amounts of Chloride, hydrocarbons, heavy metals, and other contaminants, while majority of agricultural runoff areas are often rich in sediments, nutrients, and pesticides.

Another critical aspect that has the potential to drastically impact on surface water quality in catchments is climate change, which includes changes in temperature and precipitation patterns. Whereby changes in temperature and precipitation were predicted to have significant effects on water supply, groundwater discharge, stormwater runoff, lateral flow, and nutrient loads (Djalante, 2019). Understanding how LULC, hydrology, and climate change conditions relate to the quality of water helps enhance the precision of risk assessments for surface water quality, which is crucial for managing water resources (Dash & Maity, 2019). However, it is still difficult to determine the main causes of poor surface water quality within a vast river system such as the Letaba river catchment.

According to a study by Cheng, et al. (2022), they discovered that the three land use categories (Figure 2.2) of agricultural land, forest land, and urban land have the highest severity, thus their paper focuses on these three LULC types. Among several other publications on the correlation between LULC, climate change and surface water quality, their analysis of published research revealed that these three land use types have the highest intensity (Plessis, et al., 2014). They discovered that while forest land was thought to have a less negative impact on surface water quality, agricultural and construction land had very detrimental overall effects on the aquatic environment.

Agricultural land generally has a substantial negative impact on surface water quality in small-scale buffers, although it has some favourable effects in large-scale buffers. Meanwhile, Delpha, et al. (2009) emphasised that altering the surface water quality parameters results in a negative impact on water quality as a result of rising surface water temperatures (such as dissolved oxygen, PH, dissolved organic matter, etc.).

As a result, it is necessary to consider temperature as the primary variable influencing practically all physicochemical equilibriums and biological processes of water. It is common knowledge that endothermic reactions frequently increase with temperature, changing all physicochemical "constants" (Thomas, et al., 2007). They went on to explain that a temperature increases of 10 °C can cause a chemical reaction's kinetics to double. Solubilisation, complexation, degradation, evaporation, and other water-related processes will be enhanced by rising water temperature, among others.

This phenomenon causes both a rise in the concentration of dissolved chemicals in water and a decrease in the concentration of dissolved gases worldwide. When it comes to rainstorms, they result in increased turbidity and organic debris in river waters, which degrade treatment efficiency (Tabari, et al., 2016). It has been demonstrated that this effect is not constant. This might be brought on by a combination of colder water, a change in the environment, and higher levels of natural organic matter in the natural water. It might also possibly be the reason why these scientists found that seasonal variations and independent of raw water turbidity significantly affect process robustness (Zengenia, et al., 2016; Dash & Maity, 2019; Mahmoudi, et al., 2021). Climate change-related variations in temperature, pH, and aqueous composition may potentially affect how impurities in water are absorbed by mineral phases.

The extensive cultivation of row crops and intensive planting practices have been consistently demonstrated to exert a substantial negative impact on river conditions. Studies reveal that the expansion of agricultural land, coupled with associated activities such as planting techniques, fertilizer and chemical applications, and agricultural irrigation, detrimentally affects surface water quality (Manickum et al., 2014; Akter et al., 2016; Mello et al., 2020; Mahmoudi et al., 2021). This adverse trend is particularly evident in the increased presence of sediment, dissolved organic matter, total nitrogen, and total phosphorus in surface water bodies as agricultural land is reclaimed (Edokpayi et al., 2022). Beyond chemical constituents, the ecological fallout is conspicuous, with a decline in various ecological indicators and riparian stability. Rivers heavily impacted by agriculture consistently exhibit poor ecological quality, signifying the far-reaching consequences of these land-use practices.

Degradation of surface water quality is most common in regions with more pronounced human activity and rapid land use change particularly in regions that are rapidly urbanising (such as Letaba catchment). The rapidly growing building sector and industries have significant effects on the environment, the water supply, and the soil as a result of urbanisation and ongoing developments. Impervious surfaces alter a variety of biological processes, including soil erosion, surface runoff, and nonpoint source pollution, all of which are major contributors to the deterioration of the aquatic environment (Akter, et al., 2016).

Peak flows and runoff consequently rise drastically as urbanisation quickens, altering the natural environment in the process. This changes the geographical and temporal patterns of surface runoff, the hydrological cycle processes in urban areas, and impacts the water balance. Watershed water quality changes are typically attributed in large part to urban areas. Urbanisation-related human actions may have an impact on the water quality of nearby surface water bodies (Anon., 2015). As a result, one of the main areas of interest for water quality study is the consistency of land use types in metropolitan areas. Many characteristics, including water storage capacity, evapotranspiration, interception, runoff, and emission, are connected to the fate and mechanism of degradation of water contaminants, making it challenging to fully understand some interactions.

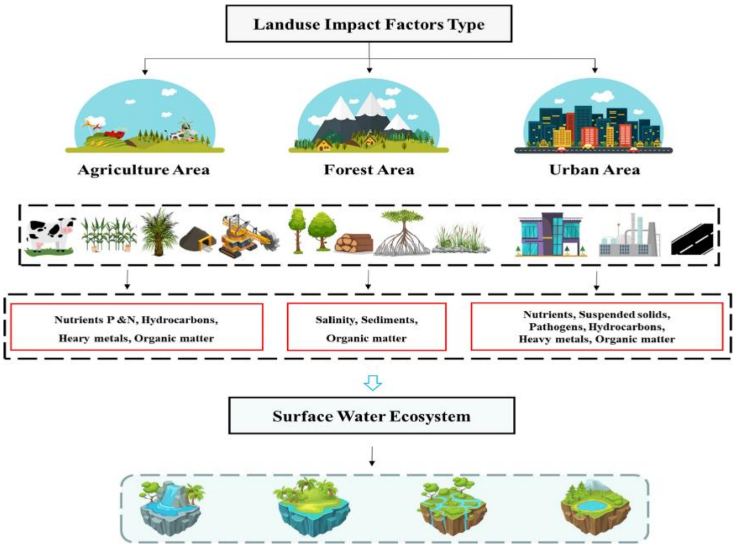


Figure 2.2: Land use and the surface water quality impact framework (Cheng et al., 2022)

2.4. The significance of Remote Sensing applications in surface water quality

Remote sensing and Geographical Information System (GIS) has covered a significant range of techniques in the sectors of agriculture, the environment, and integrated eco-environment. Remote sensing data have been the most effective method since the 1960s for learning about changes in surface water quality, land cover and land use, the mapping of features in water bodies, the effects of changing climate on surface water quality, and hydrological processes in river systems (Kadhem, 2013). Materials introduced to a surface watershed from either point or nonpoint sources have an impact on the quality of the water. Surface water quality must be managed and improved, which requires regular monitoring and evaluation (Elmahdya & Mohameda, 2023).

Hence, the development and management of water resources, hydrological modelling, flooding investigations, and other applications all benefit from spatial climate and hydrological data. Therefore, these databases' effectiveness has benefited management of water resources by increasing our understanding of hydrological processes at various scales (Akter, et al., 2016). Furthermore, a variety of techniques were employed to obtain water bodies from diverse remote sensing images, including single band density, unsupervised and supervised classification, and spectral water indices. Some of the few techniques include Tropical Rainfall Measuring Mission (TRMM) (Kummerow, et al., 1998), Climate Prediction Centre morphing technique rainfall (CMORPH), Global Satellite Mapping Precipitation (GSMaP), Normalised Difference Water Index (NDWI) (Kadhem, 2013).

For instance, in the study of Kenabatho, et al., (2017), the Notwane catchment in Botswana was used to evaluate and analyse the TRMM satellite rainfall products in terms of their correlation to the observed data. Additionally, TRMM rainfall estimates and GLM (Generalised Linear Model) based estimates of rainfall in space were contrasted (Tabari, et al., 2016). Thus, advancements in the use of remote sensing data for mapping and monitoring of surface water quality are dependent on both the accessibility of freely released satellite images (such as Landsat and Sentinel) and new technological capabilities (enhanced temporal, spectral, and spatial resolution) that can easily recognize and map water bodies on a large scale. The majority of African studies have made use of remote sensing multispectral data (Chotpantarata & Boonkaewwan, 2018; Dash & Maity, 2019; Mashala, et al., 2023).

For Example, Masocha et al. (2017) investigated whether amounts of total suspended solids (TSS) collected at 32 sampling stations in four watersheds in Zimbabwe were significantly correlated with river catchment quality assessed using remotely sensed NDVI (Normalised Difference Vegetation Index). TSS was a useful proxy for physical water quality since it provided a comprehensive assessment of physical water quality and correlates favourably with other water quality indicators including turbidity and secchi depth (Akter, et al., 2016). TSS has the additional benefit of being sensitive to changes in vegetation cover, which are easily measurable from space. Using non-linear regression, they examined the connection between mean NDVI and TSS individually for the wetter and drier catchments in Zimbabwe.

A greater comprehension of the relationship between watershed degradation and surface water quality was crucial to their study in order to tackle the threats of quality of water caused by distributed contamination. Satellite remote sensing can support field-based observations and has the potential to offer an efficient and useful tool for connecting alterations in watershed state with quality of surface water over broad spatial scales.

2.5. Remote-sensed algorithms of climate change and LULC on surface water quality

Many researchers have concentrated on land use/land cover studies due to their negative effects on the local ecosystem, vegetation, and climate change because they are often dispersed across large spatial and time scales (Plessis, et al., 2014; Mello, et al., 2020; Loukika, et al., 2021; Kadri, et al., 2023). However, it is extremely uncommon for them to be conducted simultaneously in one study. The most popular techniques for quantifying, mapping, and detecting changes in LULC patterns, as well as for analysing changes in rainfall variability and rising temperatures in regions where surface water quality is being degraded, are satellite remote sensing and GIS.

This is because these techniques use precise geo-referencing techniques, digital data formats that are suitable for computer processing, and they repeatedly collect data (Mello, et al., 2020). The accessibility of remotely sensed data with enhanced spatial and spectral resolutions, as well as temporal and multidimensional interpretations, has created momentum for the establishment of accurate relationships among different variables such as changing climate, LULC and water quality.

2.6. Climate Change algorithm analysis

One of the biggest issues facing humanity today is climate change and variability, which have taken centre stage at important international conventions. The effects of climate variability and change are negatively affecting livelihoods and posing a threat to undo previous economic advances, making Sub-Saharan Africa (SSA) one of the region’s most at risk from changing climate (Preetha, et al., 2021). The areas that are suitable for freshwater catchments are already shifting as a result of rainfall variability and rising temperatures; therefore, remote sensing is helpful in analysing rainfall trends and predicting future water quality productivity under changing climate and variabilities. Based on a parametric-system (PS) algorithm, Wang et al. (2012) created a water resources vulnerability strategy that addressed water quality challenges.

The Analytical Hierarchy Process is used in their strategy to determine the relative values of the indices taken into consideration (including drought and pollution indices). In comparison to the current Fuzzy Optimization and Gray Relational Analysis methodologies, which only permit rank analyses and qualitative level categorization, respectively, the study indicates that the PS method is more general. In the work by Kim, et al. (2019), a quantitative assessment technique for surface water quality monitoring was used to quantify the effects of droughts on water quality indicators and to diagnose surface water quality risk (WQR) by target basin to identify hotspots—areas susceptible to intense droughts. Water managers and decision-makers can acquire the WQR data for planning and decision-making related to sustainable water resource management.

They also used the Standardised Precipitation Index (SPI) algorithm to measure the drought. The SPI is spatially similar and geographically comparable, whereby a supply-side indicator, places more emphasis on the fact that droughts result in decreased precipitation, which leads to water shortages, as opposed to the relative water demands utilised in drought indices. On the other hand, Shikwambana, et al. (2021) employed runoff predictions and the climate moisture index (CMI) algorithm to measure the degree of droughts and availability of water, respectively. It is determined by taking into account soil moisture, temperature, and precipitation. As a result, the CMI and potential evapotranspiration are closely related. The CMI is a total assessment of potential availability of water that solely depends on climatic factors. The results show that, throughout the observation period, yearly minimum and maximum temperatures have increased significantly while total annual precipitation has decreased significantly. Districts in the research areas are classified as dry and water-scarce by droughts score of 0.70.

The Standardised Precipitation Index (SPI) algorithm and linear regression, Mann-Kendall and Spearman's Rho tests at the 5% significant level were used by Goic & Trajkovic (2013) to analyse the variance in precipitation on monthly, seasonal, and annual time series. Throughout the years 1980–2010, meteorological data from 12 synoptic stations in Serbia were used in the study. The results demonstrated that, at the 5% level of significance, no observable pattern was seen in the SPI-12 series. Planning the effective use of water resources, hydroelectric power, and agricultural production can be enhanced by the analysis of precipitation and SPI-12 series results.

Floods and droughts are intensive climatic extremes that frequently occur over vast areas of space and time. For the purpose of monitoring droughts and floods, a number of indicators should be created based on several factors, including precipitation, soil moisture, and runoff. In order to accurately estimate risk and make decisions, defining droughts and floods based on a single variable or index may not be sufficient. For example, Hao & Aghakouchak (2013) suggested a multivariate multi-index drought-modelling strategy employing the copula idea. The Standardized Precipitation Index (SPI) and the Standardized Soil Moisture Index (SSI) are based on probabilities combined in the suggested model, called Multivariate Standardized Drought Index (MSDI), to characterize drought and flood.

The results of the study demonstrate that MSDI predicts the beginning and end of droughts based on a combination of SPI and SSI, with the beginning of the drought being dominated by SPI and the persistence of the drought being more comparable to SSI behaviour. Overall, it is demonstrated that the suggested MSDI is a valid model for probabilistically merging various indices (Goic & Trajkovic, 2013). The difference between droughts and other climatic extremes like floods and storms, however, is that droughts last for considerably longer periods of time and are harder to predict when they start and end. For this reason, it's crucial to provide accurate and informative drought information based on a variety of indicators or variables.

2.7. LULC algorithm analysis

Land cover is referred as physical features that may be observed on the Earth's surface. It becomes Land Use when an economic purpose is incorporated. With improvements in satellite technology and processing tools, there are several ways to classify and analyse LULC satellite data based on spectral reflectance (Loukika, et al., 2021). However, one challenge is that one algorithm classifier cannot reliably produce results for LULC predictions. The performance of each algorithm classifier varies depending on a number of variables. In the study by Theres and Selvakumar (2022), Support Vector Machine and Random Forest algorithms were carried out in Google Earth engine code editor utilizing JavaScript to monitor and control hazards to the urban environmental dynamics.

Support Vector Machines (SVMs) are a group of supervised learning techniques used in regression, classification, and outliers' detection, while Random Forest (RF) algorithms are employed in classification and regression challenges. Nasiri, et al. (2022) compared seasonal composites and percentile measures, two extensively used methods for extracting time series features, and assessed how well they performed in large-scale LULC mapping using data from the Sentinel-2 (S-2) and Landsat-8 (L-8) time series. A machine learning approach called random forest (RF) was used to conceptualise the challenge (Midekisa, et al., 2017). The LULC classes were mapped using the S-2 and L-8 Operational Land Imager (OLI) time series data.

Four datasets were created using two standard composing approaches, S-2 and L-8 satellite images, and various time series set of features compositions.

Large sets of training and validation samples are typically needed to achieve good classification accuracy for remotely sensed datasets. The per-band pixel values of the four composited datasets were extracted using a number of 2280 ground polygon samples. These data were used to train the RF algorithm. RF is an ensemble learning technique that uses several decision trees (Theres & Selvakumar, 2022). Additionally, it was discovered that in this study, the algorithm outperformed other machine learning (ML) algorithms like the support vector machine (SVM). In comparison to SVM, RF required less processing time, fewer parameters, and a less amount of operator involvement. However, Mansaray, et al. (2019) discovered that the support vector machine (SVM) algorithm surpassed RF on mapping paddy rice in China by reaching overall classification accuracies of 90.80% and 89.20%. The relative overall accuracy of the outcomes from their investigation was 88%.

Thamaga, et al. (2022) also examined the effects of LULC change dynamics on the state and status of the unprotected Maungani wetland using Landsat data series (statistical analysis and SVM algorithm). In the study, generated maps from the SVM algorithm in order to comprehend the rate of conversion for the time periods between 1983 and 2019. The study's findings revealed that throughout the last 36 years, the Maungani wetland has experienced a consistent deterioration. The results of this study showed how valuable historical and archived Landsat datasets were for calculating the effects of changes in LULC on water bodies.

The Landsat dataset provides the comprehensive, readily available, and current information necessary for accurately monitoring and assessing the human impacts on water bodies. This information is helpful for improved management of local water bodies, which support rural populations' livelihoods. Whereas other researchers, like Aburas et al. (2015), employed the NDVI technique to examine spatio-temporal variations in vegetation covering and detect land cover change brought on by human activities like construction and development. However, this study primarily examines the detection of changes in landcover in the Seremban urban region, and it does not necessarily consider the effects of changes in landcover and land use on a particular variable (such as water).

In any case, their findings demonstrated that the non-vegetation class expanded between 1990 and 2010 as a result of the rising rates of built-up lands. The Seremban commercial town is located in the city's core, where the majority of alterations to the vegetative cover took place. In the research area, the land cover has changed negatively by roughly 25.53%. Despite the various algorithms used in different studies, remote sensing remains the indispensable alternative tool for tackling the difficult task associated with ground-based methodologies. It provides a functional, reliable, and comprehensive mapping approach that assesses the geographic extent and condition of water bodies across small to large areas.

By identifying baseline data on the environmental quality of water bodies, detecting threats and pressures on water bodies, and tracking any changes in their scale and condition, satellite mapping aids in better decision-making and management strategies. Numerous algorithmic techniques, including maximum likelihood, SVM, artificial neural networks, CART, RF, object-based image analysis, and decision trees, can be used to achieve the goal of any study associated with the effects of LULC on water bodies.

2.8. Mapping techniques and classification used in Climate Change and LULC change analysis on surface water quality.

For tackling the difficult challenge involved with ground-based approaches, remote sensing continues to be a crucial alternative tool. It provides a functional, consistent, and comprehensive mapping approach that assesses the geographic distribution and quality of river catchment across small to large regions (Chotpantarata & Boonkaewwan, 2018). In addition to providing an inventory for monitoring and assessing the repercussions of changing climate and LULC changes on water quality of river systems, remote sensing satellite imagery also makes it possible to acquire the historical and current information required to define surface water quality.

In order to assess the impacts of surface water quality on river catchments, determine background data on their ecosystem health, and monitor any changes in the river system extent and condition, satellite mapping is beneficial. This data is used to inform improved decision-making and management methods. In the study done by Mello, et al. (2018), for instance, map processing and spatial analysis were done using the Geographical Information System to examine the effects of LULC on the water quality of low-order streams, comparing the effects of the watershed and the riparian zone. For the purpose of producing watershed LULC maps, they used an on-screen digitizing of SPOT data obtained from the SMA-CPLA (Environment Secretariat of the So Paulo State, Environmental Planning Coordination).

The LULC classifications were water, wetlands, forest, eucalyptus, farmland, pasture, and urban, and they were pre-defined based on the technical manual on the land use of the IBGE. Utilizing a variety of methods and data sets, remote sensing has been used to map and categorize changes in climate change, land use and landcover. Particularly Landsat data have been extremely helpful in classifying various landscape elements on a wider scale. Similar to the study done by Butt, et al. (2015), all satellite data was examined by allocating per-pixel signatures and classifying the drainage basin into five classes based on the unique Digital Number (DN) values of various environmental components.

Training samples were chosen by constructing polygonal boundaries around typical sites for each predefined LULC class. The pixels contained by these polygons were used to record the spectral signatures for the various LULC types that were obtained from the satellite data. Many different supervised categorization techniques have been used extensively around the world for the analysis of climate change and LULC change (Matarira, et al., 2022). Unlike other methods, this one is more dependent on a background understanding of the subject matter and practical expertise in the field. Thus, utilizing this information, per-pixel signatures are obtained and recorded in signature files, and the raw DN of each pixel in the field are later transformed to radiance values.

Butt, et al. (2015) employed the maximum likelihood approach for the supervised classification process of the imagery, whereby the researcher controls the majority of the image classification by choosing the pixels that are indicative of the predefined set of classes. Classification accuracy, mis-classification minimisation and post-classification were improved, to use the technique more simply and effectively. Furthermore, employing data with medium spatial resolution, like that of Landsat mixed pixels, might be problematic, especially for urban surfaces, which are made up of a variety of heterogeneous characteristics, mostly made up of buildings, vegetation, roadways, soil, plants, and water.

Visual interpretation was used to resolve the mixed-pixel problem. Visual interpretation was crucial for improving classification accuracy and, as a result, the calibre of the generated land cover/land use maps. Therefore, the results produced by the supervised algorithm were significantly enhanced by visual inspection, reference data, and local knowledge. The implementation of the LULC classification is carried out to look into how the land has degraded through time and how LULC has changed, both of which may have affected the area's ability to clean itself up.

2.9. Remotely Sensed derivatives in mapping spatial distribution pattern of water bodies overtime.

Remote sensing presents a unique opportunity to provide data about water bodies in a spatially explicit way where monitoring tools are not accessible using raw data from different satellite sensors, from multispectral to hyperspectral sensors. It offers an operational tool that is timely, economical, and capable of detecting and mapping the spatial distribution and temporal dynamics of water bodies across a large geographic space (Kadri, et al., 2023). Although remote sensing offers useful prospects for water quality monitoring, this discipline is still in development, especially in the developing countries. As an illustration, this method has been utilized in a few studies to evaluate water quality levels in sub-Saharan Africa. Datasets from remote sensing can be used in many different ways (Elmahdya & Mohameda, 2023).

This data, for instance, can be used to pinpoint vulnerable water bodies, forecast their distribution, and evaluate their quality as well as the hydrological effects of LULC and climate change. Due to its continuous coverage, remote sensing also enables temporal analysis of water bodies. Radar imagery classification derivative that uses machine algorithms have been efficient in mapping open and vegetated water bodies. Machine algorithms often uses a supervised technique and calls for a substantial amount of training data, which are typically labour-intensive to gather. However, others have created techniques for automatically extracting surface water data for training through the improvement of already-existing datasets like the Landsat- and MODIS-derived static water mask (Loukika, et al., 2021).

The use of pre-existing datasets for training machine algorithms classifiers has not yet been applied to vegetated water bodies, despite the fact that this approach has a great deal of potential for use in creating an operational monitoring technique. The backscatter similarity with flat sparse vegetation landscapes is one of the major obstacles to map surface water bodies with radar imaging.

The employment of a Sand Exclusion Layer, or mask with a regularly low backscattering factor, has been used to handle such mistakes in flood mapping processes. But in order to distinguish between permanent water that would also be enclosed by the mask, this method uses relatively coarse-scale products (such as the Water Body Data (SWBD) from the Shuttle Radar Topography Mission (SRTM), the Water Indication Mask (WAM), or the global water occurrence layer (Akter, et al., 2016). Utilizing single epoch Sentinel-1 data, Hardy, et al. (2019) aimed to develop a new technique to map both exposed and vegetated water bodies. For places with open water, image objects were assigned as learning algorithm.

The worldwide water presence layer categorized the entity as exhibiting moisture for a minimum of two months annually, with selection criteria for vegetated water bodies based on a VV/VH ratio below 0.5. Among the findings, certain consistently moistened vegetative regions were also identified within this dataset, indicating sustained water presence for at least two months each year. The globally sourced water occurrence layer derived from optical data is designed primarily to delineate visible water bodies. Utilizing 59 Sentinel-1 radar datasets spanning Barotseland from 2016 to 2018, a methodology was employed to detect both exposed and vegetated water bodies. The results yielded mean accuracies of 94% (user's) and 87% (producer's) for sets of vegetated water bodies, demonstrating significant concordance with validation data.

Although, mapping dry ground over vegetated regions that had been submerged was one of the key sources of inaccuracy in the classification system that led to their identification as false positives. In this context, it is anticipated that during the early rainy season, when water is abundant and vegetation canopies are less dense, more vegetated water bodies will be mappable (Anon., 2015). Water is necessary for the well-being of the wider population, industries, and agriculture. Historically, water supply and water consumption have been managed differently in regional scale water resource analyses. The combined patterns of the two variables have not been extensively studied. For instance, Ge Sun, et al. (2005) investigated an integrated modelling approach that evaluates water by combining a model of yearly water supply with estimates of the climate, land use/land cover, and population change.

Their definition of water access was the entire amount of water that could be withdrawn from a basin. Information for three decades of historical water consumption data (1980–2007) were obtained from the Department of Marine Science's archives for a certain future period (Ishtiaque, et al., 2022). A Water Supply Stress Index (WSSI) and Water Supply Stress Index Ratio were suggested (WSSIR). At the 8-digit HUC level, the WSSI was utilized to objectively evaluate the relative magnitudes of water supply and demand. The main significant factors of water loss through evapotranspiration and hence water yield over the southern are precipitation levels and air temperature.

2.10. The implications of mapping surface water quality using Remote Sensing

Despite the reliable and sophisticated modelling algorithms and remote sensing tools, it is still difficult to assess the effects of water quality at different spatial scales. This is primarily because seized water sources and surface regions have fundamentally different water quality characteristics that are challenging to measure, especially when utilizing wideband and coarse spatial resolution sensors (Akter, et al., 2016). In contrast to surface water, which is constantly impacted by upstream flow discharge and seawater flushing, seized water sources generally never have their water quality influenced by conditions downstream.

Utilising only water samples collected from wide surface areas is insufficient for efficient surface water quality monitoring (Zavareh, et al., 2021). The assessment of the effects (such as changing climate, land use and land cover) on surface water quality using remote sensing imagery in conjunction with spatial analysis methods has thus become a crucial study area. Studies on the association between surface water quality and these effects with quantitative bounds are, however, extremely rare because prior research has concentrated on the correlation between surface water quality and these effects under imprecise limits at catchment levels (Kibena, et al., 2014; Permatasari, et al., 2017; Chotpantarata & Boonkaewwan, 2018; Loukika, et al., 2021).

Wang and Zhang (2018) used remote sensing and 3D fluorescence tools to analyse the link between the land use/cover and the quality of water. This scale was helpful for the management of quality of water, accessibility, affordability, and safety. The influence of the landscape on the quality of water depended on this scale (Zengenia, et al., 2016). Thus, determining the efficient radius of surface water contamination and preventing the origin of this contamination was the study's main challenge for effective management of surface water. The spectral properties of the study aim in multi-temporal satellite images often fluctuate due to the sensor and atmosphere, which had an impact on the collection of these image data. Therefore, an atmospheric adjustment was required for the satellite image data (Molekoa, et al., 2022). Furthermore, the spatial resolution of remote sensing satellite images is constrained, which could restrict the accurate detection of small water bodies. Although the use of remote sensing can be very advantageous, the present geospatial analysis and image processing techniques might not be adequate for understanding the properties of complicated non-linear correlations between water quality and its impacts or for forecasting future water sources (Zavareh, et al., 2021).

Therefore, in these implementations, regression models and algorithms for machine learning are employed to improve the modelling and data collection accuracy and provide greater prediction capabilities. Regardless of these implications, numerous noteworthy studies have looked into the use of remote sensing data for routine water quality monitoring. Hence, it is necessary to use freely accessible sensors, like Landsat and Sentinel, to address the aforementioned issues with the monitoring, estimate, and mapping of water bodies. These sensors provide a significant revisit interval, a wide scope of view, better resolution, and are reliable.

2.11. Conclusion

Numerous researchers have investigated many aspects of water bodies, including their properties and functions, the effects of changes in land use and land cover, and the classification and deterioration of these water bodies. Due to the changing LULC, increasing population, industrialisation, and changing climatic conditions, water quality resources are under prolonged stress and becoming progressively vulnerable. As a result, it is necessary to put in place a monitoring system that offers a reliable assessment of the surface water quality. The geographic distribution of surface water bodies and their mapping are crucial for comprehending hydrological processes and managing water resources.

Due to their detrimental effects on the local ecosystem, vegetation, and climate change as well as the fact that they are frequently scattered across broad spatial and temporal scales, many researchers have focused on land use/land cover studies. It is quite rare for them to be done in single research all at once, though. Satellite remote sensing and geographic information systems are the most widely used methods for quantifying, mapping, and detecting changes in LULC patterns, as well as for analysing changes in rainfall variability and rising temperatures in areas where surface water quality is being compromised.

3. CHAPTER THREE

Determine precipitation-based climate extremes in the Letaba Catchment, South Africa

3.1. Introduction

The Letaba Catchment, situated in the Mopani District, has emerged as a critical area for studying the impacts of extreme weather events driven by precipitation patterns. Mackellar et al. (2014) highlight the variability in precipitation, emphasizing the region's vulnerability to various weather and climate-related challenges. In recent years, the rising occurrence of extreme weather events such as floods, droughts, and heatwaves has raised significant concerns within the Letaba Catchment, posing risks to both human livelihoods and the natural environment (Andersson et al., 2020; Mahmoudi et al., 2021; Graham et al., 2022). These events are increasingly recognized as part of the new climatic norm as the effects of climate change become more pronounced.

The changing climate conditions, including rising temperatures and altered precipitation patterns, have resulted in diverse impacts on the region, affecting migrations and causing health issues (Govender & Grab, 2019). These repercussions extend beyond the immediate aftermath and affect vital societal systems, particularly healthcare, food security, and water resource management (Djalante, 2019). In the context of South Africa's economic disparities, the effects of extreme weather events vary across regions, reflecting inequality within the country (Gyamfi et al., 2016).

The impact of precipitation-based climate extremes in the Letaba Catchment varies due to South Africa's socio-economic disparities. The region, known for its varying climatic conditions and natural beauty, is increasingly vulnerable to the adverse impacts of extreme weather events, particularly those related to precipitation patterns (Mahmoudi et al., 2021).

Climate extremes, influenced by human activities, have warmed the planet, resulting in shifts in weather patterns and an increase in the frequency and intensity of extreme weather events. In the Letaba Catchment, these extremes manifest as floods, droughts, and heatwaves, impacting both the natural environment and human society (Dash & Maity, 2019). These events have far-reaching consequences, disrupting agricultural practices, causing food shortages, and prompting mass migrations, leading to health problems and societal unrest (Preetha et al., 2021). The frequency and intensity of these extreme events are increasing, linked to ongoing climate change. However, their impacts are not uniform across the region, reflecting inequality in social vulnerability and adaptation capacity (Graham et al., 2022).

Understanding the variability of vulnerability and adaptation potential is crucial for developing effective strategies to mitigate the effects of extreme weather events in the Letaba Catchment. Striving for a fair and balanced approach that considers the diverse challenges faced by different communities is essential for building a more resilient and sustainable future for all individuals in this ecologically rich area.

3.2. Materials and Methods

3.2.1. Precipitation data Collection and sources

Collecting precipitation data is a fundamental step in understanding precipitation patterns, especially when studying climate extremes in a specific region like the Letaba Catchment (Nyamwanza & Kujinga, 2016; Sun, et al., 2018). In this study, the precipitation data in the form of rainfall was obtained from South African Weather Services (SAWS). SAWS is a reputable source for meteorological information, including rainfall measurements, and plays a crucial role in providing valuable data for research related to climate and weather patterns in South Africa (Bopape1, et al., 2021). The use of SAWS data ensures the reliability and credibility of the rainfall information, making it a dependable source for understanding precipitation patterns in the Letaba Catchment and supporting the study's objectives.

The collection of rainfall data from the South African Weather Services involved a systematic and precise process (Figure 3.1). The process began with obtaining permission and access to rainfall records maintained by the South African Weather Services. These records were typically stored in digital formats, commonly in Excel spreadsheets. The Excel format allowed for structured storage of the data, organized by date, time, and location of rainfall measurements. Weather stations across the Letaba Catchment area were responsible for monitoring and recording rainfall measurements at specific intervals. These stations are strategically positioned to capture a broad representation of the region's precipitation. Each station maintains its dataset, capturing rainfall information daily, monthly, or annually, depending on the station's operational procedures.

The collected data includes various parameters related to rainfall, such as the amount of rainfall measured in millimetres, the date and time of measurement, and the geographical location of the weather station. Quality control measures are often implemented to ensure accuracy and consistency in the collected data (Zengenia, et al., 2016). This involves checks for possible errors, outliers, or inconsistencies, as well as data validation procedures to maintain data integrity. Once obtained, the Excel format provided a convenient way to store, manage, and analyse the collected rainfall data. Analysis techniques, such as statistical methods and trend analysis, were then applied to interpret the data. These analyses aimed to identify patterns, trends, and variations in rainfall within the Letaba Catchment over specific time frames. Overall, the collection of rainfall data from the South African Weather Services in Excel format involved the systematic acquisition and organization of crucial information that forms the basis for understanding precipitation patterns and their impacts on the Letaba Catchment in South Africa.

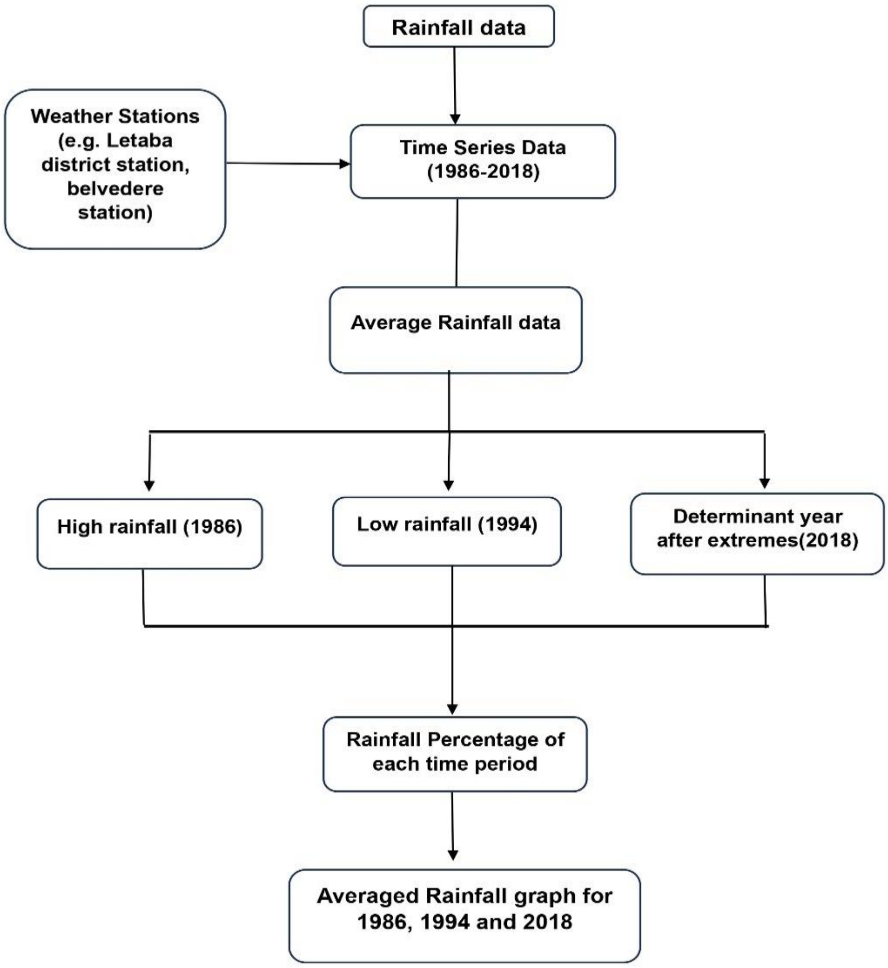


Figure 3.1: Flow chart illustrating the use of rainfall information in the research.

3.2.2. Rainfall data pre-processing

The selection of the study's timeframe is from 1986 to 2018, which was initially necessitated by the availability of data from the South African Weather Services (SAWS). Since the study's aim is to assess climate extremes, therefore it was important to determine these climate extremes within the timeframe. This process entailed the identification of specific years characterized by both high and low precipitation levels. The emphasis was on extreme high and low rainfall events, and this entailed carefully examining the years when these extremes occurred. Following the determination of extreme climate events, the subsequent step involved investigating the consequences and developments that unfolded in the aftermath of these extremes, all within the same designated timeframe.

SAWS provided weather data from multiple weather stations across the Letaba Catchment. However, due to varying station coverage within the stipulated timeframe, a deliberate selection process was initiated. This entailed identifying the weather stations that consistently provided data within the specified timeframe, thereby ensuring a comprehensive and consistent analysis. As a result, data from seven weather stations—such as Belvedere, Letaba district station and Hans Merensky Hoerskool—were chosen for the study due to their consistent and reliable data coverage over the designated timeframe.

The chosen weather stations were pivotal in providing a cohesive dataset that captured the dynamics of rainfall patterns within the Letaba Catchment. By focusing on these specific stations with complete data, the study aimed to analyse the variations in extreme precipitation events and their repercussions, observing the subsequent changes in the region's environmental, hydrological, and socio-economic aspects. The examination of data from these selected weather stations enabled a detailed assessment of the impact and the effects of extreme high and low rainfall events. This approach facilitated a nuanced understanding of how the extremes influenced the local environment, ecosystems, and communities, providing valuable insights into the implications and changes that occurred post these extreme precipitation events within the region.

3.2.3. Statistical Analysis of the climate extremes determination

In this study, we focused on specific years within our timeframe. We selected 1986 as a year with unusually high rainfall, 1994 as a year marked by notably low precipitation and 2018 which was chosen as the determinant variable to evaluate the conditions after all the determined climatic extremes have occurred. The comprehension of the study was conducted through the analyses of the historical rainfall patterns within the Letaba Catchment, whereby daily data received from various weather stations was aggregated and transformed into monthly averages, effectively representing the period from January to December. This approach aimed to create a standardized representation of monthly data for the years 1986, 1994, and 2018 from each weather station, allowing for a thorough statistical analysis.

Given the study's broad scope covering the entire Letaba Catchment, it was crucial to ensure a comprehensive and inclusive representation of the region's rainfall patterns. To achieve this, the approach was, since the study did not focus on any weather station, rainfall data was then averaged for each month across all the weather stations. Daily data obtained from various weather stations were processed to generate monthly averages, offering a representation of the period from January through December. Subsequently, the average monthly data from all weather stations were combined and further averaged to represent specific months. The process entailed averaging the collected data from all weather stations for each specific month to represent monthly rainfall data of each year (Table 3.1).

Table 3.1: Average rainfall data

	Rainfall Data (mm)		
Months	**1986**	**1994**	**2018**
January	7	13	7
February	14	10	12
March	7	6	6
April	20	7	5
May	15	3	4
June	6	1	2
July	1	2	2
August	6	4	2
September	3	5	3
October	14	13	6
November	14	5	5
December	11	13	7
Total Average	10	7	5

3.3. Results and Discussion

3.3.1. Monthly Rainfall Patterns in the Letaba Catchment: A Comprehensive Analysis of Average Precipitation

The climate in South Africa exhibits a diverse range of rainfall patterns across various regions. The country typically encounters its primary rainy season during the summer months, which generally spans from October through to March. Following this, a drier period prevails from April to the early days of October. Within this overarching timeline, the core summer months typically extend from December to March, while the winter months are often observed between May and August. However, the onset and duration of the rainy season can vary significantly depending on the specific geographic location within South Africa. The rainfall distribution is influenced by various factors including the geographical positioning of the area, its altitude, and its proximity to different water bodies such as oceans, rivers, and lakes (Dash & Maity, 2019). These factors collectively contribute to the distinctiveness in the amount and timing of rainfall in various parts of the country.

Regions closer to coastal areas, for instance, tend to experience different precipitation patterns compared to inland areas. Similarly, areas situated at higher altitudes often encounter different rainfall distribution compared to lower-lying regions (Zengenia, et al., 2016). These diverse geographic and environmental factors play a significant role in shaping the unique and varied rainfall patterns observed throughout South Africa. The Letaba catchment typically conforms to the established monthly precipitation patterns commonly observed across South Africa. This consistency in precipitation trends serves as a hallmark of the region's climatic distribution, providing a baseline for understanding its seasonal rainfall expectations. The analysis of rainfall trends within the Letaba catchment for the years 1986, 1994, and 2018 unveils noteworthy variations in precipitation patterns (Figure 3.2).

In 1986, the area experienced a substantial surge in rainfall, marking a significant departure from the anticipated average. The heightened levels of precipitation during this year were notably above the usual standards for the region. Conversely, in 1994, the recorded rainfall levels displayed a considerable decrease, signifying a notable contrast to the unusually high levels witnessed in 1986. The subsequent assessment for 2018 demonstrated a further decline in rainfall compared to 1994. Notably, the average rainfall in 2018 depicted a substantial reduction, indicating a significant decrease in overall precipitation when contrasted with the preceding years.

These divergent patterns of rainfall accumulation across the specified years emphasize the inconsistent and fluctuating nature of precipitation in the Letaba catchment. Understanding these fluctuations is crucial for assessing the region's water resource management, ecological balance, and the potential impact on various sectors reliant on consistent or predictable precipitation levels. The stark contrasts observed among these years prompt a deeper exploration of the factors influencing these irregularities and their long-term implications for the local environment and water systems. In 1986, the Letaba region experienced an exceptional increase in rainfall, surpassing the anticipated average levels of precipitation. This surplus of high rainfall brought various advantages, particularly in agriculture. The increased moisture supported crop growth, significantly enhancing yields and benefiting agricultural productivity. Moreover, the abundant rainfall replenished water reserves such as rivers, lakes, and aquifers, contributing to improved water availability for domestic, agricultural, and industrial use. It also fostered healthier ecosystems by promoting greener landscapes and supporting a diverse range of flora and fauna.

However, along with the positive effects, the elevated precipitation brought certain challenges. The surplus rain caused potential flood risks, leading to damage in infrastructure, loss of property, and posing risks to human safety. Moreover, the excessive rainfall triggered soil erosion, impacting agricultural productivity and causing sediment build-up in water bodies. Additionally, the increased runoff increased the risk of water contamination, potentially carrying pollutants into water sources, thereby impacting surface water quality. In contrast, 1994 experienced a significant decline in rainfall compared to the relatively high levels observed in 1986. This marked reduction in precipitation had multifaceted consequences.

The decrease in rainfall negatively affected crop production, resulting in reduced crop yields, impacting food production and agricultural livelihoods. The decline also contributed to water scarcity, leading to shortages in agricultural, industrial, and domestic water supply, affecting communities and ecosystems. The lower rainfall during this period also stressed ecosystems, impacting biodiversity and wildlife habitats, potentially causing long-term ecological disruptions. Continuing this trend, 2018 demonstrated a continued decrease in rainfall compared to 1994. This decline had substantial implications, particularly concerning water availability and agricultural productivity. The decreased precipitation signified a notable reduction in overall volume compared to previous years.

These fluctuations highlight the dynamic and variable nature of climate patterns within the Letaba catchment. Understanding these variations is crucial for effective water resource management, environmental sustainability, and disaster preparedness in the region. Analysing these climatic anomalies provides valuable insights into the challenges and opportunities posed by changing precipitation patterns in Letaba catchment.

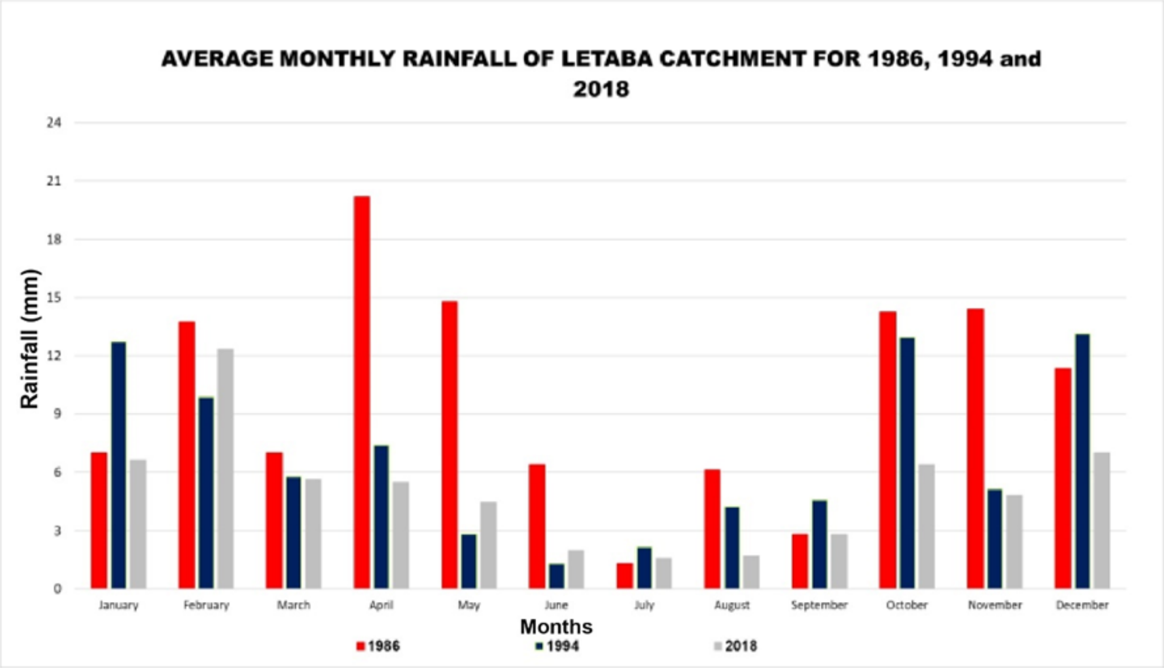


Figure 3.2: Average monthly rainfall at Letaba catchment for 1986,1994 and 2018

3.3.2. Comparative Analysis of Annual Rainfall Percentages: Trends in Precipitation Patterns for 1986, 1994, and 2018

The analysis of annual rainfall percentages within the Letaba catchment for the years 1986, 1994, and 2018 reveals intriguing trends, particularly when examining summer and winter months. These specific monthly comparisons between the years uncover substantial variations in precipitation levels, indicating the fluctuating nature of rainfall patterns in this region. During the summer months, the year 1986 displayed a mix of lower and higher rainfall percentages when compared to 1994. In December 1986 experienced a lower percentage of rainfall at 36%, contrasting with 1994's relatively higher 42% figure. The subsequent months showed substantial differences, with January 1986 receiving only 26% of rainfall, significantly less than the notably higher 48% observed in January 1994. However, in February 1986 exhibited a surge in rainfall at 39%, slightly higher than the 33% recorded in 1994. Likewise, March 1986 continued this trend with a higher percentage of 36%, while 1994 noted a slightly lower 32%.

Transitioning to the winter months, the disparities between the years became more pronounced. May 1986 saw a substantially higher rainfall at 68%, while May 1994 experienced a significantly reduced 14%. Similarly, June 1986 displayed a pronounced contrast with 67% against 11% in June 1994. Moving forward, July 1986 presented a lower percentage of 20% compared to a remarkable surge of 40% in July 1994. In August 1986 maintained a higher rainfall percentage of 50% in comparison to 1994's 33%. However, the overall annual rainfall for 1986 significantly exceeded that of 1994, demonstrating a marked difference with 45% against 31%. These distinctive variations highlight the dynamic and fluctuation nature of rainfall within the Letaba catchment.

The notable differences in summer and winter months between 1986 and 1994 underscore the irregularities and differences in precipitation patterns over different periods. Understanding these variances becomes instrumental in comprehending the region's water resource management and environmental implications, guiding strategic decisions for managing water resources and ecological balance within the Letaba catchment. While 1986 and 1994 exhibited distinctive trends in rainfall, 2018 presents a different scenario, where the year did not bring significant differences compared to the other two years. Throughout the summer months, the data for 2018 presents varying rainfall figures in comparison to the convention years, 1986 and 1994 (figure. December 2018 had a notably low rainfall percentage of 22%, contrasting sharply with the higher values recorded in both 1986 and 1994.

January 2018 reflected similar rainfall to that of 1986, with a percentage of 26%, deviating from the trend observed in 1994. However, February 2018 demonstrated higher rainfall percentages compared to 1994, standing at 33%, and March 2018 exhibited similar rainfall to that of 1994, recorded at 32%. Transitioning into the winter months, May 2018 received slightly more rainfall than in 1994, with a percentage of 18%, while June 2018 exhibited higher rainfall compared to 1994 at 22%. July 2018 matched the amount of rainfall observed in 1994 at 40%, and in August 2018, a mere 17% was recorded, significantly lower than the other years. Despite certain months in 2018 equating or surpassing specific periods of higher rainfall in other years, the annual percentage for 2018 concluded at 23%, marking a lower overall annual rainfall when compared to the preceding years.

This analysis emphasizes the noteworthy disparities in rainfall percentages across the different months of 2018 compared to the convention years, highlighting an erratic pattern within the Letaba catchment. Despite occasional similarities or surpassing rainfall levels from specific months in previous years, the overall annual percentage remained lower in 2018. Understanding these varying trends in precipitation for 2018 in contrast to 1986 and 1994 is vital for comprehending the evolving nature of rainfall within the Letaba catchment. These insights offer critical data for evaluating the region's water resource management and formulating strategies for sustainable resource utilization in the future.

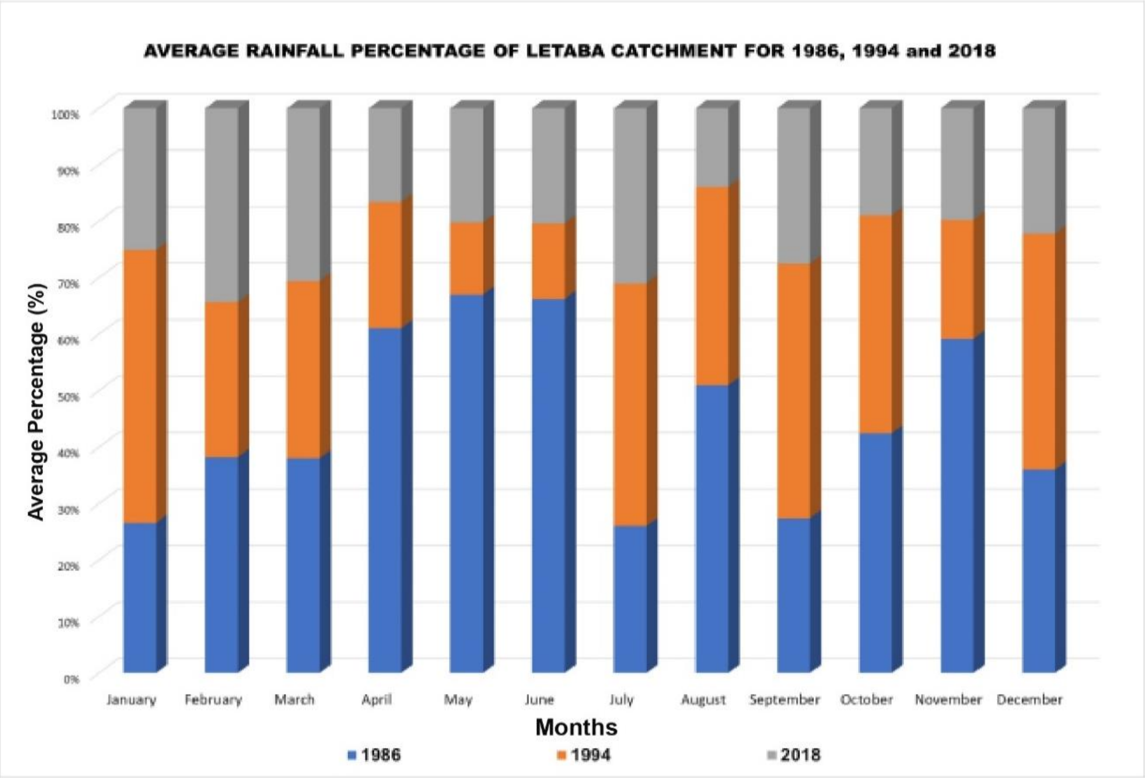


Figure 3.3: Average percentage of rainfall for 1986, 1994 and 2018 at Letaba Catchment.

3.4. Conclusion

The analysis of precipitation-based climate extremes in the Letaba catchment has unveiled the intricacies and fluctuations in rainfall patterns influenced by diverse geographical and environmental factors. This region demonstrates a conformity to established monthly precipitation trends, while experiencing distinct summer and winter characteristics. The variability in the rainy season's onset and duration highlights the localised nature of precipitation influenced by geographic positioning and proximity to water bodies. Examining the years 1986, 1994, and 2018, 1986 revealed substantial rainfall advantages that significantly impacted agriculture, ecosystem health, and water availability, although it was accompanied by challenges such as flood risks and soil erosions.

In contrast, 1994 witnessed a notable decrease in rainfall, adversely impacting crop production, water resources, and ecosystems. This trend continued into 2018, indicating a consistent decline in rainfall, affecting both water availability and agricultural output. These variations underscore the inconsistent nature of precipitation in the Letaba catchment, posing challenges across various sectors and emphasising the necessity for a comprehensive understanding to effectively manage water resources and plan sustainably. The importance of comprehending and analysing these climatic anomalies cannot be understated; it is crucial for adapting to changing precipitation patterns.

This highlights the urgency for robust water resource management, preservation of ecological balance, and strategic planning. The dynamic nature of rainfall in the Letaba catchment presents challenges but also opportunities, emphasizing the need to adapt to these changing climatic patterns for a more sustainable and resilient future.

4. CHAPTER FOUR

Map Land use and Land cover (LULC) using remotely sensed Landsat time series data in Letaba catchment, South Africa

4.1. Introduction

Land use and land cover (LULC) is a global phenomenon that greatly impact ecosystems, human well-being, and the trajectory of sustainable development. Land use encompasses the various activities and purposes for which land is utilised, ranging from agriculture and urban development to forestry and conservation (Matarira, et al., 2022). On the other hand, land cover characterises the physical coverage of the Earth's surface, encompassing features like forests, grasslands, urban areas, and water bodies. Changes in LULC occur due to human activities such as urbanization, deforestation, and agriculture, leading to consequences for ecosystems, biodiversity, and overall environmental health (Chotpantarata & Boonkaewwan, 2018).

This study embarks on a comprehensive exploration of this complex changes of LULC (Figure 4.1), directing its focus toward the Letaba catchment in South Africa. Within the dynamic context of the Letaba catchment, the ever-evolving patterns of LULC changes serve as a captivating lens through which the implications of human interventions on the landscape come into play. The Letaba catchment, situated in the heart of South Africa, presents the nature of environmental challenges shaped by a number of factors. The increase in population, urbanization, encroachment of agricultural and urban areas into once pristine forests, and the degradation of vital forest resources collectively contribute to the transformative shifts in land utilisation patterns (Buenaobra, et al., 2021).

These shifts, in turn, exert a depressing impact on the hydrological dynamics of the watershed, intricately altering surface runoff rates and volumes. The imperative to comprehend the driving forces behind changes in land use becomes increasingly apparent, particularly in the global context of transitioning from natural landscapes to more anthropogenically impacted areas (Matarira, et al., 2022). This study places recognition on the importance of understanding and managing these changes, underscoring the significance of embracing sustainable land use practices to maintain environmental equilibrium.

However, this imperative is met with challenges, especially in the rural landscapes of sub-Saharan African countries, where consistent monitoring of LULC changes remains an ongoing challenge (Elmahdya & Mohameda, 2023). The Letaba catchment, with its distinctive geographical features and rich historical tapestry of land utilisation, emerges as an ideal canvas for the in-depth exploration of the impact of human interventions on land use. Remote sensing technology, coupled with the innovative cloud-computing excellence of the Google Earth Engine platform are used to unravel the complex of LULC changes over time (Mashala, et al., 2023). Remote sensing, with its expansive coverage over temporal and spatial dimensions, opens unprecedented opportunities to delve into the historical archives of land cover changes, offering a clear understanding on their implications on the landscape.

Inspired by the successes of related studies that harnessed remote sensing for mapping LULC changes, this study aspires to contribute unique insights into the complex evolving changes of LULC patterns within the Letaba catchment. Implementing advanced digital data-based change detection techniques, the study aims to assess various nature of LULC alterations and recommend improved strategies in managing these changes (Loukika, et al., 2021). In essence, the study aims to map and enhance our comprehension of the impact of changing land use practices on the complex terrain of the Letaba catchment and similar areas, facilitating the development of well-informed and sustainable land management approaches.

4.2. Materials and Methods

A graphical illustration of a systematic representation used to assess and map changes of LULC is shown in Figure 4.2. This evaluation encompasses five defined stages. **Firstly**, satellite imagery was acquired to secure essential spatial data. **Secondly**, the acquired satellite images underwent a series of pre-processing steps to enhance their quality and suitability for subsequent analysis. **Thirdly**, the process entails supervised classification, in which the different land cover types are classified into specific categories based on their spectral signatures. The **fourth stage** entails a critical accuracy assessment which was performed to validate the classification outcomes, involving a thorough comparison with ground-truth data or other high-quality reference sources.

Lastly, building upon the supervised classification and accuracy evaluation, the creation of detailed LULC maps takes place, as well as the change detection that occurred from 1986 to 2018 and this offers a comprehensive spatial depiction of alterations in land cover within the study area. This visual representation in Figure 4.2 serves as a valuable guide for comprehending the step-by-step process applied in the analysis of LULC mapping.

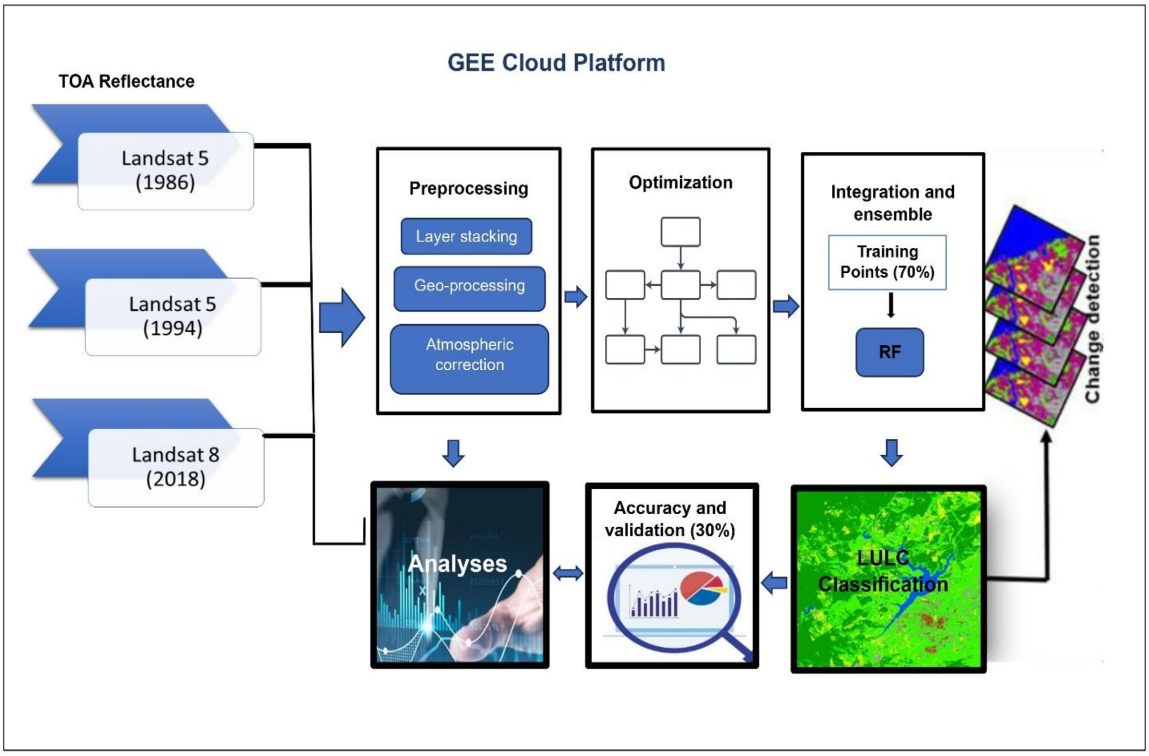


Figure 4.2: Systematic flow chart showing methodological steps.

4.2.1. Ground observations data

High-resolution data sourced from Google Earth Engine (GEE) played a crucial role in the collection of a substantial dataset of the study comprising 1020 training data points. Whereby within each training class, there were a total of 170 training points allocated for analysis and classification. These data points served as essential ground truth references for the years 1986, 1994, and 2018. The primary objective of integrating the ground truth references into the GEE platform was to facilitate the training process for generating highly precise LULC maps for the Letaba watershed. It is worth noting that this methodology adhered to well-established machine learning evaluation standards.

The imported training data points were thoughtfully partitioned into two distinct sets: 70% of the data were allocated for training purposes, while the remaining 30% were reserved for validation. This division ensured rigorous evaluation and validation of the classification process, thereby verifying the accuracy and reliability of the generated LULC maps. To enhance the comprehensiveness and accuracy of the classification, the Letaba watershed was categorized into seven distinct land cover types. This systematic and detailed approach to data collection and integration was instrumental in ensuring the precision and robustness of the final LULC maps for the years 1986, 1994, and 2018.

4.2.2. Data acquisition and processing

The study collected Landsat 5 and Landsat 8 Top of Atmosphere (TOA) reflectance data, utilizing "LANDSAT/LT05/C02/T1_TOA" for 1986 and 1994 and "LANDSAT/LC08/C02/T1_TOA" for 2018 from the Google Earth Engine (GEE) cloud database, accessible through the provided link: https://earthengine.google.com/. These datasets offer rich spectral information with Landsat 5 providing 7 bands and Landsat 8 offering 13 bands, all at a spatial resolution of 30 meters. To ensure data reliability, a crucial step involved filtering out unwanted elements like clouds and shadows. This was achieved by applying the 'QA_PIXEL' function to eliminate these undesirable elements from the images, enhancing the dataset's overall quality. The process of filtering and creating mosaics was accomplished using the 'filter' function, setting specific date parameters from January 1st to December 31st for the respective years.

Furthermore, the resultant images were confined to the study area's boundaries using the 'filter. Bound() function, ensuring that the analysis focused solely on the defined region of interest. Following this, the dataset underwent essential preprocessing steps to standardize and prepare it for analysis. Normalization techniques were applied to rectify variations in illumination and minimize the impact of clouds, ensuring a more uniform dataset for subsequent analysis. Subsequently, the images were subjected to enhancement and smoothing methods, refining the data quality to facilitate accurate analysis and interpretation. This meticulous data acquisition and processing approach was pivotal in curating high-quality, filtered images suitable for in-depth analysis of land use and land cover changes across the specific time periods. The detailed and standardized data preparation is fundamental for accurate remote sensing analysis, ensuring a reliable foundation for assessing changes in the landscape over time.

4.2.3. Image classification

The Random Forest (RF) classifier algorithm is a powerful machine learning method extensively utilized for assessing the impacts of land use and land cover (LULC) changes using remote sensing data (Phan, et al., 2020). Its application within platforms like Google Earth Engine (GEE) has proven invaluable for analysing and classifying changes occurring over different time periods, such as 1986, 1994, and 2018. RF is an ensemble learning technique known for its immunity to data noise and overfitting, making it particularly adept at handling remote sensing data. Its robustness stems from the construction of multiple de-correlated decision trees. These trees are bootstrapped, meaning that they are trained on random subsets of the data, and their predictions are aggregated to make a final classification. The final output is determined by the mode of predictions from these individual trees.

The strength of RF lies in its ability to manage high-dimensional data while maintaining high accuracy in classification tasks. Numerous studies (Mello, et al., 2020; Preetha, et al., 2021; Mashala, et al., 2023) and comparisons have demonstrated that RF often outperforms other popular classification methods, including Support Vector Machines (SVM), classification and regression tree (CART), Naive Bayes (NB), in various applications (Avci, et al., 2023). RF's ensemble approach, which combines the predictions of multiple decision trees, tends to yield superior accuracy and robustness, particularly when dealing with complex and multidimensional data. Enhanced Processing Speed through Variable Selection: RF incorporates a feature selection mechanism by evaluating the importance of variables or features (Avci, et al., 2023). This allows for the identification of the most informative attributes, contributing to faster processing times. By focusing on the most relevant features, RF can streamline the classification process and reduce computational demands.

This sets it apart from other traditional classification methods such as maximum likelihood, single decision trees, or single-layer neural networks. Studies (Chotpantarata & Boonkaewwan, 2018; Buenaobra, et al., 2021; Elmahdya & Mohameda, 2023; Avci, et al., 2023) have demonstrated the superiority of RF in achieving better accuracies and managing complex datasets. This algorithm's versatility and robustness make it an ideal choice for analysing LULC changes over time, offering a more reliable and accurate assessment compared to many other conventional methods. Its ability to create an ensemble of trees and aggregate predictions makes it more resilient to noise and outliers, leading to more robust predictions. Overall, the Random Forest classifier stands out as a highly effective and efficient method for classifying remote sensing data, especially in the context of assessing land use and land cover changes, owing to its ability to manage complex data, resist overfitting, and deliver superior accuracy in classification tasks.

4.2.4. Classification Accuracy Assessment

In the context of land use and land cover (LULC) change mapping, accuracy assessment plays a pivotal role in understanding the reliability and fidelity of classification outcomes concerning ground truth information (Elmahdya & Mohameda, 2023). For the assessment of LULC change maps created for the years 1986, 1994, and 2018, a meticulous accuracy evaluation process was undertaken. To evaluate the classification accuracy for each year, a subset of 250 reference points (representing 30% of the dataset) was utilized for validation. Each year, including 1986, 1994, and 2018, underwent this evaluation to generate a confusion matrix within the Google Earth Engine (GEE). Key assessment metrics such as producer accuracy (PA), overall accuracy (OA), and user accuracy (UA) were calculated, providing insights into the agreement between the ground truth and the classification outcomes.

Kappa was excluded from the evaluation due to its criticized suitability for accuracy assessment in certain contexts. The field data samples were divided into two categories: 70% for training and 30% for testing purposes. The 70/30 split approach aimed to create a substantial training dataset while preserving a significant portion for computing accuracy statistics. This strategy ensures that the classification model is well-trained on a large representative dataset, while the remaining portion is reserved for validation and assessment. An error matrix was employed as a critical tool to evaluate the accuracy of the classification process, measuring overall accuracy, user accuracy, and producer accuracy concerning the reference data.

It provided a comprehensive assessment of the agreement, omission, and commission among the classification results and the training data. By analysing the error matrix, the study was able to identify and understand how classification errors occurred, offering crucial insights into the nature and causes of misclassifications or discrepancies. This rigorous accuracy assessment process aids in validating the accuracy and reliability of the LULC change maps for different years, enabling a more informed understanding of the classification outcomes and their alignment with the actual landscape conditions. It forms the bedrock for reliable and insightful analysis of land cover changes over time.

4.2.5. LULC Change Detection

The assessment of existing Land Use and Land Cover (LULC) types within the Letaba catchment over different time frames—1986, 1994, 2018, and the cumulative change between 1986 and 2018—was conducted to estimate and analyse alterations in the landscape. This evaluation allowed for the quantification of LULC changes across these defined time periods using a post-classification comparison technique. This method involves independently classifying images from different time frames and then comparing the resulting LULC maps to identify changes. The advantage of this approach lies in its ability to provide comprehensive information regarding both the magnitude and direction of changes occurring in the landscape.

By assessing changes on a pixel-by-pixel basis, this technique reveals alterations in land cover or land use classes between different time periods, despite potential spectral differences due to atmospheric conditions, sun angle variations, or other sensor-related factors. This approach is valuable for understanding shifts in the environment over time. The post-classification comparison technique identifies changes by overlaying LULC maps from different dates that were generated through the classification process. By scrutinizing the differences between these maps, it becomes possible to determine which areas have undergone change and discern the nature of the specific changes within each land cover/land use class. As a result of this comprehensive analysis, an overall change detection map was produced for the entire period from 1986 to 2018.

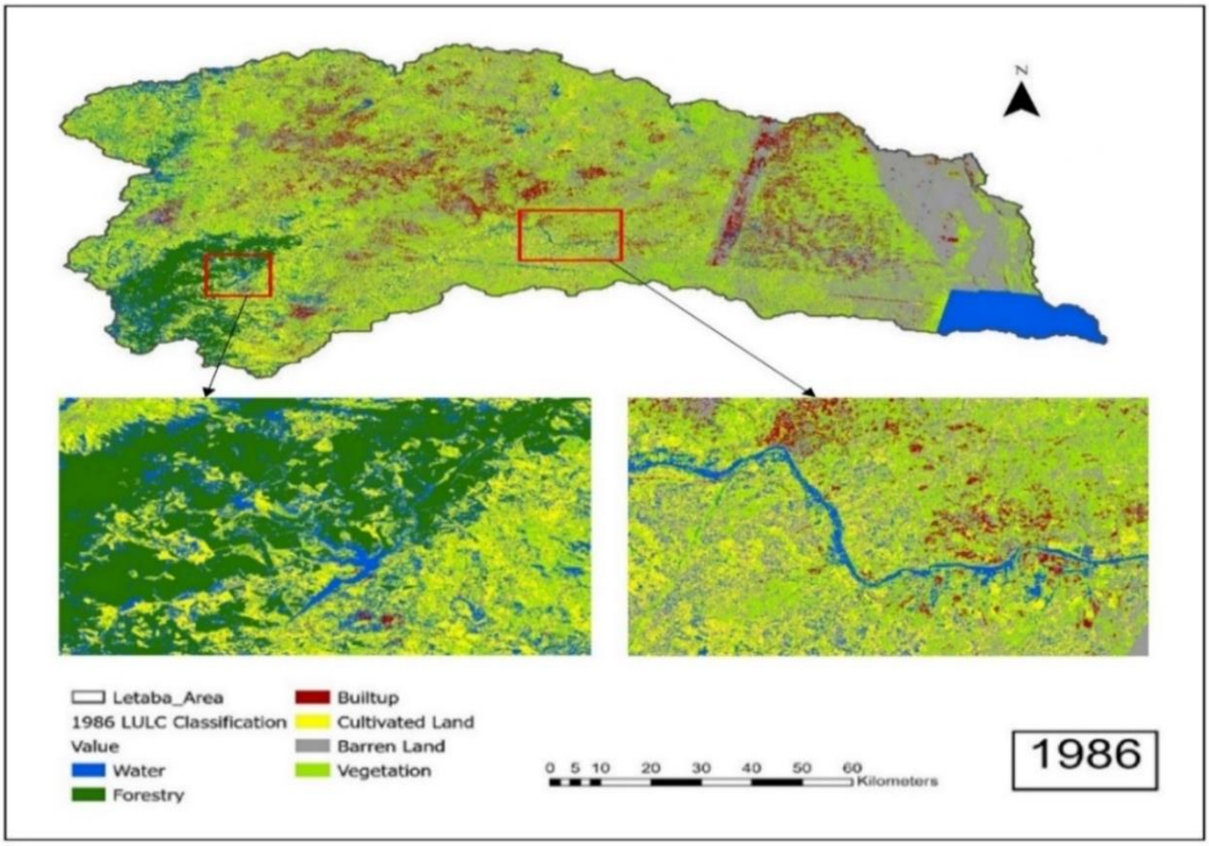
This map visually represents the cumulative LULC conversions, offering insights into the various changes occurring within the landscape. For instance, this approach could reveal trends such as an increase in built-up areas or a significant decrease in the extent of wetlands, providing a clear illustration of the evolving landscape and the shifts in specific land cover and land use classes over time. In summary, the change detection method applied in this study provides a detailed and systematic analysis of LULC alterations over different time periods, offering a valuable understanding of the dynamics of land transformation within the Letaba catchment area.

4.3. Results and discussion

4.3.1. Satellite-derived LULC change (1986-2018)

The RF-derived maps show a comprehensive insight into the evolving land use patterns within the Letaba catchment over the specified timeframe (Preetha, et al., 2021). In 1986, the region experienced favourable conditions, characterised by abundant rainfall that not only sustained rich vegetation but also contributed to the presence of diverse aquatic habitats. This indicated a crucial ecological system supported by adequate water resources. The contrast observed in the 1994 maps pointed to a notable shift, with decreased precipitation leading to water scarcity. The impact on the hydrological dynamics was evident, emphasizing the sensitivity of the catchment to climatic variations. As the analysis extended to 2018, challenges persisted with observable degradation of water bodies. Despite these ongoing issues, the adaptive capacity of the ecosystem and effective resource management strategies became apparent.

The observed challenges in the Letaba catchment underscore the vulnerability of the landscape, indicating potential limitations in current environmental management practices to effectively mitigate the adverse effects of changing climatic conditions. The ongoing issues, including the degradation of water bodies, signal a strain on the resilience of the catchment. This suggests that additional efforts may be required to enhance adaptive capacity and address the complex interplay between climate, land use, and water resources. These findings accentuate the urgency for intensified monitoring efforts and a reassessment of existing management approaches to ensure the ecological integrity of the Letaba catchment. The dynamic nature of environmental systems demands a proactive and adaptive stance, necessitating a deeper understanding of the intricate relationships between climatic variables and land use changes. The challenges observed may serve as a call to action, prompting a revaluation of strategies to foster a more sustainable and resilient future for the Letaba catchment.



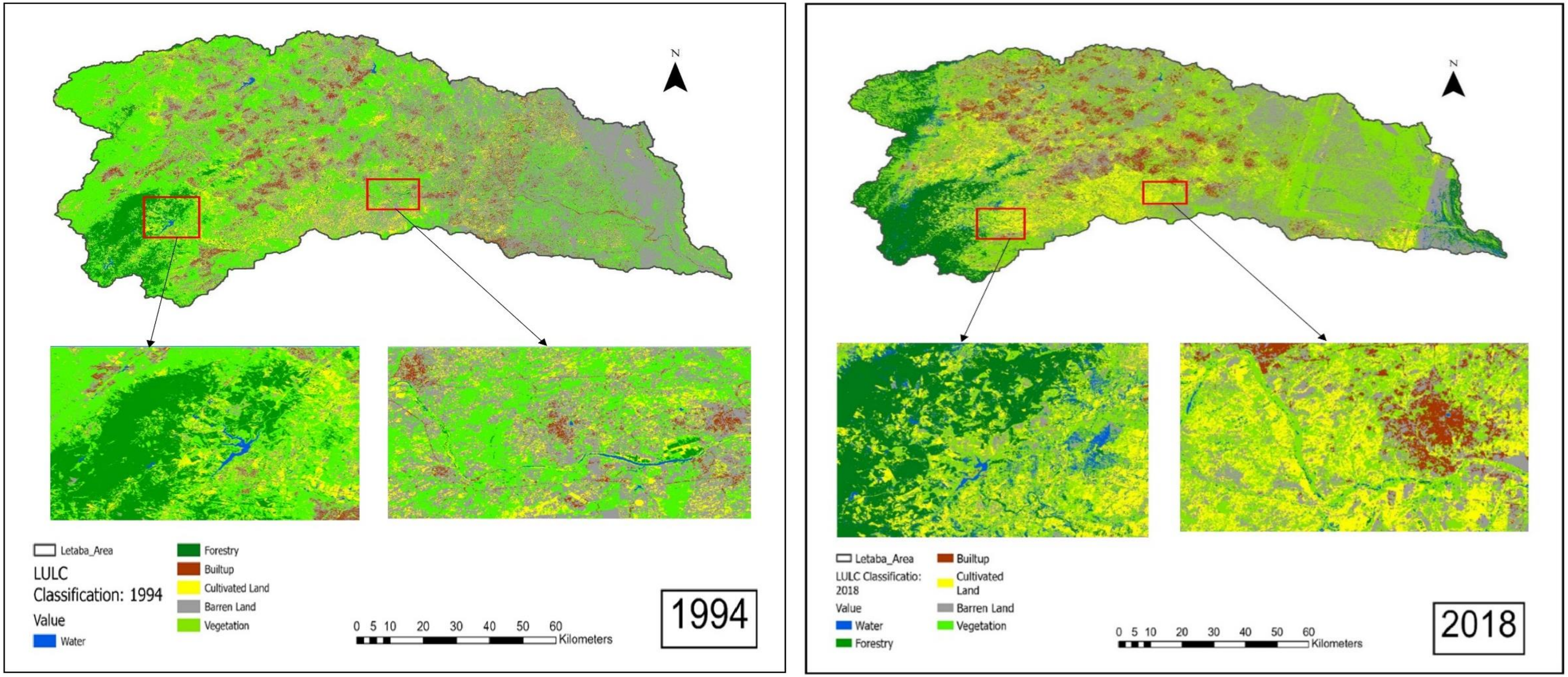


Figure 4.3: Spatial patterns representing the identified changes in land use and land cover maps during the periods 1986, 1994, and 2018

4.3.2. Spatio-temporal change analysis

The in-depth spatio-temporal analysis of Land Use and Land Cover changes within the Letaba catchment provides a substantial understanding of the complex dynamics that have unfolded over the study period, spanning critical years of 1986, 1994, and 2018. These shifts, as shown in Figure 4.3 and comprehensively tabulated in Table 4.1 illustrate a complex narrative of changing anthropogenic impacts on the region's land utilisation patterns This assessment, conducted through the lens of Remote Sensing and utilising the Random Forest (RF) classifier, explores the transformations in land cover patterns for the selected years 1986, 1994, and 2018. These three distinct time points serve as temporal standard, allowing for a comprehensive assessment of the changing environmental aspects impacted by both natural processes and anthropogenic activities.

In the foundational year of 1986, the Letaba catchment exhibited a landscape dominated by vegetation, constituting a substantial 38% (4936 km^2) of the total area. This was closely followed by Barren Land, covering 32% (4113 km^2), while built-up areas accounted for 11% (1528 km^2), and forestry carved out its space at 6% (803 km^2). Water bodies, crucial components of the catchment's hydrological system, comprised 5% of the landscape, reflecting a delicate balance that could be influenced by the anticipated rainfall and climate patterns. However, a closer examination of the 1994 maps revealed a noticeable decline in precipitation, leading to a decrease in water bodies and a subsequent impact on the catchment's hydrological equilibrium. The water bodies, which covered 602 km^2, experienced a substantial reduction, emphasising the sensitivity of these ecosystems to climatic variations.

Despite this, the transition from 1986 to 1994 witnessed overarching trends whereby forestry changed (from 6% to 13%), built-up areas (from 11% to 12%), and cultivated land (from 5% to 6%). Conversely, water bodies underwent a great reduction from 13% to 5%, indicative of the complex interplay between climate and land use changes. The subsequent leap to the year 2018 marked a continued transformation in the Letaba catchment's LULC dynamics. Whereby water bodies further decreased to 256 km^2 (2%), forestry contracted to 706 km^2 (5%), and vegetation slightly decreased from 4679 km^2 (34%) to 4411 km^2 (32%). In contrast of this, built-up areas expanded from

1532 km^2 (12%) to 1763 km^2 (13%), cultivated land grew from 767 km^2 (6%) to 905 km^2 (7%), and barren land surged from 3846 km^2 (28%) to 5859 km^2 (43%) (Figure 4.5). This temporal trajectory underscores the dynamic nature of the Letaba catchment's landscape, shaped not only by natural processes but significantly influenced by anthropogenic activities.

The observed fluctuations in LULC patterns highlight the vulnerability of the catchment's ecosystems to both climatic variations and human-induced changes. Moreover, the complex change between land use alterations and the subsequent impact on water bodies signifies the delicate balance required for sustainable environmental management. Furthermore, the trend analysis from 1994 to 2018 indicates that water bodies, forestry, and vegetation were influenced by other LULC changes, signifying the interconnected nature of land use dynamics. This observation reinforces the impact of human activities on essential resources within the catchment, particularly highlighting the effects of industrial developments.

The comprehensive classification results from 1986 to 2018 indicates the complex interplay of LULC changes, emphasising the need for sustainable and informed management strategies to mitigate adverse impacts on the Letaba catchment's ecological integrity. In essence, the rich LULC landscape of the Letaba catchment, as shown through this analysis, revels a need for narrative of adaptability, resilience, and the ongoing dialogue between human activities and environmental responses.

Table 4.1: Area summary for LULC coverage between 1986 to 2018 (km^2).

	AREA COVERAGE (km^2)					
LULC Classes	**1986**	**Percentage (%)**	**1994**	**Percentage (%)**	**2018**	**Percentage (%)**
Water	1824	13	602	5	256	2
Forestry	803	6	1016	8	706	5
Built-up Area	1528	11	1532	12	1763	13
Cultivated Land	708	5	767	6	905	7
Barren Land	4113	30	3846	31	5859	42
Vegetation	4936	35	4679	38	4411	32

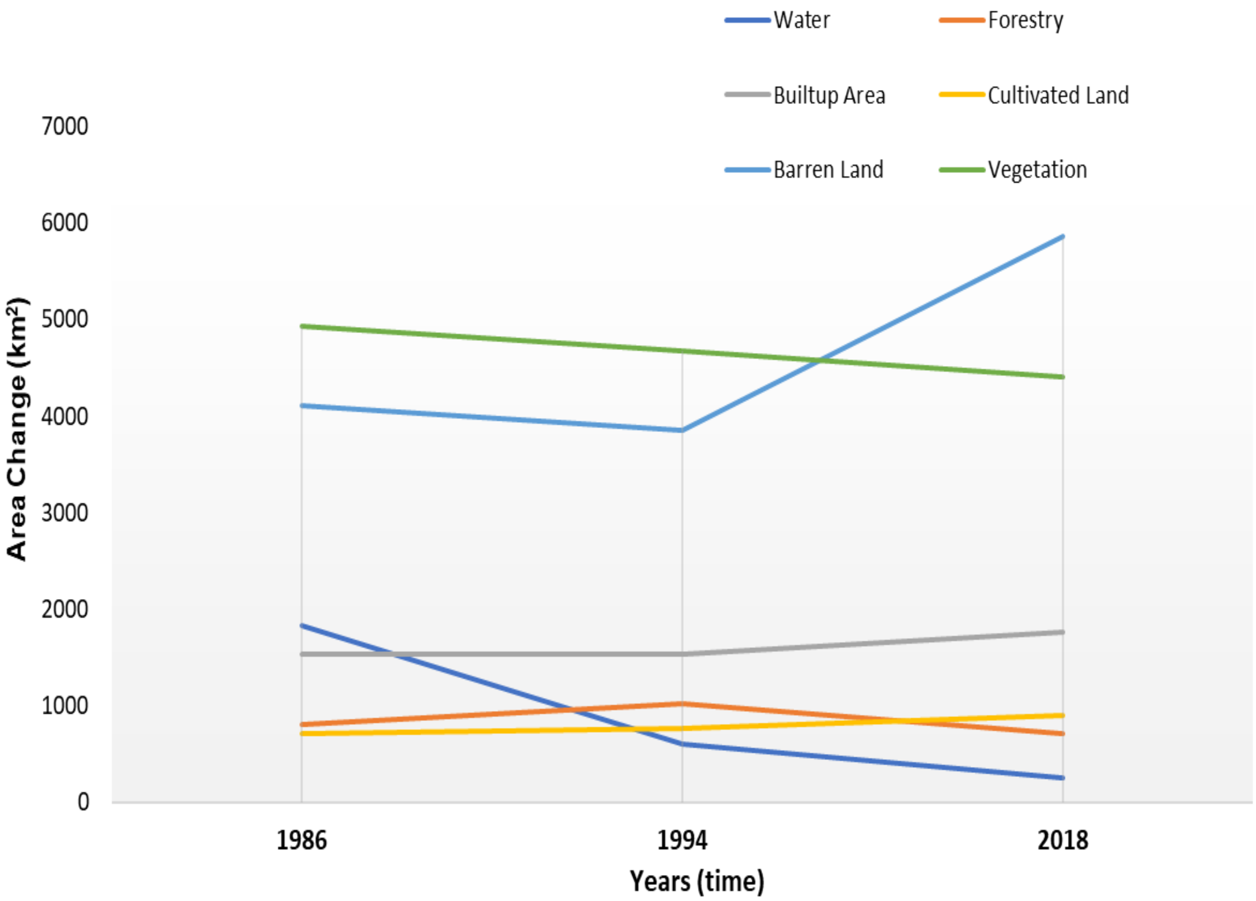


Figure 4.5: LULC change time series variation from 1986 to 2018.

4.3.3. LULC classification and accuracy assessment

The Random Forest (RF) classifier exhibited remarkable proficiency in delineating various Land Use and Land Cover (LULC) classes, achieving overall accuracies (OAs) of 0.95, 0.99, and 0.93 for the years 1986, 1994, and 2018, respectively (Figure 4.6). To enhance the precision assessment, User Accuracy (UA) and Producer Accuracy (PA) values were computed for each class across all years. Despite the inherent challenge of water bodies being in close proximity to other classes, the RF model adeptly captured nuances in the upstream region of the Letaba watershed. Notably, the water bodies class demonstrated outstanding accuracy, attaining a flawless 100% in both PAs and UAs for the year 1986, maintaining consistently high values ranging from 95% to 98% across all temporal periods.

Similarly, the accuracy of the water bodies class remained consistently elevated, with PAs ranging between 95% and 100%, and UAs also ranging from 95% to 100%. In contrast, the barren land class exhibited relatively lower classification accuracies, with PAs fluctuating from 88% to 100% throughout all temporal frames. This underscores the efficacy of the RF classifier in precisely categorizing diverse LULC classes, providing a robust foundation for further analyses and a nuanced interpretation of landscape changes within the Letaba catchment across the studied time span.

Table 4.2: Derived error matrix for LULC classification accuracies: Overall Accuracy (OA), Producer Accuracy (PA) and User Accuracy (UA) for the 1986, 1994, and 2018

1986	***Water***	***Forestry***	***Built-up Area***	***Cultivated Land***	***Barren Land***	***Vegetation***	***Total***	***UA (%)***
Water	65	0	0	0	0	0	65	100
Forestry	0	50	0	0	1	0	51	98
Built-up Area	0	0	44	0	2	0	46	96
Cultivated Land	0	0	2	38	0	0	40	95
Barren Land	0	0	1	0	58	1	60	97
Vegetation	0	2	0	0	5	61	68	90
Total	65	52	47	38	66	62	**329**	
PA (%)	100	96	94	100	88	98		

1994	**Water**	**Forestry**	**Built-up Area**	**Cultivated Land**	**Barren Land**	**Vegetation**	**Total**	**UA (%)**
Water	52	0	0	1	2	0	55	95
Forestry	1	43	0	0	1	0	45	96
Built-up Area	1	0	33	0	2	0	36	92
Cultivated Land	0	0	0	53	0	0	53	100
Barren Land	0	0	4	1	60	0	65	92
Vegetation	1	0	0	2	3	74	80	93
Total	55	43	37	57	68	74	**334**	
PA (%)	95	100	89	93	88	100		

2018	**Water**	**Forestry**	**Built-up Area**	**Cultivated Land**	**Barren Land**	**Vegetation**	**Total**	**UA (%)**
Water	55	0	1	0	0	0	56	98
Forestry	0	44	0	0	0	0	44	100
Built-up Area	0	0	65	2	0	0	67	97
Cultivated Land	0	0	1	67	0	2	70	96
Barren Land	0	1	0	0	60	2	63	95
Vegetation	0	0	1	1	0	68	70	97
Total	55	45	68	70	60	72	**370**	
PA (%)	100	98	96	96	100	94		

4.3.4. Change detection measurements that occurred during 1986-2018

The dynamic analysis of land use and land cover (LULC) changes within the Letaba Catchment from 1986 to 2018 reveals a substantial decline in the spatial extent of water bodies, forestry, and vegetation, contrasting with notable changes in other LULC classes. This period witnessed a great reduction in the spatial expanse of critical classes such as water bodies, forestry, and vegetation, underscoring the significant impact of growing population pressures and intensified anthropogenic interventions. Figure 10 graphically shows the consequential changes, emphasising the extensive conversion of once-dominant land covers, namely the substantial decrease in vegetation coverage (4936 km^2), forestry areas (803 km^2), and water bodies (602 km^2).

In their stead, a visible expansion of built-up areas, cultivated lands, and barren land has unfolded, indicating the dynamic interconnection between human activities and the environmental landscape. The various trends prompt an in-depth exploration of the driving forces behind these alterations, considering factors like urbanization, agricultural expansion, and industrial developments that collectively contribute to the changing environmental footprint of the Letaba Catchment. Understanding these complex changes becomes imperative for informed decision-making in sustainable land management, emphasizing the need for holistic strategies that balance human development with ecological preservation.

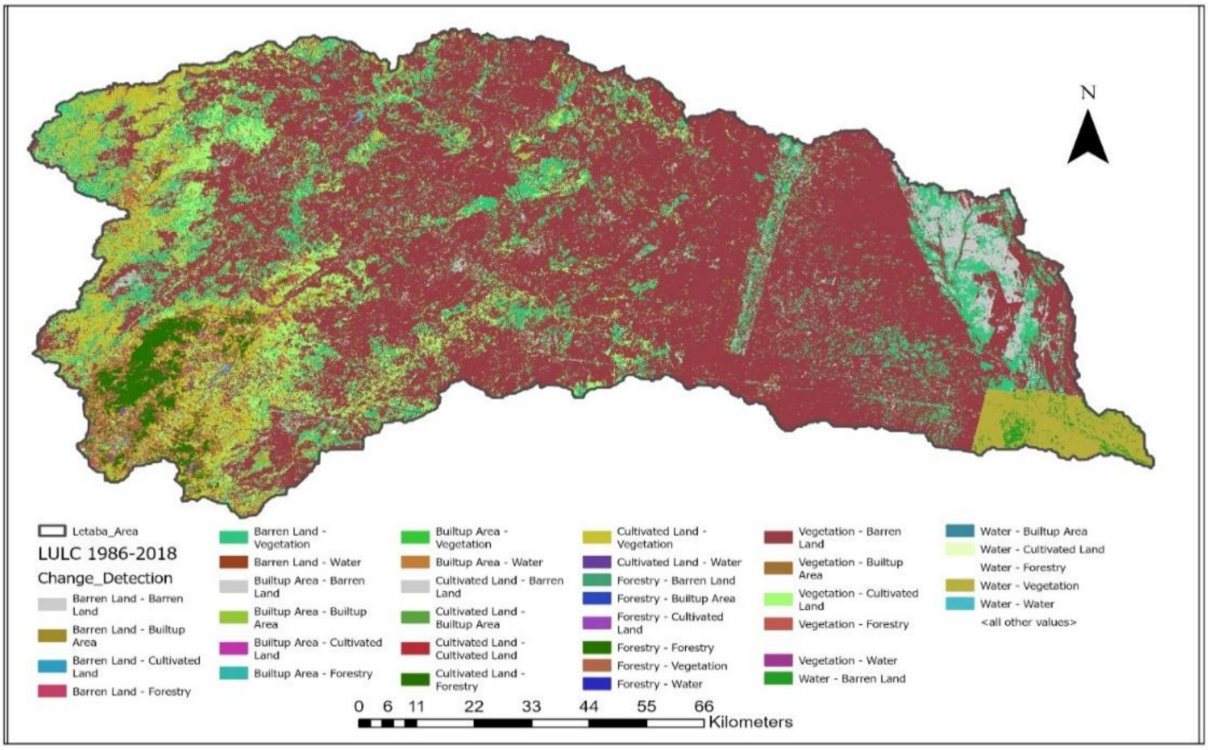


Figure 4.7: Comprehensive overall conversion of LULC changes in Letaba catchment during analysing process (1986-2018)

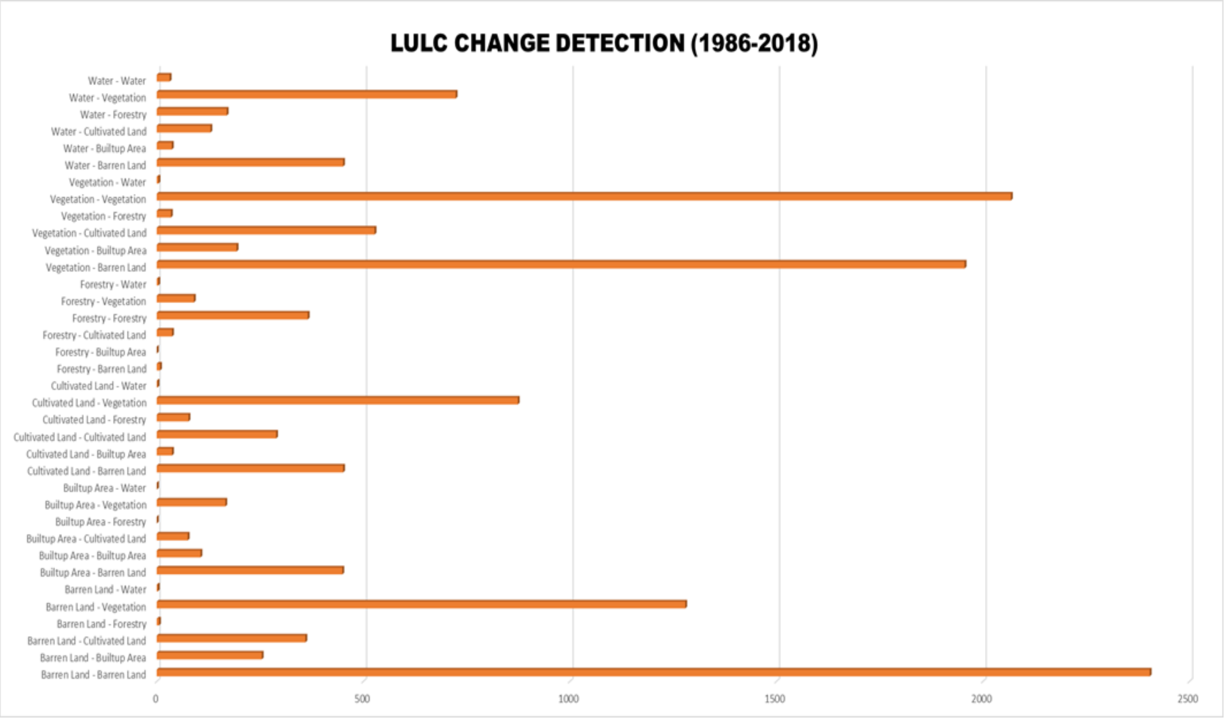


Figure 4.8: Area showing the conversion of Letaba catchment classes to other LULC classes.

4.4. Conclusion

This study delved into a comprehensive analysis of the Letaba Catchment's land use/land cover changes, revealing a dynamic and complex environmental landscape. Using the integrated time-series Landsat data and the Random Forest algorithm, we mapped the historical trends in LULC from 1986 to 2018, aiming to address the degradation of essential resources such as water bodies and ecosystems. The findings showed a significant change in water bodies, vegetation, and forestry, with evident shifts toward built-up areas, cultivated land, and barren land. The observed dramatic shrinkage of vegetation, from 4936 km^2 (38%) in 1986 to 4411 km^2 (32%) in 2018, emphasizes the urgency of addressing LULC change dynamics.

The study highlights the efficacy of historical Landsat data series in providing accessible and up-to-date information crucial for accurate monitoring of LULC changes. The impact of degradation and industrialisation on water, forestry, and vegetation underscores the critical role of these changes in surrounding communities. Moreover, the steady deterioration of LULC classes over the years necessitates a holistic framework approach in environmental resource management to combat the challenges posed by LULC changes for the sustainability of catchment areas. This work serves as a valuable guideline for future LULC assessments, monitoring, and planning, emphasising the importance of informed decision-making and sustainable practices in the face of evolving environmental landscapes.

5. CHAPTER FIVE

Investigate the state of surface water quality in Letaba catchment, South Africa

5.1. Introduction

Water quality represents a critical dimension in environmental science and public health, serving as a fundamental determinant of its suitability for human consumption. The complex effect of natural processes and anthropogenic activities contributes to the dynamic composition of water, influencing its overall quality (Akter, et al., 2016). The parameters defining surface water quality are diverse, encompassing physical, chemical, and microbiological attributes, each holding implications for human health when exceeding predetermined acceptable limits. The evaluation of water quality, a multidimensional concept encapsulating physical, chemical, and biological attributes, is indispensable for comprehending the condition of aquatic systems and safeguarding their ecological integrity (Anon., 2015).

The geographic and climatic diversity of South Africa introduces a unique set of challenges in managing surface water quality. From the arid landscapes of the Northern Cape to the lush regions of KwaZulu-Natal, each area grapples with its specific ecological and anthropogenic influences on surface water quality (MacKellar, et al., 2014). The Letaba Catchment is situated in the northeastern part of South Africa, and it stands as a vital hydrological region within the Limpopo River Basin. One of the defining features of the catchment is the presence of the Drakensberg Mountain range, which serves as a primary source of numerous rivers and tributaries that flow through the catchment (Gokool, et al., 2019). The agricultural landscape within the Letaba Catchment is diverse, with farming activities ranging from citrus orchards to sugarcane plantations. This agricultural footprint, while contributing significantly to the regional economy, also introduces challenges related to water management, including issues of irrigation efficiency, nutrient runoff, and potential impacts on surface water quality.

Sustainable agricultural practices and water conservation initiatives are crucial for maintaining the delicate balance between agricultural productivity and environmental stewardship within the catchment. Recognising the significant role of water quality is essential, as it directly influences the viability of ecosystems, the availability of safe drinking water, and the functionality of various industrial and agricultural processes

(Mekonnen & Hoekstra, 2015). Internationally, the meticulous delineation of standards and guidelines for surface water quality is a responsibility shouldered by esteemed entities such as the World Health Organization (WHO) and the Centres for Disease Control (CDC). These organizations, through the establishment of exposure standards and permissible levels for chemical contaminants in drinking water, provide an indispensable compass for nations seeking to safeguard public health (Dash & Maity, 2019).

In the South African context, the commitment to upholding stringent standards is exemplified through the South African National Standards (SANS) and the South African National Drinking Water Standard (SANS 241), delineating the criteria that govern the attainment of potable water within the nation's borders. Ongoing monitoring and management efforts, often guided by the SANS and the SANS 241, aim to ensure that water quality within catchments meets stringent standards (World Health Organization, 2017). This narrative contradicts the complex reality wherein imperceptible substances may be present, representing a more profound comprehension of the complicated factors influencing surface water quality. The pursuit of good-quality water, therefore, transcends regional boundaries, aligning with global aspirations encapsulated within the framework of the Sustainable Development Goals (SDGs) (Näschen, et al., 2019).

This goal, however, is not without its challenges, as the contemporary world struggles with the compounding effects of climate variability, growing populations, economic constraints, and the far-reaching repercussions of developmental goals. Within the broad spectrum of surface water quality management, the appearance, taste, and odour aspects of drinking water represents significant importance as crucial factors to be considered (MacKellar, et al., 2014). Factors such as industrial activities, agriculture, and urbanization contribute to the complexity of the challenge, requiring various understanding of regional variations and tailored approaches to water quality management (Akter, et al., 2016). The Letaba Catchment shows an example of the broader challenges faced in water resource management – balancing the needs of ecosystems, agriculture, and communities while addressing the impacts of climate variability and human activities.

This introduces a layer of subjectivity and cultural context into the broader discourse on surface water quality management, urging a more various approach that transcends mere scientific metrics. It is important to recognize that constituents of health concern not only impact human well-being directly but also exert a great influence on the sensory attributes of water (Graham, et al., 2022). Taste, odour, and appearance thresholds for acceptability are inherently variable, contingent upon individual preferences and the socio-environmental context. Although specific guideline values have been reasonably set for substances that are directly associated with negative health effects, it's noteworthy that the sensory characteristics may lead to the rejection of water even at concentrations considerably lower than those representing health risks (Gokool & Chetty, 2019).

The goal of ensuring surface water quality unfolds as a complex tapestry woven with the threads of scientific investigation, socio-cultural complexities, and global imperatives. As concerted global initiatives converge toward the critical importance of sustainable water management, the achievement of high-quality water extends beyond being solely a scientific goal. Hence, the study aims to investigate the condition of quality of water to bridge the gap between scientific rigour and the broader societal imperative for clean and sustainable water.

5.2. Material and Methods

5.2.1. Water quality data collection and sources

The acquisition of historical water quality data stands as a fundamental step in unravelling the complex natural variations and trends in quality patterns within a specific region, such as the Letaba Catchment. The study obtained water quality data from the Department of Water and Sanitation (DWS), a governmental department entrusted with the responsibility of South Africa's water and sanitation resources. The mission of DWS it’s the commitment to serve the people of South Africa by making a positive impact on the country and its population. It catalyses positive impacts on the nation's sustainable development and adopts a service and delivery-oriented approach, aiming to lead its sector and empower collaborators with the knowledge and capacity necessary for the effective delivery of water services.

The department's commitment to cutting-edge technology and fostering a supportive environment for its personnel aligns seamlessly with the goals of this study, enhancing reliability of the surface water quality data crucial for understanding water quality dynamics in the Letaba Catchment. The collection of data sourced from the DWS ensures the reliability and credibility of water information, establishing it as a dependable source for comprehending water quality patterns within the Letaba Catchment and aligning with the aim of this study. The collection process adheres to a systematic framework, initiated by obtaining permission and access to surface water quality parameter records maintained by the DWS. Typically stored in digital formats, with Excel spreadsheets being a prevalent choice, these records are structured to include crucial details such as date, time, and name of parameters of water quality measurements.

The collected data include physical and chemical parameters, encompassing parameters like pH levels, ammonium and nitrogen concentrations, total solids, and others. Quality control measures are of great importance in maintaining the integrity of the collected data, regular checks for errors, outliers, and inconsistencies, coupled with data validation procedures to ensure data accuracy and reliability. The Excel format not only streamlines the storage of information but also serves as a robust platform for subsequent data management and analysis. Statistical methods and trend analyses constitute the next phase, analysing the organised data to illustrate patterns, trends, and variations in surface water quality over specified timeframes.

In essence, the comprehensive collection of water quality data from the DWS in the form of Excel spreadsheets represents a systematic and meticulous aim. This dataset serves as a key principle for understanding surface patterns and their far-reaching impacts on the Letaba Catchment. The commitment to precision, reliability, and methodological analyses in this data acquisition process reinforces the credibility of findings and contributes significantly to the scientific understanding of water dynamics in this vital geographical region.

Table 5.1: Graphical table representing Data used.

Parameters	Spatial Resolution	Period of record	Sources
Water quality parameters			
Physical parameters:			
Electrical conductivity (EC)	Monthly	1986 - 2018	Department of Water and Sanitation (**DWS**)
Turbidity (NTU)	Monthly	1986 - 2018	
Total Suspended Solids (TSS)	Monthly	1986 - 2018	
Chemical Parameters:			
Total Nitrogen (mg/L)	Monthly	1986 - 2018	
Nitrogen	Monthly	1986 - 2018	
Total Phosphorus	Monthly	1986 - 2018	
PH	Monthly	1986 - 2018	
Chemical Oxygen Demand (COD)	Monthly	1986 - 2018	

5.2.2. Water quality pre-processing

The delineation of the study's timeframe, spanning from 1986 to 2018, was primarily driven by data availability, a crucial consideration in ensuring the validity and comprehensiveness of the investigation into surface water quality state within the Letaba Catchment. The goal of this research is to delve into the state of water quality, necessitating an exploration of specific parameters that shows both physical and chemical aspects. The chosen years, namely 1986, 1994, and 2018, were strategically selected to construct a cohesive dataset that spans key points in time, facilitating a thorough examination of surface water quality trends. The initial step in this process involved a focused effort to identify and understand the variations in water quality parameters during the chosen years.

The emphasis was placed on meeting the standard requirements for drinkable and acceptable water, aligning with the broader goal of safeguarding water resources for both ecological and human well-being. The initial phase of this investigative process involved examination of the identified surface water quality parameters during the selected years (1986 and 1994). This investigation aimed to understand the historical state of water within the Letaba Catchment, offering insights into any deviations from established standards and shedding light on the baseline conditions. This historical perspective is crucial for comprehending the trajectory of water quality in the region. Subsequently, the study transitioned to assessing the more recent state of water quality using the available data from 2018.

This deliberate focus on the latest available data provided an analysis of the contemporary state of water quality within the Letaba Catchment. By comparing and contrasting the parameters and conditions from the past (1986 and 1994) with those in 2018, the study aimed to unravel the dynamics of surface water quality dynamics over time. These chosen years are not arbitrary; they represent critical link that collectively contribute to a comprehensive understanding of the Letaba Catchment's surface water quality. Through this temporal analysis, the research sought to show not only the immediate state of surface water quality but also the effects and implications of extreme development activities that may have occurred in the region to compromise the state of water.

The analysis of data from 1986, 1994, and 2018 provided a unique lens through which to examine how local activities, environmental dynamics, and community interactions have influenced water quality parameters. This holistic approach aimed to capture not just isolated moments but the broader trajectory of changes, offering valuable insights into the intricate interplay between human activities, extreme weather events, and the state of water resources in the Letaba Catchment. In essence, the selected timeframe becomes a narrative thread weaving together historical perspectives and contemporary realities, fostering a nuanced understanding of the Letaba Catchment's water quality patterns. This approach allows the research to transcend mere data points, offering a rich and detailed exploration of the complex interactions shaping the hydrological landscape of the region.

5.2.3. Statistical analysis of water quality parameters

In this study, a focus was placed on specific years within our selected timeframe, namely 1986, 1994, and 2018. The rationale behind this careful selection was to assess the conditions of water in the Letaba Catchment after the occurrence of identified climatic extremes and the implementation of developmental activities in the area. By strategically choosing these years, we aimed to analyse the water quality dynamics in particular to how they are impacted by both natural climatic events and anthropogenic activities. The methodology employed for the comprehension of the study involved a detailed analysis of historical water quality patterns within the Letaba Catchment.

Daily data received from the Department of Water and Sanitation was aggregated and transformed into monthly averages, effectively representing the period from January to December in each of the chosen years. This approach was designed to create a standardised representation of monthly data for 1986, 1994, and 2018, facilitating a thorough statistical analysis and ensuring a robust understanding of the temporal variations in surface water quality. Given the expansive scope of the study covering the entirety of the Letaba Catchment, it was imperative to adopt a comprehensive and inclusive approach in representing the region's diverse types of water quality parameters. This involved the careful averaging of collected data for each specific month, resulting in a comprehensive dataset that encapsulates the monthly water quality parameters for each of the chosen years.

This analysis not only ensures a standardised and consistent representation of the Letaba Catchment's water quality but also provides a great foundation for subsequent analyses. The approach of combining and averaging monthly data allows for a nuanced exploration of temporal trends, enabling the identification of patterns, variations, and potential correlations within the selected years. This process lays the groundwork for a comprehensive and detailed examination of the state of water quality within the Letaba Catchment during the specified years, shedding light on the complex interplay of climatic factors and human activities influencing the region's hydrological dynamics.

5.2.4. Essential criteria for water quality: Standard requirements

The primary objective of the Guidelines for standard requirements for drinking-water quality is the safeguarding of public health. Recognizing water as an indispensable resource for sustaining life, the guidelines emphasize the necessity of ensuring a satisfactory, adequate, safe, and accessible supply for all. The improvement of access to safe drinking water is not only crucial for the health of individuals but also yields tangible benefits for the broader environment. In this study, water quality parameters are categorized into two distinct types: physical parameters and chemical parameters, with adherence to the standards outlined by the South African Health Standards (SAHS) and the South African National Standard for Drinking Water (SANS 241).

- **Physical Parameters**:
  - Turbidity:

    Turbidity, expressed in nephelometric turbidity units (NTU), actions as an indicator of water cloudiness stemming from suspended particles like clay, silts, chemical precipitates (e.g., manganese and iron), organic particles (e.g., plant debris), and organisms. Elevated turbidity levels can result from suboptimal source water quality, inadequate treatment, and disturbances within distribution systems. Large municipal water supplies are expected to consistently produce water with no visible turbidity, maintaining levels below 0.5 NTU before disinfection at all times and averaging 0.2 NTU or less. However, smaller supplies, particularly those with limited resources, may face challenges in achieving such standard required levels.

    Visibility of turbidity: below 4 NTU, turbidity is detectable only using instruments, but at 4 NTU and above, a milky white, muddy, red-brown, or black suspension becomes visible. Consumers often associate turbidity with safety concerns, even though most particles contributing to turbidity may have no direct health significance. The perception of turbid water as unsafe can lead to reduced water consumption or the use of alternative, potentially unsafe water sources.

- Electrical Conductivity:

  Electrical conductivity (EC) serves as a measure of a solution's ability to conduct an electrical current. This property arises from the presence of ions in the solution, and as the concentration of ions increases, so does the conductivity. The conductivity of water, therefore, becomes a direct indicator of the ion concentration within the solution. In practical terms, electrical conductivity is a crucial parameter for assessing the suitability of water for various purposes, including water irrigation and firefighting. The measurement of EC is instrumental in understanding how efficiently a solution can carry an electrical current, and this has direct implications for its application in specific contexts. Pure water, being devoid of significant ion concentrations, is known to be a poor conductor of electricity.

  It is the dissolved ions in water that contribute to its electrical conductivity. The presence of ions, which may include dissolved salts and minerals, enhances the ability of water to conduct electricity. In the context of water irrigation, electrical conductivity is used as an indicator of the water's salinity and the potential for soil damage. High levels of conductivity may suggest elevated salt content, which, if not managed appropriately, can adversely affect soil quality and crop growth. The standard for water conductivity is often measured in microsiemens per centimeter (μS/cm) or millisiemens per centimeter (mS/cm) and is generally considered acceptable at ≤170 at 25 ºC. This standard provides a quantitative benchmark for assessing the quality of water concerning its electrical conductivity.

- **Chemical parameters:**
- Nitrogen:

  Nitrogen is a key component in water quality assessments, playing a significant role in environmental health and ecosystem balance. It exists in various forms in water, with the two most commonly monitored being nitrate (NO_3^-) and ammonium (NH_4^+). Nitrogen compounds in water primarily originate from agricultural runoff, wastewater discharges, industrial activities, and atmospheric deposition. Ammonium is another form of nitrogen found in water, often originating from decomposing organic matter, wastewater, and agricultural activities. It can be converted to nitrate through microbial processes in water and soil. Like nitrate, elevated ammonium levels can contribute to eutrophication, impacting the ecological balance of aquatic ecosystems.

The standard for nitrogen concentration in water is typically set to a maximum allowable level to ensure surface water quality meets health and environmental guidelines. In many cases, this standard is expressed in terms of milligrams per litter (mg/l). The specified standard for nitrogen content in water is commonly established at ≤0.9 mg/l. This limit serves as a regulatory benchmark to prevent excessive nitrogen levels that could potentially impact human health, aquatic ecosystems, and overall surface water quality. Adhering to such standards is crucial for managing nitrogen pollution and maintaining the balance of nitrogen compounds in water bodies.

- PH:

  pH, a fundamental aspect of surface water quality, gauges the acidity or alkalinity of a solution on a scale ranging from 0 to 14. In the context of water, a pH below 7 signifies acidity, while a pH above 7 indicates alkalinity. The importance of maintaining optimal pH levels is underscored by its influence on chemical and biological processes. For drinking water, a pH between ≥5 and ≤9.7 at 25 ºC is deemed standard, ensuring both palatability and human health. Beyond human consumption, pH significantly impacts environmental ecosystems, affecting nutrient availability and toxicity.

  Regulatory bodies set these standards to strike a balance supporting aquatic life, minimizing corrosion in water distribution systems, and ensuring water acceptability for diverse purposes. Water treatment processes often involve pH adjustments, emphasizing the role of pH in stabilizing surface water quality. Variations in pH, influenced by geological factors and organic matter, underscore the need for comprehensive water quality assessments. In essence, maintaining pH within specified standards is vital for responsible water management, safeguarding both human and environmental well-being.

- Phosphorus:

  Phosphorus is a crucial element in water quality assessment, playing a significant role in the ecological balance of water resources. It is often monitored due to its potential to cause nutrient-related environmental issues, primarily eutrophication. Phosphorus enters water bodies through various sources, including agricultural runoff, wastewater discharges, and industrial activities. In the context of water quality standards outlined by SANS 241-1, which sets guidelines for drinking water in South Africa, specific requirements for phosphorus levels are established to ensure safe and acceptable water quality.

  The established water quality standards mandate that phosphorus concentrations in lakes or streams should not surpass 0.025 mg/L, while for rivers, the acceptable limit is set at 0.1 mg/L. Adhering to these defined standards is crucial to uphold and preserve the overall surface water quality in these aquatic environments. Nevertheless, managing phosphorus in water is crucial because excessive levels can lead to nutrient enrichment, stimulating the growth of algae and aquatic plants. This overgrowth can result in oxygen depletion, harm aquatic life, and degrade surface water quality. Therefore, even in the absence of a specific numerical standard, monitoring and controlling phosphorus levels in water are essential aspects of responsible water management to prevent adverse environmental impacts.

- Chemical Oxygen demand (COD):

  Chemical Oxygen Demand is a key parameter in water quality assessment, providing insights into the number of organic pollutants present in water. COD measures the quantity of oxygen required to chemically oxidize organic substances in water, reflecting the overall organic pollution load. The standard requirement for COD is often set by environmental regulations to ensure that water bodies maintain acceptable levels of organic pollutants. Specific standards may vary by region or regulatory body, but they generally establish maximum allowable COD concentrations to protect aquatic ecosystems and public health. COD in drinking water specifies that the limit should be less than 5.0 milligrams per litter (mg/L).

This stringent limit reflects the importance of maintaining low levels of organic pollutants in drinking water to ensure its safety for human consumption. COD is a vital parameter in water quality management, reflecting the level of organic pollution in water bodies. Establishing and adhering to standard requirements for COD helps prevent environmental degradation, supports the health of aquatic ecosystems, and ensures the availability of safe and sustainable water resources.

5.3. Results and Discussion

5.3.1. Physical Properties

The comprehensive analysis of temporal variations in water quality parameters across the years 1986, 1994, and 2018 provides nuanced insights into the dynamic and complex nature of water resources. In the context of 1986, the examination of electrical conductivity unfolds a distinctive pattern. At the onset of the year, the conductivity levels were notably high, gradually decreasing through March. However, a subsequent and rapid increase in electrical conductivity was observed, culminating in a return to standard equilibrium throughout the rest of the months. Remarkably, during this period, turbidity remained conspicuously absent from recorded values, suggesting a relative absence of suspended particles that typically influence water clarity.

Conversely, the year 1994 introduces a divergent narrative in temporal water quality dynamics. Electrical conductivity commenced at a comparatively lower level and recorded nothing during the months of July and August. Nevertheless, from September onward, a swift and substantial increase in electrical conductivity was noted, followed by a subsequent decrease in December. Intriguingly, this fluctuation in electrical conductivity corresponded with a lack of turbidity values during the period of low electrical conductivity, adding a layer of complexity to the dynamic interplay between these two crucial water quality parameters. Fast forward to the year 2018, where the analysis unveils a compelling scenario. The commencement of the year was marked by exceptionally high levels of both turbidity and electrical conductivity.

Notably, these elevated levels endured until July, beyond which no further measurements were recorded. The sustained elevation in electrical conductivity raises concerns, suggesting a continual influx of dissolved ions indicative of potential water contamination. Simultaneously, the prolonged increase in turbidity levels implies compromised visual clarity, attributable to factors such as suboptimal source water quality, treatment inefficiencies, or disruptions within distribution systems. The overarching interpretation of these temporal variations underscores the vulnerability of water resource to dynamic changes in ion concentrations and suspended particle levels. Interpreting these results, the escalation in electrical conductivity becomes a pivotal indicator of potential water impurities, given that pure water, devoid of significant ion concentrations, is known to be a poor conductor of electricity.

The fluctuating patterns observed across the years underscore dynamic changes in ion concentrations, urging a meticulous approach to ongoing monitoring and management of water resources. Additionally, the sustained increase in turbidity levels in 2018 suggests a potential decline in water quality. Lastly, the in-depth analysis of temporal variations in electrical conductivity and turbidity over the years 1986, 1994, and 2018 necessitate the need for continuous and vigilant monitoring. The complex interplay of these water quality parameters shows a narrative extending beyond mere fluctuations, emphasizing the need for adaptive strategies to address the challenges posed by dynamic changes in ion concentrations and water clarity over time.

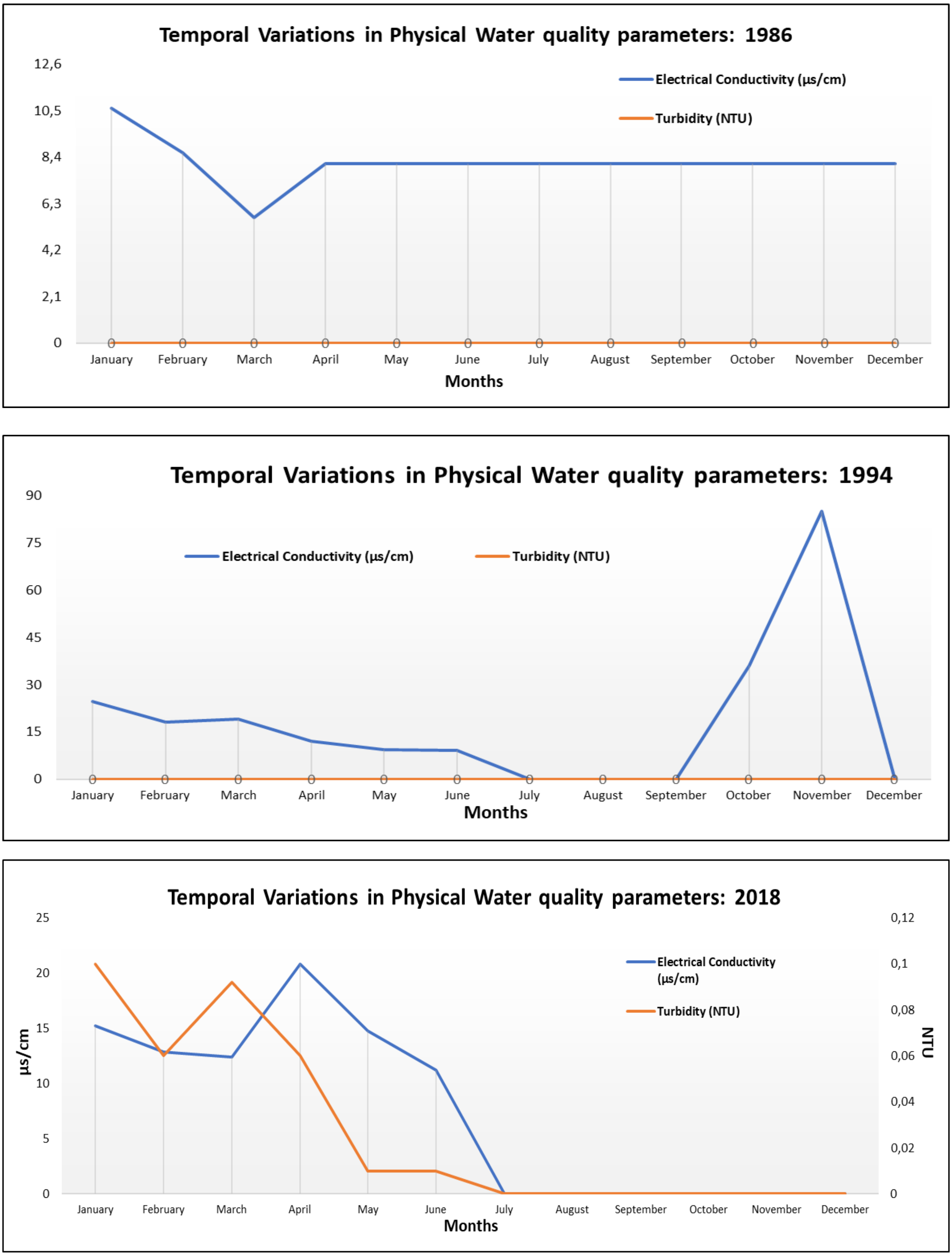


Figure 5.2: Temporal Dynamics of Key Water Quality Parameters: showing Fluctuations in Physical Characteristics for 1986, 1994 and 2018.

5.3.2. Chemical Properties

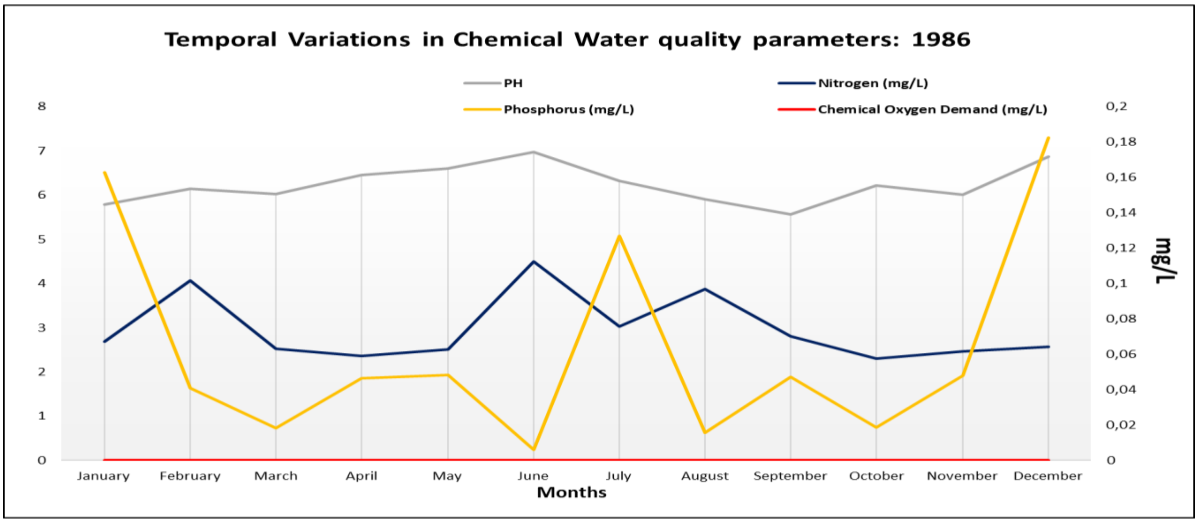
The temporal variation of chemical parameters in water quality over the years 1986, 1994, and 2018 reveals complex patterns that shows light on the dynamic interactions within water quality parameters. In 1986, the pH levels demonstrated stability, fluctuating within the range of ≥5 and ≤9.7 throughout the year, reflecting water conditions suitable for drinking. Contrasting with this stability, the phosphorus parameter exhibited notable variability. The year commenced with elevated phosphorus levels (0.05 mg/L), decreasing in February and March. However, a subsequent increase in April and May initiated a fluctuating trend that persisted until the end of the year, concluding with heightened phosphorus levels at 0.08 mg/L.

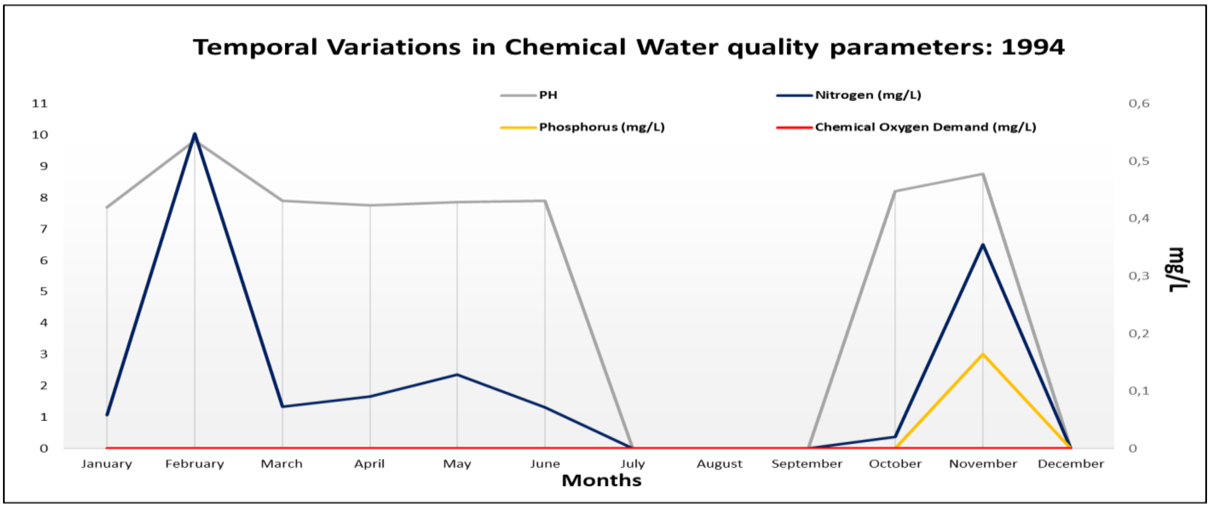
Nitrogen in 1986, started at low concentrations and underwent fluctuations throughout the year reaching 0.06 mg/L by December. Remarkably, chemical oxygen demand (COD) levels were not recorded, indicating a lack of organic pollutants during this period. Transitioning to 1994, the pH levels began at acceptable level of 7.69, but the course delineated complex and challenging trends. After a gradual increase in February, a subsequent decline occurred from March leading to stagnation from March to June. A noticeable drop post-June resulted in no recorded pH values in July, August, and September. A rapid and substantial increase in October and November was followed by minimal pH level records in December. This odd pH level raises concerns about water stress and potential contamination.

Phosphorus levels in 1994 were absence of until November and in November low amounts were recorded, followed by no records in December. The dynamic fluctuations in nitrogen levels throughout the year underscore the complexity of nutrient dynamics and potential implications for surface water quality. Similarly, COD levels were not recorded, leaving uncertainties about the organic pollution status during this period. In the context of 2018, the pH levels started at a concerning amount of 0.02, indicating acidity. The pH level increased in April and May, however, the levels remained below 7, signalling ongoing stress on surface water quality. From July to December, no pH amounts were recorded, introducing additional uncertainties.

Phosphorus levels in 2018 exhibited fluctuations, starting with minimal amounts, increasing in March, decreasing in April, and eventually reaching 0 records. Unlike previous years, nitrogen levels were not recorded in 2018, presenting a deviation from the observed nutrient dynamics. However, COD, a critical parameter reflecting organic pollution, showed minimal levels from January to June, with no records from July onwards, leaving questions about the potential presence of organic pollutants in the latter half of the year.

The detailed examination of temporal variations in chemical parameters offers valuable insights into the complex dynamics of surface water quality. The observed patterns in pH, phosphorus, nitrogen, and COD levels highlight the need for continuous monitoring and proactive management to ensure the sustainability and health water sources. The deviations observed in 1994 and 2018 underscore the sensitivity of surface water quality to environmental changes, emphasizing the importance of a holistic and adaptive approach in managing and preserving water resources.





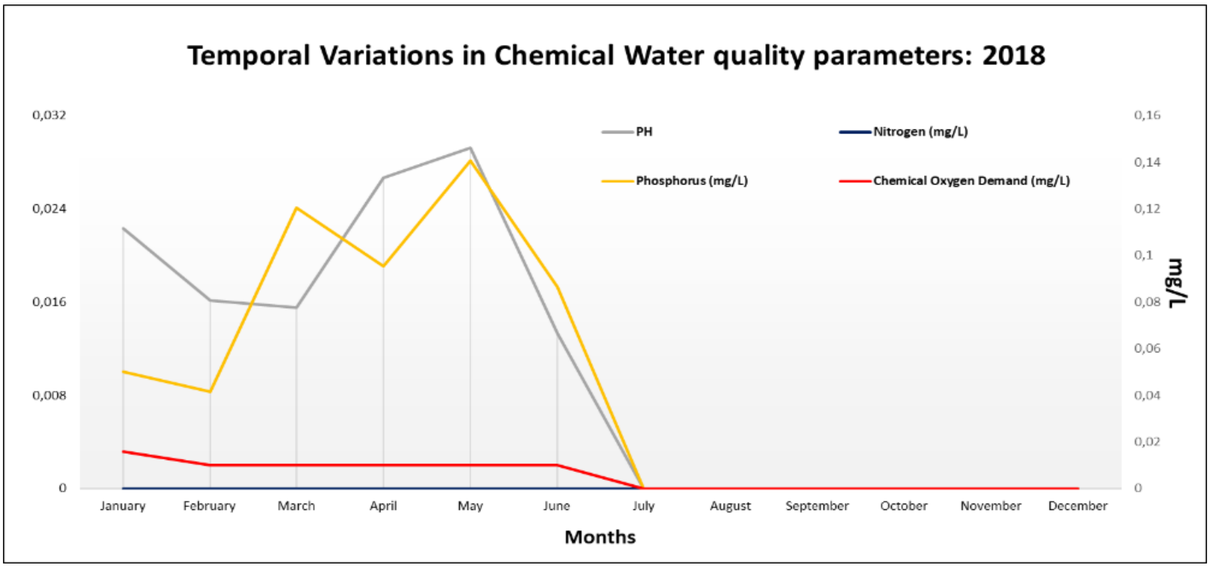


Figure 5.3: Temporal dynamics of key water quality parameters: showing fluctuations in chemical characteristics for 1986, 1994 and 2018.

5.3.3. Statistical analysis of average water quality parameters: Exploring the Physical and Chemical Aspects.

In a comprehensive analysis of the temporal dynamics of physical and chemical variations in the specific years 1986, 1994, and 2018, discerning insights emerge regarding the water quality parameters under consideration. The turbidity levels, a crucial indicator of water clarity, were consistently found to be below 0.2 NTU in all three years, meeting the standard requirement. This adherence to turbidity standards reflects positively on the visual quality and potential sediment content within the water during these respective years. Similarly, electrical conductivity, a critical indicator of the concentration of dissolved ions in water, demonstrated conformity with water quality standards across 1986, 1994, and 2018, with values consistently below 170 μS/cm.

This alignment with established standards reinforces the notion that the water under consideration remained within acceptable conductivity limits, signifying minimal ionic concentration and suggesting a lack of significant contaminants influencing the electrical conductivity. Nevertheless, a notable deviation emerges in 1994 concerning nitrogen levels (0,11 mg/L), surpassing the standard limit of 0.9 mg/l. This discrepancy signals a potential stressor on the water quality, as elevated nitrogen concentrations can contribute to nutrient pollution and ecological imbalances. The temporal assessment becomes a crucial tool in identifying periods of heightened stress and aids in formulating targeted mitigation strategies. The examination of pH levels revelled that both 1986 and 1994 demonstrated adherence to acceptable standards for drinkable water (Table 5.2).

However, in 2018, 0,01 was recorded to show a decline from these standards was observed, with pH levels falling below the acceptable range of ≥5 and ≤9.7, indicating acidity. The acidic nature of the water in 2018 could have great implications for aquatic life and ecosystem health, emphasizing the need for further investigation into potential sources and mitigative measures. Turning attention to phosphorus levels, all three years—1986, 1994, and 2018—reported concentrations below the standard limit of 0.1 mg/l. This consistency in adhering to phosphorus standards implies acceptable levels of this nutrient, crucial in averting eutrophication and preserving surface water quality. Lastly, the assessment of Chemical Oxygen Demand (COD) levels during the specified years revealed values consistently below the standard requirement. This absence of available COD in the water signifies low organic pollutant levels, suggesting that the water samples were not under significant stress from organic pollutants during the assessed periods. The detailed analysis of temporal dynamics in physical and chemical parameters provides a clear understanding of surface water quality variations over the specified years. While the majority of parameters align with established standards, the notable deviation in nitrogen levels in 1994 and the acidic pH observed in 2018 underscore the importance of ongoing monitoring and targeted interventions to ensure the resilience and sustainability of water ecosystems.

Table 5.2: Illustrates the average values of water quality pertaining to both physical and chemical parameters.

PHYSICAL PARAMETERS			
	1986	**1994**	**2018**
EC (µs/cm)	8,16	17,79	7,27
Turbidity (NTU)	0	0	0,03
CHEMICAL PARAMETERS			
	1986	**1994**	**2018**
Nitrogen (mg/L)	0,07	0,11	0,00
Phosphorus (mg/L)	0,06	0,01	0,04
PH	6,24	5,49	0,01
COD (mg/L)	0,00	0,00	0,01

5.4. Conclusion

The in-depth analysis of the temporal dynamics of surface water quality parameters spanning the years 1986, 1994, and 2018 offers a comprehensive understanding of the health and sustainability of the studied water resources. The consistent adherence to turbidity and electrical conductivity standards suggests a commendable maintenance of water clarity and ion concentration, meeting prescribed quality norms. However, the elevated nitrogen levels in 1994 raise concerns about potential stress on the water system, necessitating further investigation into the sources and impacts of heightened nitrogen concentrations. The pH levels revealed a decline from acceptable standards in 2018.

This deviation prompts a focused inquiry into the factors contributing to the observed acidity, highlighting the need for proactive measures to address potential surface water quality issues. On a positive note, phosphorus levels across the years remained within acceptable limits, mitigating the risk of nutrient-induced eutrophication. The consistently low levels of Chemical Oxygen Demand (COD) underscore a positive aspect of surface water quality, indicating a limited presence of organic pollutants. However, this also prompts a consideration of the potential ecological implications of minimal organic content in the. The temporal variations in water quality parameters underscore the dynamic nature of aquatic environments.

The findings emphasize the importance of continuous monitoring and adaptive management strategies to ensure the resilience and sustainability of water resources. Addressing the identified anomalies, particularly in nitrogen concentrations and pH levels, is crucial for the effective management and preservation of surface water quality. As we navigate the complexities of water ecosystems, the insights gained from this study contribute to a more informed and proactive approach to safeguarding our vital water resources for current and future generations.

6. CHAPTER SIX

Assess the effects of Climate Extremes and Land use landcover (LULC) on surface water quality in Letaba Catchment.

6.1. Introduction

The complex relationship between surface water quality and the environment is a subject of great importance, with the dynamic changes of climate extremes, land use and land cover (LULC) emerging as significant aspects shaping the quality of water in Letaba catchments. Within this context, the Catchment, situated in a region characterised by diverse ecosystems, provides an ideal setting for significant analysis of the impacts of climate extremes and LULC on s (Näschen, et al., 2019). The rapid growing population, urbanisation, and LULC changes have emerged as pressing challenges for effective water resources management. The alteration of land use and land cover within a catchment can significantly impact basin hydrology, influencing critical factors such as evaporation, soil infiltration capacity, and surface and subsurface regimes (Wanda, et al., 2016).

The rising global concern surrounding declining surface water quality emphasises the cruciality of addressing the complex interaction between expanding anthropogenic activities and the looming specter of climate change, both of which pose imminent threats to the delicate balance of the water cycle (Tabari, et al., 2016). The Letaba Catchment encompasses a complex dynamic of land uses and natural habitats. This catchment is not only vital for sustaining the ecological balance of the region but also serves as a critical water source for agricultural, industrial, and domestic purposes. However, the impacts of climate extremes in the form of altered precipitation patterns, increased temperatures, and heightened frequency of extreme weather events, alongside various dynamics of land use and land cover changes, has introduced a layer of complexity to the delicate balance of the Letaba Catchment (Manickum, et al., 2014).

As growing populations continue to reshape urban landscapes and alter the impacts of land use practices, their collective effects extend far beyond the visible transformation of physical aspect. In particular, the interaction of these aspects has emerged as a crucible for water resources where changes in LULC resonate through complex hydrological structure, greatly influencing important components such as evaporation, soil infiltration capacity, and the dynamic interplay of surface and subsurface water resources (Matarira, et al., 2022). Climate extremes, in the context of this study, encapsulate both the intensification of extreme weather events, such as floods and droughts, and the long-term shifts in temperature and precipitation patterns.

These phenomena, often contribute to global climate change and have the potential to exert great impacts on the surface water quality of the catchment, influencing water availability, flow regimes, and, critically, surface water quality. Moreover, the rapid change between climate extremes, LULC changes and surface water quality, driven by anthropogenic activities, increase the vulnerability of the Letaba Catchment to environmental stressors (Elmahdya & Mohameda, 2023). The impacts unfold in the form of pollution of water bodies by agricultural nutrients, elevating the levels of eutrophication hazards.

Anthropogenic activities introduce a large number of pollutants into the catchments, this includes agricultural sediments, nutrients, pesticides, and industrial effluents. The alteration of natural landscapes, it's often a consequence of expanding human settlements and agricultural practices, amplifies the susceptibility of water bodies to contamination (Loukika, et al., 2021). The resultant changes in runoff patterns and nutrient loading have surge effects on the chemical, physical, and biological characteristics of water, necessitating a thorough examination of the relationship between land use changes and surface water quality. This study seeks to unravel the intricate connections between climate extremes, land use and land cover changes, and surface water quality within the Letaba Catchment.

The various nature of these relationships demands a comprehensive analysis to discern not only the individual impacts of climate and land use changes but also their synergistic effects on the aquatic ecosystems. Through an in-depth analysis of these interconnected factors, this research aims to contribute valuable insights to the broader discourse on water resource management, climate adaptation, and sustainable land use practices in regions grappling with environmental change (Akter, et al., 2016). The alterations in seasonal and annual streamflow induced by climate change have great effects on the hydrological characteristics of watersheds.

Additionally, climate change induces shifts in sediment flux and river morphology, further impacting river ecosystems.

The increased challenges associated with extreme climate events are particularly concerning, with even a modest 1 °C increase in warming projected to elevate these challenges significantly. Climate extremes utilise a perceptible impact on the hydrological dynamics of the Letaba Catchment (Mahmoudi, et al., 2021). The shifting precipitation patterns, intensified droughts, and extreme weather events are indicated as stressors, disrupting the natural flow of water bodies, altering sediment transport, and triggering changes in nutrient cycling. These climatic changes, coupled with the complex interplay of LULC changes, amplify the challenges faced by water resources.

The alteration of natural land cover, whether through deforestation, urban expansion, or agricultural intensification, introduces high amounts of pollutants into catchment—sediments, nutrients, pesticides—propagating a cascade of effects on surface water quality (Chotpantarata & Boonkaewwan, 2018). Understanding the intricate relationships between climate extremes, LULC dynamics, and surface water quality requires a nuanced analysis that considers spatial and temporal scales, water quality parameters, landscape composition, and the intensity of land use practices. In essence, the combination of fast urban growth, significant changes in land use, and the looming threat of climate change creates a complex set of challenges for managing water resources (Elmahdya & Mohameda, 2023).

Addressing these challenges requires a thorough and flexible approach that considers the interconnections between these factors. To tackle these issues effectively, we need to go beyond conventional limits. This involves combining scientific knowledge, sustainable land use methods, and inventive water management strategies to navigate the unpredictable waters of the future.

6.2. Materials and Methods

6.2.1. Data Collection methods and sources for Surface Water Quality, Climate Extremes, and LULC

The fundamental step towards understanding the complex environmental dynamics within the Letaba Catchment requires acquiring of historical data related to climate extremes, LULC, and surface water quality. This encompasses a methodologically diverse approach, collecting data from authoritative sources to ensure a comprehensive understanding of the region's complex natural variations, trends and the analysis of the impacts of climate extremes and LULC on water quality. In this chapter outputs of the preceding on surface water quality and LULC assessment was used.

Water Quality Data:

At the core of the study investigation lies the collection of surface water quality data in the form of parameters, which stands as a fundamental pillar in comprehending the impacts of climate extremes and LULC of the Letaba Catchment. The study obtained water quality data from the Department of Water and Sanitation (DWS), a governmental department entrusted with the responsibility of South Africa's water and sanitation resources. The DWS emerged as reliable source to collect surface water quality data. The data procured from DWS encompassed a spectrum of parameters, including but not limited to nutrient levels, turbidity, and pollutant concentrations. Such granular data holds the key to show the spatial and temporal dynamics of surface water quality within the Letaba Catchment.

Climate Extremes Data:

The historical data of climate extremes, particularly the rainfall patterns that shape the hydrological dynamics of the Letaba Catchment, were sourced from the South African Weather Services (SAWS). Functioning as the authoritative custodian of meteorological information in South Africa, SAWS provides a robust dataset detailing the historical temporal dynamics of climatic events, specifically extreme weather phenomena such as high and low precipitations. The integration of this data was crucial in providing a contextual framework for our research and understanding the complex correlation between fluctuations in climate and patterns in surface water quality.

Land Use Land Cover (LULC) Data:

Google Earth Engine (GEE) was used to obtain LULC data with the effort to analyse how natural and human forces shape the Letaba Catchment's terrestrial landscape, as well as the impacts of anthropogenic activities on surface water quality. This technology made it easier to retrieve important information about the land cover changes over time by utilising sophisticated remote sensing capabilities. It is possible to identify changes in agricultural practices, deforestation, and urbanization by using LULC data in the form of area. The incorporation of such geographical data enhanced our efforts to create a thorough account of how both natural and human activities influenced the land use dynamics of the Letaba Catchment.

Integration for Holistic Analysis:

The analytical approach of the study was based on the combination of data from these different but complimentary sources. Through the integration of climate extremes data from SAWS, LULC data from Google Earth Engine, and surface water quality data from DWS, our study aims to identify the interrelated patterns and trends that shape the Letaba Catchment's environmental structure. This integrative methodology was critical to the search of a nuanced knowledge of how climatic extremes and changing land use contribute to the complicated tapestry of surface water quality dynamics. The aim of the study is not only to examine individual variables but also to shed light on how these elements interact, providing useful information for the responsible management of water resources and the environment in the area.

Table 6.1: Illustration of Data used in the study.

Parameters	Spatial Resolution	Period of record	Sources
Climate extremes parameter			
Rainfall	Daily (averaged to monthly)	1986-2018	South African Weather Services (**SAWS**)
Water Quality Parameters			
Physical Parameters			Department of Water and Sanitation (**DWS**)
Electrical conductivity (EC)	Monthly	1986-2018	
Turbidity (NTU)	Monthly	1986-2018	
Chemical Parameters			
Nitrogen	Monthly	1986-2018	
Phosphorus	Monthly	1986-2018	
PH	Monthly	1986-2018	
Chemical Oxygen Demand (COD)	Monthly	1986-2018	
LULC Classification Parameters			
Area	**km^2**	1986-2018	Google Earth Engine *https://earthengine.google.com*

6.2.2. Integration of Pre-processed Outputs:

The study's timeframe, which ranged from 1986 to 2018, was determined by data availability, confirming the study's validity and comprehensiveness. Therefore, data on rainfall, surface water quality, and land use and land cover (LULC) were selected to create a coherent dataset covering the years 1986, 1994, and 2018. Classified images were generated for each chosen year by the Random Forest (RF) classifier technique implemented in the GEE platform to classify LULC changes. To conduct a further correlation study with data on surface water quality, the area of classified images in square kilometres was obtained. Thus, to test the significance of the correlation, rainfall data and water quality measures were aggregated for each chosen year. This complex integration of pre-processed data paves the way for an all-encompassing analysis of trends in surface water quality, relationships with climate indicators, and the effects of LULC changes in the Letaba Catchment over the years.

6.2.3. Statistical methods employed for assessing impacts of climate extremes and LULC on water quality.

An array of statistical approaches was used to highlight the impacts on surface water quality measures through comprehensive investigation of the complex relationships between climate extremes, land use land cover (LULC), and water quality within the Letaba Catchment. Correlation analysis is one of these techniques that has become essential for assessing and comprehending relationships between different environmental factors. Correlation analysis was used to determine and measure the extent and trend of interactions between climate extremes, LULC changes, and particular surface water quality measures. Correlation analysis was used to evaluate linear correlations by computing Pearson correlation coefficients. This was done with an emphasis on the relationship between rainfall data and water quality metrics. Simultaneously, Spearman rank correlation was used to investigate non-linear correlations, particularly those between LULC changes and surface water quality trends.

Pearson Correlation Coefficients (Linear Relationships - Rainfall Data on Water Quality):

Pearson correlation is well-suited for evaluating linear correlations between variables, making it an excellent choice for assessing the relationship between rainfall data and surface water quality measures. We measured the degree and direction of the linear relationship between the variables using Pearson correlation coefficients (Figure 6.2). A positive connection is indicated by positive coefficients, whereas a negative correlation is indicated by negative coefficients. The strength of the association is indicated by the coefficient's magnitude.

$$r = \frac{\sum \left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum \left(x_i - \bar{x}\right)^2 \sum \left(y_i - \bar{y}\right)^2}}$$

Figure 6.2: Pearson Correlation formular

Spearman Rank Correlation (Non-linear Relationships - LULC on Water Quality): To evaluate non-linear connections—which are vital to investigate when examining the effects of LULC changes on the dynamics of surface water quality—Spearman rank correlation is a useful tool for capturing consistent relationships. We assessed the consistent nature and significance of the interaction between LULC changes and water quality measures using Spearman rank correlation (Figure 6.3). This approach yields a more widely applicable measure of association and is less susceptible to anomalies (formular).

Linear Relationships (Rainfall Data): The correlation study revealed insights on the relationships between changes in surface water quality measures and variations in rainfall, a significant climatic extreme. For instance, positive correlations may indicate dilution effects and an improvement in surface water quality with more rainfall, but negative correlations may indicate runoff and higher pollutant concentrations. Non-linear Relationships (LULC Changes): The Spearman rank correlation analysis enabled us to find complex non-linear relationships between LULC changes and surface water quality. This is especially helpful in comprehending the more complex and non-linear ways that changes in land cover may affect water quality measures.

$$r = 1 - \frac{6\sum d^2}{n^3 - n}$$

Figure 6.3: Spearman Rank Correlation formular

6.3. Results and Discussion

6.3.1. Unveiling the Significant relationship: Analysing the Impact of Climate Extremes (Rainfall) on Water Quality:

The analysis of surface water quality parameters in conjunction with rainfall data for the years 1986, 1994, and 2018 yielded sophisticated observations into the complex relationship between climatic conditions and surface water quality dynamics within the Letaba Catchment. For the years 1986, 1994, and 2018, the analysis revealed no significant relationship between electrical conductivity and rainfall. This observation indicates a lack of notable impact of rainfall on electrical conductivity during these years. The consistent absence of a correlation across the three years indicates that variations in rainfall did not contribute to discernible changes in electrical conductivity, highlighting a degree of stability in this parameter. Similar to electrical conductivity, no significant relationship was identified between phosphorus levels and rainfall in 1986, 1994, and 2018.

This consistent lack of correlation implies that fluctuations in rainfall did not exert a substantial impact on phosphorus concentrations within the water. The stability observed in phosphorus levels across the three years suggests a consistent phosphorus environment irrespective of changes in precipitation. In contrast to electrical conductivity and phosphorus, the analysis revealed a noticeable positive correlation between turbidity and rainfall specifically in the year 2018. The observed observation brings to light an interesting paradox: even with the reduced rainfall that was observed in 2018, as discussed in Chapters 3 and 4, there was still heightened turbidity in the water.

This disparity implies that variables other than the amount of rainfall impacted the dynamics of turbidity in the Letaba Catchment during this time. The analysis's positive association suggests that the low rainfall events in 2018 may not be the only cause of the increased turbidity. Instead, the concurrent occurrence of elevated turbidity and low rainfall extremes implies the potential impacts of anthropogenic activities and agricultural practices within the Letaba Catchment. This implication suggests a complex interconnection of various factors, including sediment runoff, erosion, and other sediment-laden processes.

In essence, the turbidity levels observed in 2018 appear to be intricately linked to human activities and land-use practices rather than being solely dictated by the volume of precipitation. This detailed understanding highlights the complex interplay between environmental variables and surface water quality, emphasising the necessity of taking human factors into account in a comprehensive manner when interpreting the dynamics of turbidity parameters in the Letaba Catchment. Similar to turbidity, rainfall in 2018 was positively correlated with nitrogen, pH, and chemical oxygen demand (COD). This significant connection indicates excessive anthropogenic activities and agricultural practices in the region. The observed positive correlations highlight the complex relationship between land uses, climatic events, and water quality parameters, and suggest that rainfall might not have an effect on water quality.

The absence of significant relationships between rainfall and water quality parameters in 1986 and 1994 implies a relatively stable surface water quality environment during those years. This stability suggests that water contamination during these periods was less likely, emphasising the resilience of water quality in the face of varying climatic conditions. The observed positive correlations in 2018, particularly with turbidity, nitrogen, pH, and COD, raise concerns about potential water contamination. The associations suggest that industrial activities, anthropogenic impacts, or agricultural practices during this period might have contributed to alterations in water quality parameters.

The detailed analysis consists of the dynamic nature of the relationship between rainfall and water quality parameters. While stability was observed in 1986 and 1994, the notable correlations in 2018 revels the vulnerability of water quality to external factors during periods of decreased precipitation. These findings contribute to a deeper understanding of the complex interdependencies shaping water quality dynamics within the Letaba Catchment over the examined years.

Table 6.2: Illustration of the significant correlation between climate extremes (Rainfall) and water quality.

Parameters	P-Value			Correlation Relationship
	2018	**1994**	**1986**	
		Physical Parameters		
Electrical conductivity (EC)	0,278 (-)	0,641 (-)	0,763 (-)	No Significant relationship all years
Turbidity (NTU)	0,023 (+)	0,711 (-)	0,458 (-)	Significant relationship in 2018
		Chemical Parameters		
Nitrogen	0,013 (+)	0,822 (-)	0,275 (-)	Significant relationship in 2018
Phosphorus	0,805 (-)	0,700 (-)	0,598 (-)	No Significant relationship all years
PH	0,0001 (+)	0,623 (-)	0,347 (-)	Significant relationship in 2018
Chemical Oxygen Demand (COD)	0,003 (+)	0,711 (-)	0,458 (-)	Significant relationship in 2018

6.3.2. Unveiling the Significant relationship: Analysing the Impact of Land use and Landcover (LULC) on Water Quality:

Analysis of LULC and surface water quality measures shows remarkable temporal trends, providing insights on the relationship between land-use practices and water quality in the Letaba Catchment. A significant finding emerged in 1986: where selected water quality parameters showed a perfect negative connection with LULC. This suggests that for this specific year, there was no connection between land use, land cover, and surface water quality. The absence of correlation suggests a level of independence between land-use patterns and water quality parameters, indicating a potential equilibrium in the environmental dynamics during 1986. Similar findings were made in 1994 (Mello, et al., 2020; Preetha, et al., 2021; Molekoa, et al., 2022) when it was discovered that there was no significant relationship between LULC and a few water quality parameters—electric conductivity excluded.

Electrical conductivity is a sign that ions, including dissolved salts and minerals, may exist, even if in small quantities. This low connection implies that, even while land-use changes have little effect on some water quality parameters, the addition of ions may have signalled minor changes in the water's composition in 1994. Contrary to the 1994 scenario, a clear change was noted in 2018 with a perfect correlation between LULC and water quality parameters like turbidity, phosphorus, and COD. Changes in land use are likely to have an influenced greater impact on surface water quality for the year. The ideal connection indicates that changes in water quality parameters and changes in land cover classes correlated precisely.

The correlation that emerged in 2018 suggests that contemporary land-use practices in the Letaba Catchment may have an impact on the surface water quality. The positive significance observed in 2018, particularly with three parameters—turbidity, phosphorus, and COD—raises concerns about potential water stress or contamination. This may be attributed to the evolving land-use activities in the region, pointing towards a heightened impact on water quality. The optimal connection highlights the necessity for a thorough investigation of human-caused environmental changes and their effects on the water bodies through showing a clear correlation between the changing landscape and the observed fluctuations in these surface water quality measures.

In summary, the temporal dynamics revealed through the analysis a shifting interplay between LULC and water quality in the Letaba Catchment. The findings from 1986 and 1994 point to a comparatively stable environment, while the optimal correlation from 2018 points to a greater impact of changing land use on water quality. These results add to a more complex knowledge of how land use, human activity, and the condition of the water resources in the area under study have changed over time.

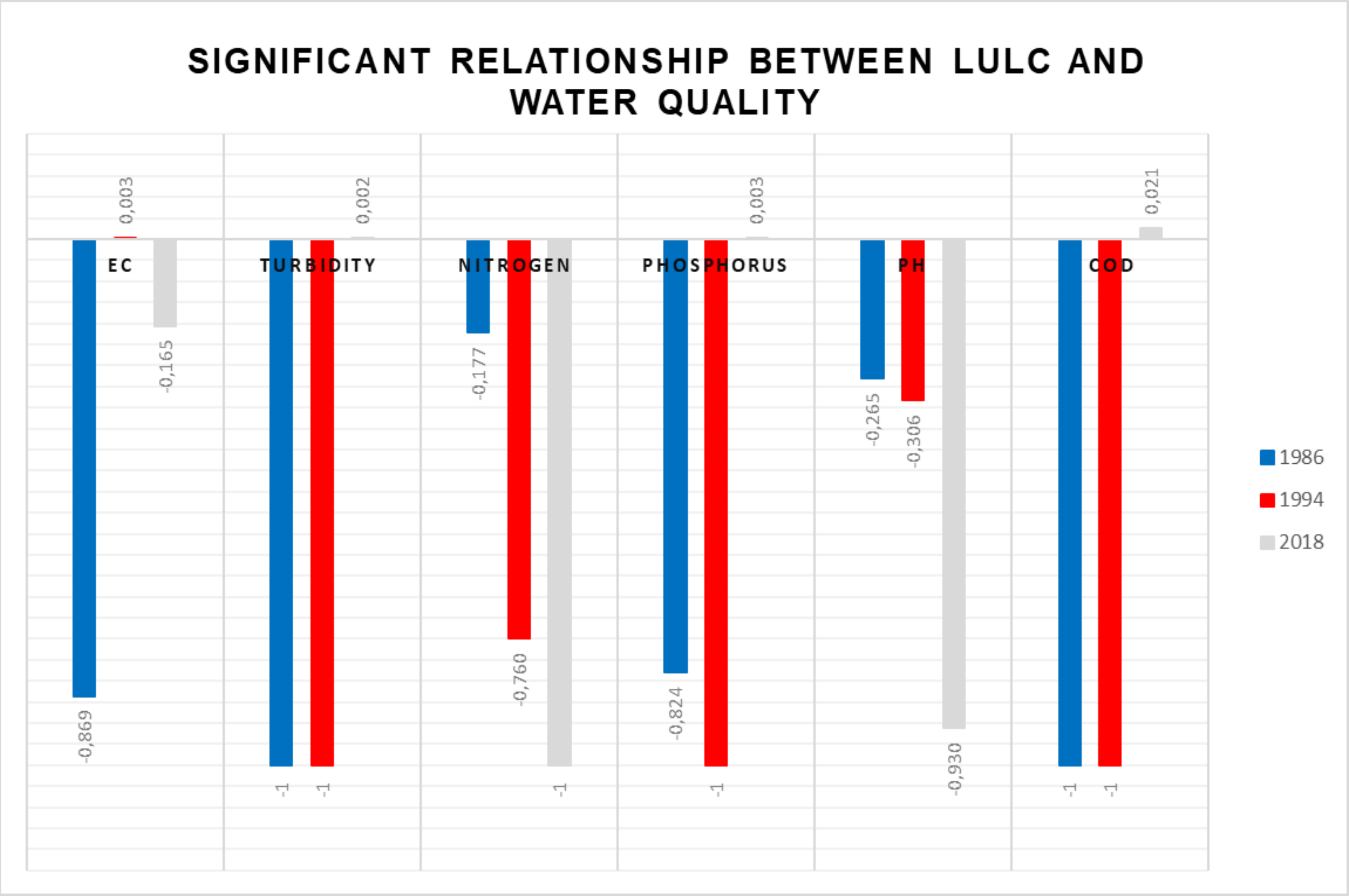


Figure 6.5: Illustration of the significant correlation between LULC and water quality.

6.4. Conclusion

The analysis conducted to unravel the connections between climate extremes, LULC and surface water quality parameters in the Letaba Catchment provides fascinating insights on the dynamic processes of the increasingly changing ecosystem. The subtle interaction observed in 1986, 1994, and 2018 has been significantly affected by the temporal dimension. A compatible balance or some independence between rainfall, land-use patterns and water quality over the period is implied by the 1986 lack of significant connection between rainfall, LULC and water quality parameters. This equilibrium, however, undergoes a subtle shift in 1994 with the emergence of a correlation, notably in electrical conductivity, indicating potential alterations in water composition linked to ions.

Among the water quality parameters, turbidity, phosphorus, and COD are the ones that exhibit a positive correlation with surface water quality, making 2018 a significant year. The findings suggests that during this time, water quality was more sensitive to contemporary land-use practices. The positive significance observed in 2018, particularly with parameters indicative of water stress or contamination, raises concerns about the influence of evolving land-use activities on the quality of water. The study consists of the dynamic nature of the relationship between climate extremes, LULC, and surface water quality, emphasizing the need for a holistic approach to water resource management. The observed patterns suggest that as the landscape transforms, so too does the delicate balance of water quality parameters.

Anthropogenic activities, industrial processes, and agricultural practices in the Letaba Catchment play a crucial role in shaping the quality of water resources, as evidenced by the significant correlations identified. As we navigate the complex factors of environmental developments, these findings show valuable insights for sustainable water resource management. Recognising the temporal variations and the evolving impact of land uses on surface water quality provides a foundation for informed decision-making and proactive measures to preserve the quality of our available water sources in the Letaba Catchment. The journey through this analysis serves as a reminder of the interconnectedness of natural systems and the responsibility we bear in ensuring the longevity and vitality of our water resources for generations to come.

7. CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

7.1. Conclusion

In conclusion, this study has focused on understanding how climate extremes and LULC impact water quality in the Letaba Catchment. With a specific emphasis on water quality, the study reveals great impact of climate change extremes on the chemical and physical parameters of the water within the catchment. Through various analysis methods, we've developed an understanding of the impacts and challenges in the face of the surface water quality changes. The escalating challenges associated with extreme climate events, particularly with projections of even a modest 1 °C increase in warming, emphasize the urgent need for adaptive strategies.

Our analysis of extreme weather conditions, like irregular precipitation patterns, has shown how these events impacted the water quality parameters in the Letaba Catchment. The changing precipitation patterns intensified low and high rainfalls whereby they acted as stressors disrupting the quality of water. On the contrary, the year 1994 experienced a significant reduction in rainfall, negatively affecting the cultivation of crops, water reservoirs, and ecosystems. This pattern persisted until 2018, signifying a continuous drop in precipitation levels that had adverse effects on water availability and agricultural productivity. These fluctuations highlighted the irregularity of rainfall in the Letaba catchment, presenting difficulties across different sectors. Moreover, the complex interplay of climate and land use changes amplifies the challenges faced by water resources in the Letaba Catchment. The evolving landscape dynamics observed from 1986 to 2018 underscore the need for adaptive water resource management strategies to address the increasing pressures on the water resource. This research aimed to contribute valuable insights to the broader discourse on sustainable environmental practices.

The findings necessitate proactive measures in water resource management, emphasizing the importance of climate adaptation strategies and sustainable land use practices. As we confront the impacts of environmental change, this study advocates for a holistic and integrated approach to ensure the resilience and sustainability of water resources in regions susceptible to climate extremes and evolving land use patterns.

7.2. Recommendations

In light of the findings from this research, several recommendations are put forth to guide effective water resource management, climate adaptation, and sustainable land use practices in the Letaba Catchment and similar regions facing environmental changes. Firstly, there is a crucial need for the adoption of Integrated Water Resource Management (IWRM) strategies that comprehensively address the interconnected dynamics of climate, land use changes, and water systems in particular surface water quality. This holistic approach should foster collaboration among diverse stakeholders, including legislation and policies, local communities, and environmental organizations.

Additionally, investing in climate-resilient infrastructure is important to mitigate the impacts of extreme climate events. This includes the development of robust water storage and distribution systems, flood control measures, and adaptive strategies for managing climate extremes conditions. Adaptive land use planning policies should be established, incorporating both current and future climate scenarios, with a focus on sustainable practices and zoning regulations. Strengthening monitoring and early warning systems is imperative to track changes in precipitation patterns, river morphology, and water quality, enabling timely responses to emerging challenges. Community engagement and education programs are vital for fostering environmental stewardship and promoting water conservation efforts at the local level.

Implementation of ecosystem restoration initiatives, such as reforestation projects and wetland restoration, can enhance the landscape's natural capacity to cope with climate-induced changes. Ongoing research, data sharing, and policy integration are essential for informed decision-making and the development of adaptive strategies. Building the capacity of local authorities and communities through training programs and workshops will empower them to implement effective water resource management practices. Lastly, implementing international collaboration and knowledge exchange can increase global expertise in addressing climate challenges, facilitating the adoption of best practices and shared learning experiences in managing water resources in a changing climate.

7.3. Limitations of the study

While this study contributes valuable insights into the complex interactions between climate, land use changes, and surface water quality in the Letaba Catchment, it is essential to acknowledge several limitations that may influence the interpretation and generalization of the findings. Firstly, the distribution of weather stations in the Letaba Catchment poses a limitation as they are not uniformly located to cover all areas of the catchment coupled with incompleteness of rainfall data. The non-uniform distribution may introduce spatial biases in the analysis, particularly considering that Letaba's mean annual precipitation varies across different parts of the catchment. The data obtained from the South African Weather Services (SAWS) lacked recent information beyond 2018, and some stations lacked historical data.

The use of historical satellite images also presents limitations. The images available for the year 1986 did not cover the entire Letaba Catchment, leaving a small portion of the area unaccounted for. This spatial gap introduces potential bias, particularly if the omitted area exhibits distinct land use or climate characteristics. In summary, while this study provides valuable insights, these limitations highlight the need for cautious interpretation and suggest avenues for further research to enhance the comprehensiveness and accuracy of future assessments of the Letaba Catchment and similar regions.

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