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**GEOSPATIAL TECHNIQUES TO PREDICT THE SPATIAL DISTRIBUTION  
OF WATER QUALITY IN NYANDUNGU WETLAND**

**A PROJECT REPORT**

*Submitted in partial fulfilment of the requirements for the award of*

**A MASTER OF SCIENCE DEGREE IN WATER RESOURCES AND  
ENVIRONMENTAL MANAGEMENT**

*Submitted by*

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## **BONAFIDE CERTIFICATE**

*This is to certify that the master's thesis entitled “**Geospatial techniques to predict the spatial distribution of water quality in Nyandungu wetland**” is a record of original bonafide work done by Armand ISSEINE MOUHORO (Reg.No: 221031981) in partial fulfilment of the requirement for the award of masters of science in Water resources and environmental management of University of Rwanda, College of Science and Technology during the Academic Year 2023-2024.*

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**DECLARATION**

I declare that this Dissertation contains my own work except where specifically acknowledged

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## CERTIFICATION

This research thesis has been submitted for examination with my approval as university supervisor.

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## ABSTRACT

The Nyandungu wetland, located in a rapidly urbanising region, is facing significant water quality challenges due to increasing human activities. This study aims to provide a comprehensive spatial analysis of *E. coli* contamination in the wetland, using kriging interpolation methods to map the distribution of this pollutant. *E. coli* was chosen as the main indicator of pollution because of its prevalence and implications for public health, serving as a critical marker for faecal contamination in water bodies. To achieve the objectives of this research, water samples were taken from various points in the Nyandungu wetland. These samples were analyzed for *E. coli* concentrations and their geographical coordinates were recorded to facilitate spatial analysis. The study used variogram analysis to understand the spatial structure of the data, followed by kriging interpolation to estimate *E. coli* concentrations at unsampled locations. The results were visualized using ArcGIS 10.8, creating thematic maps and interpolated surfaces illustrating the spatial distribution of *E. coli* contamination. These visualizations were enhanced by overlaying other geographical layers, providing a complete context for the analysis. The results revealed significant spatial variability in *E. coli* concentrations in the wetland, with some areas showing higher levels of contamination. For instance, observed concentrations ranged from as low as 10 CFU/100ml at some sampling points to as high as 94,300,000 CFU/100ml at others. Kriging interpolation predicted *E. coli* concentrations at unsampled locations, with values ranging from -5,065,838 CFU/100ml to 23,817,700 CFU/100ml, indicating areas of both potential underestimation and overestimation of contamination. These results highlight the need for targeted interventions to mitigate sources of pollution and protect the wetland ecosystem.

In addition to *E. coli*, other water quality parameters such as pH, temperature, biochemical oxygen demand (BOD), dissolved oxygen (DO) and heavy metals were analyzed to provide an overall understanding of the state of the wetland. These parameters were also spatially analyzed to identify areas of concern and their potential impact on the ecological health of the wetland.

In conclusion, this research provides a detailed methodological framework for the spatial analysis of water quality using kriging interpolation. The knowledge gained from this study is crucial for the sustainable management of the Nyandungu wetland and can inform future efforts to monitor and improve water quality in similar ecosystems.

**Key words:** Nyandungu wetland, water quality, *E. coli* contamination, kriging interpolation, spatial analysis, geospatial techniques, ArcGIS, wastewater treatment

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## LIST OF ABBREVIATIONS

- **GIS:** Geographic Information System
- **GPS:** Global Positioning System
- **RS:** Remote Sensing
- **DO:** Dissolved Oxygen
- **BOD:** Biological Oxygen Demand
- **pH:** Potential of Hydrogen (measure of acidity or alkalinity)
- **E. coli:** Escherichia coli
- **DO:** Dissolved Oxygen
- **Cd:** Cadmium
- **Cu:** Copper
- **Mn:** Manganese
- **Pb:** Lead
- **REMA:** Rwanda Environment Management Authority
- **Kriging:** A geostatistical interpolation technique
- **RMSE:** Root Mean Square Error
- **MAE:** Mean Absolute Error

# CHAPTER 1 INTRODUCTION

## 1.1 Background

Water is a vital resource for life on Earth [1]. It plays an important role in maintaining ecosystems[2], supporting biodiversity [3] and providing essential ecosystem services [4]. Water quality depends on several physico-chemical and biological parameters such as pH, conductivity, turbidity, nutrient concentrations (such as nitrates and phosphates), and the presence of microbiological contaminants [5]. Good water quality is essential not only for the health of aquatic ecosystems but also for human well-being, as water is used for drinking, irrigation, recreation and various industrial activities [6].

Degradation of water quality can have serious consequences. For ecosystems, it can lead to a loss of biodiversity, disruption of food chains and a reduction in the productivity of aquatic habitats [7]. For humans, poor water quality can lead to water-related diseases, affect food production, and involve high economic costs for water treatment and resource management [6].

The Nyandungu wetland, located in the heart of the city of Kigali, Rwanda, is a precious ecosystem that plays a crucial role in hydrological regulation, water purification and the provision of habitats for a wide variety of flora and fauna. However, the area is facing major water quality challenges due to increasing human pressures.

Rapid urbanization and industrialization around the wetland are leading to the discharge of untreated domestic and industrial waste into watercourses, increasing levels of chemical and biological contaminants [8]. Excessive use of fertilizers and pesticides in neighbouring agricultural areas contributes to nutrient and chemical loads in run-off water, leading to eutrophication and degradation of water quality [9]. Deforestation and unsustainable agricultural practices increase soil erosion, leading to excessive sedimentation and increased turbidity in wetland waters [10].

These specific pollution problems have a direct impact on the health of aquatic ecosystems and the human populations that depend on these resources. It is therefore crucial to establish effective water quality monitoring and forecasting systems to manage and reduce these impacts.

Water quality monitoring and forecasting are key elements in the sustainable management of water resources. Regular monitoring helps to detect changes in water quality parameters, identify sources of pollution, and assess the effectiveness of management measures in place.

Forecasting, for its part, makes it possible to anticipate future variations in water quality, plan preventive action and reduce the risks to ecosystems and human health [11].

The use of advanced technologies, such as Geographic Information Systems (GIS) and spatial interpolation methods like kriging, offers powerful tools for improving water quality monitoring and forecasting [12]. ArcGIS, in particular, enables effective visualization and analysis of spatial data, facilitating informed decision-making for water resource management [13].

## **1.2 Problem Statement**

The Nyandungu wetland in Rwanda is a critical ecological zone that plays an important role in water purification, biodiversity conservation and flood control. However, this wetland is under increasing threat from various forms of pollution, which pose serious risks to human and wildlife health and compromise the wetland's ecological functions [14].

Despite its importance, there is no comprehensive data on water quality throughout the Nyandungu wetland, mainly due to the logistical and financial constraints associated with in-depth field sampling. Consequently, there is an urgent need to estimate water quality parameters at unsampled locations in the wetland to obtain a full understanding of contamination levels and their spatial distribution [15].

This study aims to fill this gap by using geostatistical interpolation methods, in particular Ordinary Kriging, to estimate water quality parameters at unobserved points in the Nyandungu wetland. Using water quality data obtained by the University of Rwanda laboratory, this research aims to create a detailed spatial representation of water quality across the wetland. The results of this study will provide essential information for environmental management and policy development, enabling targeted interventions to mitigate pollution and protect this vital ecosystem.

## **1.3 Research Objectives**

### **1.3.1 Main objective:**

Predicting the spatial distribution of pollution and water quality using geospatial tools.

### **1.3.2 Specific objective:**

- To define the key parameters used to assess water quality.

- To spatially visualize water quality measurements: Use geographic information systems (GIS) and remote sensing techniques to map water quality data.
- To interpolate data to estimate water quality at unobserved points: Apply geostatistical interpolation methods (kriging) to predict water quality values in unsampled areas.
- To evaluate the accuracy of predictions: validate prediction models by comparing interpolated values with field data, and calculate accuracy

#### **1.4 Research questions**

- Spatial Distribution of Pollution and Water Quality: How can geospatial tools be used to predict the spatial distribution of pollution in the Nyandungu wetland?
- Key Parameters for Water Quality Assessment: What are the key parameters needed to effectively assess water quality in the Nyandungu wetland?
- Visualization and Mapping of Water Quality Data: How can geographic information systems (GIS) and remote sensing techniques be used to visualize and map water quality measurements in the Nyandungu wetland?
- Interpolation and Estimation of Water Quality: Which geostatistical interpolation is most effective for estimating water quality at unobserved points in the Nyandungu wetland? How can these methods be applied to provide reliable and accurate predictions of water quality?
- Validation and Accuracy of Predictions: How can the accuracy of water quality prediction models be assessed and validated using field data in the Nyandungu wetland?

#### **1.5 Hypothesis**

The hypotheses of this study are as follows:

- Water quality in the Nyandungu Wetland varies spatially based on pollution sources and local environmental characteristics.
- The kriging method, applied using ArcGIS tools, accurately predicts the spatial distribution of water quality parameters.
- Thematic maps generated by spatial interpolation provide useful information for water quality management and restoration in the wetland.

## **1.6 Scope of the study**

This study focuses on the Nyandungu Wetland and its catchment located in the Kigali region of Rwanda. The scope of the study includes:

- **Data Collection:** Gathering water quality data from various sampling points within the Nyandungu Wetland.
- **Application of Kriging Method:** Utilizing the kriging method for spatial interpolation of water quality data, using ArcGIS software to generate thematic maps.
- **Data Analysis and Visualization:** Analyzing the collected data and interpreting the results through thematic maps. This analysis will help identify critical areas and potential sources of pollution.
- **Management Recommendations:** Formulating recommendations for the management and restoration of water quality in the Nyandungu Wetland based on the study results.

## **1.7 Research significance**

### **1.7.1 Contribution to Scientific Knowledge**

This study makes a significant contribution to understanding the spatial distribution of water quality in urban wetlands. By utilizing advanced interpolation techniques, it provides detailed and precise information that can guide future research and management practices.

### **1.7.2 Data-Driven Management Tools**

By developing data-driven management tools, this study assists wetland managers and local authorities in making informed decisions to enhance water quality. Thematic maps and predictive models generated by this study can be used to monitor and effectively manage water resources.

### **1.7.3 Practical Implications**

The findings of this study have significant practical implications for the conservation of aquatic ecosystems and public health. By identifying critical areas and pollution sources, this study offers specific recommendations for water quality management and restoration, contributing to the region's sustainable development.

#### **1.7.4 Community Engagement**

By raising awareness among local communities about water quality importance and involving them in management efforts, this study promotes sustainable community engagement. Active community participation is essential for the long-term success of water quality management initiatives.

#### **1.7.5 Replicability and Applicability**

The methodologies developed in this study can be replicated and applied in other similar contexts. The results and spatial interpolation techniques can serve as a reference for future studies and the implementation of water resource management practices in other urban wetlands.

## **CHAPTER 2 LITERATURE REVIEW**

### **2.1 Introduction**

Wetlands are among the most productive and valuable ecosystems on the planet, offering a multitude of ecological, economic and social benefits. These areas, characterized by water-saturated soils that may be permanently or seasonally flooded, encompass a variety of landscapes such as marshes, swamps, bogs and fens. The ecological importance of wetlands extends far beyond their borders, influencing water quality, climate regulation and biodiversity conservation on a global scale [16].

### **2.2 Threats to wetland ecosystems**

Despite their importance, wetlands are among the world's most threatened ecosystems. Human activities such as agriculture, urban development and industrialization have led to widespread degradation and loss of wetlands. Drainage and land reclamation for agriculture and infrastructure projects disrupt the hydrological balance of wetlands, leading to habitat loss and reduced ecological functionality. Pollution from agricultural run-off, industrial discharges and untreated wastewater further compromises water quality and biodiversity in wetlands [17].

Climate change poses a further threat to wetlands, altering precipitation patterns and increasing the frequency of extreme weather events. Rising temperatures and altered hydrological regimes can lead to changes in wetland vegetation and hydrology, affecting their ability to provide ecosystem services. Sea-level rise, in particular, threatens coastal wetlands with inundation and salinization, impacting both their ecological integrity and the communities that depend on them [18].

### **2.3 The need for effective wetland management**

Given the essential functions and benefits of wetlands, effective management strategies are essential to ensure their sustainability. Degradation and loss of wetlands not only compromise their ecological and economic benefits, but also pose significant risks to water quality, flood control and biodiversity. It is therefore imperative to adopt comprehensive management approaches that integrate conservation, restoration and sustainable use of wetland resources [19].

## **2.4 Wetlands in wastewater treatment**

Wetlands are increasingly recognized as effective natural systems for wastewater treatment due to their ability to remove a wide range of pollutants through a variety of mechanisms. These mechanisms include physical filtration, chemical adsorption and biological processes, each playing a crucial role in maintaining water quality. Understanding these mechanisms in detail is essential to optimizing the use of wetlands for wastewater treatment and ensuring their long-term sustainability [20].

### **2.4.1 Pollutant removal mechanisms**

#### **2.4.1.1 Physical filtration**

Physical filtration is one of the main mechanisms by which wetlands remove pollutants from wastewater. This process involves the trapping and settling of particles, including suspended solids, sediments and debris, as water flows through the wetland. The dense vegetation and complex root systems of wetlands act as natural filters, slowing the flow of water and allowing particles to settle out of the water column. This reduction in flow velocity promotes sedimentation and prevents the resuspension of deposited particles, thus improving water clarity and quality [21].

In addition to trapping larger particles, physical filtration in wetlands also contributes to the removal of smaller particulate pollutants, such as colloids and fine sediments. The complex network of plant roots and stems provides a large surface area for the binding and aggregation of these fine particles, facilitating their removal from the water. This process is particularly effective in removing pollutants associated with particles, such as heavy metals, phosphorus and organic contaminants [20], [21].

#### **2.4.1.2 Chemical adsorption**

Chemical adsorption is another essential mechanism by which wetlands remove pollutants from wastewater. This process involves the binding of dissolved contaminants to the surface of soil particles, organic matter and plant roots in the wetland. Chemical adsorption is governed by a variety of forces, including electrostatic attraction, van der Waals forces and chemical bonding, which facilitate the attachment of pollutants to solid surfaces [22].

One of the key elements of chemical adsorption in wetlands is the presence of organic matter, such as peat, humus and decomposed plant material. These organic substances have a high

affinity for a wide range of pollutants, including heavy metals, nutrients and organic compounds. The high surface area and complex structure of organic matter enhances its ability to adsorb contaminants, thereby reducing their concentration in water [23], [24].

Soil particles, particularly clay minerals, also play an important role in chemical adsorption. The negatively charged surfaces of clay particles attract and bind positively charged ions, such as heavy metals (lead, cadmium and zinc) and ammonium. This process, known as cation exchange, contributes to the immobilization and removal of these contaminants from water [25].

In addition, the presence of iron and aluminium oxides in wetland soils can facilitate phosphate adsorption, reducing the risk of eutrophication [26].

#### **2.4.1.3 Biological processes**

Biological processes are perhaps the most diverse and dynamic mechanisms for removing pollutants from wetlands. These processes involve the activity of micro-organisms, plants and animals that interact with pollutants in a variety of ways, contributing to the overall efficiency of wastewater treatment [27].

##### **2.4.1.3.1 Microbial activity**

Microorganisms, including bacteria, fungi and protozoa, play a crucial role in the degradation and transformation of pollutants. Through processes such as biodegradation, nitrification, denitrification and sulphate reduction, these microorganisms can break down organic matter, convert harmful substances into less toxic forms and remove nutrients from the water. For example, aerobic bacteria can break down organic pollutants in the presence of oxygen, while anaerobic bacteria can perform similar functions in oxygen-depleted conditions. This microbial activity is vital for the removal of organic contaminants, nitrogen compounds and other pollutants [28], [29].

#### **Plant Uptake and Phytoremediation:**

Wetland vegetation plays a crucial role in removing pollutants through processes like uptake and phytoremediation. Wetland plants can absorb nutrients like nitrogen and phosphorus from water, incorporating them into their biomass. This mechanism not only assists in nutrient removal but also helps prevent eutrophication, a phenomenon often causing harmful algal blooms and oxygen depletion in aquatic environments. Moreover, certain wetland plant species

can accumulate heavy metals and other toxic substances in their tissues, thereby reducing the concentration of these pollutants in water sources [30].

### **Rhizosphere Interactions:**

The rhizosphere, the soil area surrounding plant roots, exhibits significant microbial activity and interactions. Plants release organic compounds through their roots that serve as a food source for microorganisms, promoting their growth and activity. This mutualistic relationship enhances pollutant degradation within the rhizosphere [31]. Additionally, wetland plant root systems create diverse microenvironments with varying oxygen levels, supporting both aerobic and anaerobic microbial processes. This microbial habitat diversity facilitates the concurrent removal of different pollutant types [32].

### **Animal Contributions:**

Various animal species, including invertebrates and amphibians, contribute to pollutant removal in wetlands. Through feeding and burrowing activities, these animals aid in the decomposition of organic matter, enhancing microbial activity. Some animals also bioaccumulate pollutants in their tissues, further supporting the elimination of contaminants from water bodies [33].

The intricate combination of physical, chemical, and biological processes within wetlands establishes a highly efficient system for wastewater treatment. By leveraging the natural capacities of these ecosystems, significant advancements in water quality improvement can be achieved while fostering biodiversity and ecological well-being [34]. The comprehension and optimization of these processes are essential for the sustainable utilization of wetlands in wastewater treatment and in addressing the escalating challenges of water pollution [35].

## **2.5 Challenges in wetland wastewater treatment**

Wetlands, known for their effectiveness in treating wastewater, encounter various challenges that jeopardize their health and functionality. Among the predominant challenges is the impact of land use alterations, encompassing agricultural practices, urban expansion, and industrial operations[35]. These activities introduce an array of pollutants into wetlands, leading to degradation and compromised wastewater treatment efficiency [36].

## **2.5.1 Impact of Land Use on Wetland Health**

### **2.5.1.1 Agricultural activities**

Agricultural practices stand out as a significant source of pollutants that detrimentally influence wetland health. The application of fertilizers, pesticides, and herbicides in agricultural activities results in the runoff of these chemical substances into adjacent wetlands [36]. Fertilizers, abundant in nitrogen and phosphorus, contribute to nutrient pollution, potentially causing eutrophication, a phenomenon marked by rapid algal and aquatic plant proliferation. Eutrophication depletes oxygen levels within water bodies, inducing hypoxic conditions detrimental to aquatic life [35].

Conversely, the use of pesticides and herbicides introduces toxic compounds into wetlands, accumulating in plant and animal tissues, leading to bioaccumulation and biomagnification throughout the food chain [33]. The presence of these noxious substances can diminish biodiversity, alter species composition, and impede the ecological functions of wetlands [34]. Also, the agricultural disturbance of lands, notably ploughing and irrigation, can instigate soil erosion and sedimentation within wetlands. Augmented sediment loads can suffocate aquatic habitats, diminish water transparency, and disrupt the natural hydrology of wetlands [37].

### **2.5.1.2 Urban development**

Urbanization poses significant threats to wetland health by discharging pollutants from residential, commercial, and infrastructural ventures. Stormwater runoff serves as a primary source of pollution in urban settings. Impermeable surfaces like roads, parking lots, and rooftops impede water infiltration, heightening surface runoff containing a mix of pollutants like oils, heavy metals, nutrients, and sediments into wetland areas [38].

The progression of urban areas also accentuates habitat fragmentation and loss. Wetlands are frequently drained or filled to accommodate buildings, roads, and other infrastructure, resulting in diminished wetland area and connectivity. This habitat loss not only reduces the wastewater treatment capacity of wetlands but also diminishes their capability to sustain biodiversity and provide other ecosystem services [39].

### **2.5.1.3 Industrial activities**

Industrial engagements represent another notable source of pollutants threatening wetland functionality. Industries discharge diverse contaminants, including heavy metals, organic compounds, and thermal pollutants, into proximate water bodies such as wetland [40]s. Heavy

metals like lead, mercury, and cadmium are particularly detrimental due to their persistence in the environment and propensity to bioaccumulate within organisms, posing risks to wildlife health and human well-being through contaminated water and food consumption [41].

Organic compounds such as solvents, hydrocarbons, and industrial chemicals also pose substantial hazards to wetland ecosystems, being toxic to aquatic life, disrupting endocrine systems, and diminishing reproductive success. Moreover, certain organic pollutants exhibit resistance to natural degradation processes, perpetuating long-term contamination of wetland environments [42].

Thermal pollution ensuing from the discharge of heated water from industrial activities can perturb the temperature dynamics of wetlands. Elevated water temperatures can reduce dissolved oxygen levels, impacting the survival of temperature-sensitive species and altering aquatic community compositions. Additionally, thermal pollution can foster the proliferation of invasive species that outcompete native flora and fauna, further undermining the ecological integrity of wetlands [43], [44].

## **2.6 Geospatial techniques in wetland management**

Geospatial techniques, such as Geographic Information Systems (GIS) and remote sensing, have transformed the way wetlands are monitored, assessed, and managed. These technologies provide powerful tools for the collection, analysis, and interpretation of spatial data, enabling more effective and sustainable management of wetland ecosystems [12]. This section delves into the advantages of geospatial techniques in wetland management, drawing on the works of [12].

### **2.6.1 Advantages of geospatial techniques**

#### **2.6.1.1 Continuous surveillance and monitoring**

One of the key advantages of geospatial techniques is the ability to continuously monitor wetlands on a large scale. Remote sensing, for instance, enables data collection from satellites and drones, providing extensive spatial and temporal coverage. This capability is particularly valuable for tracking changes in wetlands, such as variations in vegetation cover, water levels, and the impacts of anthropogenic activities. [12] Emphasize that remote sensing offers valuable insights for detecting long-term modifications in wetland ecosystems, facilitating informed decision-making for their conservation and management.

### **2.6.1.2 Precision and data detail**

GIS and remote sensing provide unparalleled precision and detail in collecting and analyzing spatial data. High-resolution satellite images and Light Detection and Ranging (LiDAR) data enable the precise mapping of wetland features like topography, vegetation, and water bodies. Lunetta [45] demonstrate that the use of high-resolution geospatial data enhances the ability to identify and delineate wetlands, even in complex and heterogeneous environments [45]. This precision is essential for developing tailored management plans and assessing the effectiveness of conservation measures.

### **2.6.1.3 Multi-temporal analysis and change detection**

Geospatial techniques also enable multi-temporal analysis, which involves comparing data collected at different time points to detect changes in wetlands. This capability is crucial for understanding ecological dynamics and long-term trends. For instance, Jensen [46] explains how multi-temporal analysis of satellite images can reveal degradation or restoration trends in wetlands, providing vital information to guide management interventions[46]. Change detection allows for swift responses to emerging threats such as urbanization, intensive agriculture, or the impacts of climate change.

### **2.6.1.4 Integration of multi-source data**

GIS provides the capacity to integrate and overlay data from multiple sources, including satellite images, field surveys, and environmental databases. This integration facilitates a holistic understanding of wetland ecosystems and the factors influencing them. Nsengiyumva [12] underline the importance of combining geospatial data with socio-economic and hydrological information for integrated and sustainable wetland management [12]. Integrating these datasets enables the development of predictive models and management scenarios that consider the complex interactions between natural and anthropogenic factors.

### **2.6.1.5 Accessibility and information sharing**

Geospatial technologies also enhance the accessibility and sharing of information among various stakeholders involved in wetland management. Online GIS platforms and geospatial data portals make it easy to disseminate information to managers, decision-makers, and the public. Lunetta [45] emphasize that the transparency and availability of geospatial data strengthen collaboration and coordination among stakeholders, fostering participatory and inclusive wetland management [45]. Moreover, access to updated and reliable data facilitates

public awareness and education on the importance of wetland conservation, encouraging active participation in their protection.

#### **2.6.1.6 Evaluation of management effectiveness**

Geospatial techniques are valuable for evaluating the effectiveness of wetland management and restoration measures. By providing accurate and up-to-date data, they enable monitoring of progress and adjustment of management strategies based on outcomes. For example, Jensen [46] explains how satellite images can assess changes in vegetation cover and water levels post-implementation of restoration projects [46]. This ongoing evaluation is crucial to ensure that management interventions meet their objectives and to identify areas requiring adjustments.

#### **2.6.1.7 Cost reduction and time savings**

The use of geospatial techniques can also reduce costs and time required for monitoring and managing wetlands. Data collection through remote sensing and GIS analysis allows for quicker and more cost-effective coverage of large areas compared to traditional field survey methods. Nsengiyumva [12] note that the cost and time efficiency of geospatial techniques make them particularly suitable for large-scale wetland management projects where resources may be limited [12]. Furthermore, the ability to automate certain analyses and utilize predictive models can further enhance the efficiency of management operations.

### **2.7 Kriging method**

Kriging is a sophisticated geostatistical method used for spatial interpolation. It is widely recognized for its ability to provide optimal estimates and associated measures of uncertainty [12]. This section explores the theory and principles of the kriging method, as well as its applications in the field of water quality [47].

#### **2.7.1 Theory and principles of the kriging method**

##### **2.7.1.1 Kriging theory**

Origin: The kriging method is named after the South African geostatistical Danie Krige, who developed it for mineral reserve estimation. It was formalized by Georges Mat heron in the 1960s [48].

### 2.7.1.1.1 Fundamental principle

Kriging is based on the assumption that spatial variables exhibit spatial dependence structure, meaning that points close in space are more similar than distant points. This dependence is modelled by a variogram [49].

**Variogram:** The variogram is a function that describes the variation in the difference between point values as a function of the distance separating them [50]. It is defined by:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (2.1)$$

Where  $\gamma(h)$  is the value of the variogram at distance  $h$ ,  $N(h)$  is the number of point pairs separated by distance  $h$ , and  $Z(x_i)$  is the value of the variable at point  $x_i$ .

**Variogram Models:** Variograms can be fitted to several theoretical models such as the spherical, exponential, Gaussian models, etc. The choice of the model depends on the data nature and the observed spatial structure.

### 2.7.1.2 Types of kriging

- **Ordinary Kriging:** The most common form of kriging, which assumes a constant but unknown mean in the study area.
- **Universal Kriging:** Used when the mean is assumed to systematically vary in space, often based on explanatory variables.
- **Simple Kriging:** Assumes a constant and known mean.
- **Co-Kriging:** Utilizes correlated auxiliary variables to improve estimates.

### Mathematical formulation:

Estimation: The interpolated value  $Z^*(x)$  at a location  $X$  is a weighted linear combination of the measured values:

$$Z^*(x) = \sum_{i=1}^n \lambda_i Z(x_i) \quad (2.2)$$

Where  $\lambda_i$  are the weights determined by minimizing the mean squared error of the estimation, subject to the absence of bias.

Kriging System of Equations: The weights  $\lambda_i$  are obtained by solving a system of linear equations based on the variogram and the distances between the measurement points and the point to be estimated.

## **2.8 Application of Geospatial Techniques in Wetland Management**

Geospatial techniques have played an essential role in wetland management in Africa, as shown by several case studies. In the Bugesera wetlands of Rwanda [12], researchers used remote sensing, GIS analysis and field sampling to map wetlands, identify pollution sources and assess heavy metal contamination, revealing high levels of lead, cadmium and mercury. In Kenya, J. Ambundo [51] applied kriging to assess groundwater quality in the Mbagathi River catchment, identifying areas of high pollution using spatial distribution patterns of pH, electrical conductivity and nitrate levels. Similarly, H.G. Rendilicha and Halake Guyo [52] used kriging to study the impact of land use on groundwater quality in the Mid River Njoro catchment, identifying areas of poor water quality. In addition, S. Mwendwa [53] carried out a detailed soil survey in the Upper Kabete Campus Field, using kriging to map heavy metal concentrations and identify hot spots of contamination. Collectively, these studies underline the effectiveness of geospatial techniques in monitoring the environment, detecting pollution and informing sustainable management practices in African wetlands.

## **CHAPTER 3 METHODOLOGY**

### **3.1 Introduction**

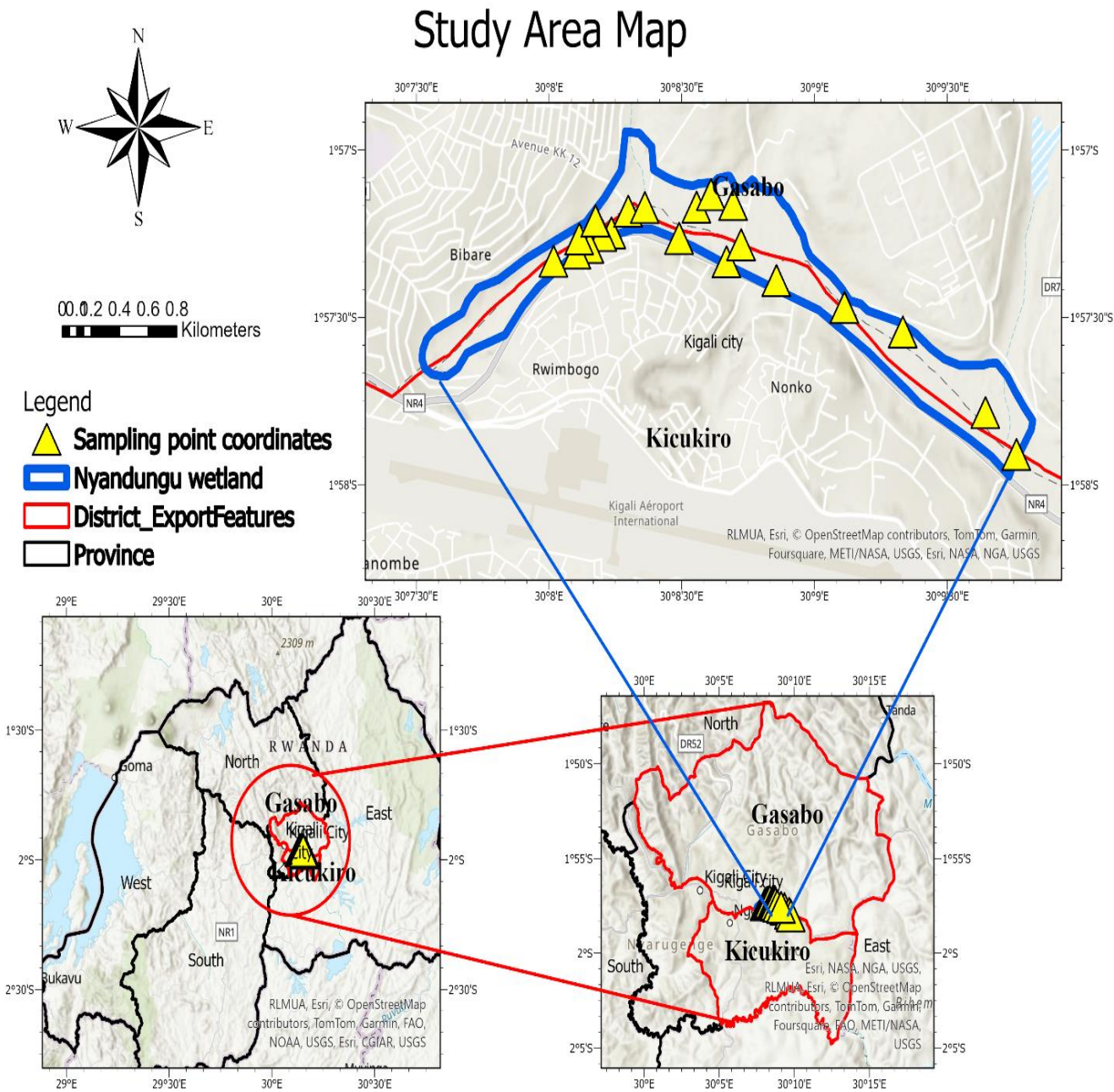
This chapter describes the methods and principles used in this study. It includes a detailed description of the study area, sample collection and preservation processes, research materials and tools, and data analysis methods. The aim is to provide a clear and comprehensive understanding of the methodological approaches adopted to assess water quality and interpret the results obtained.

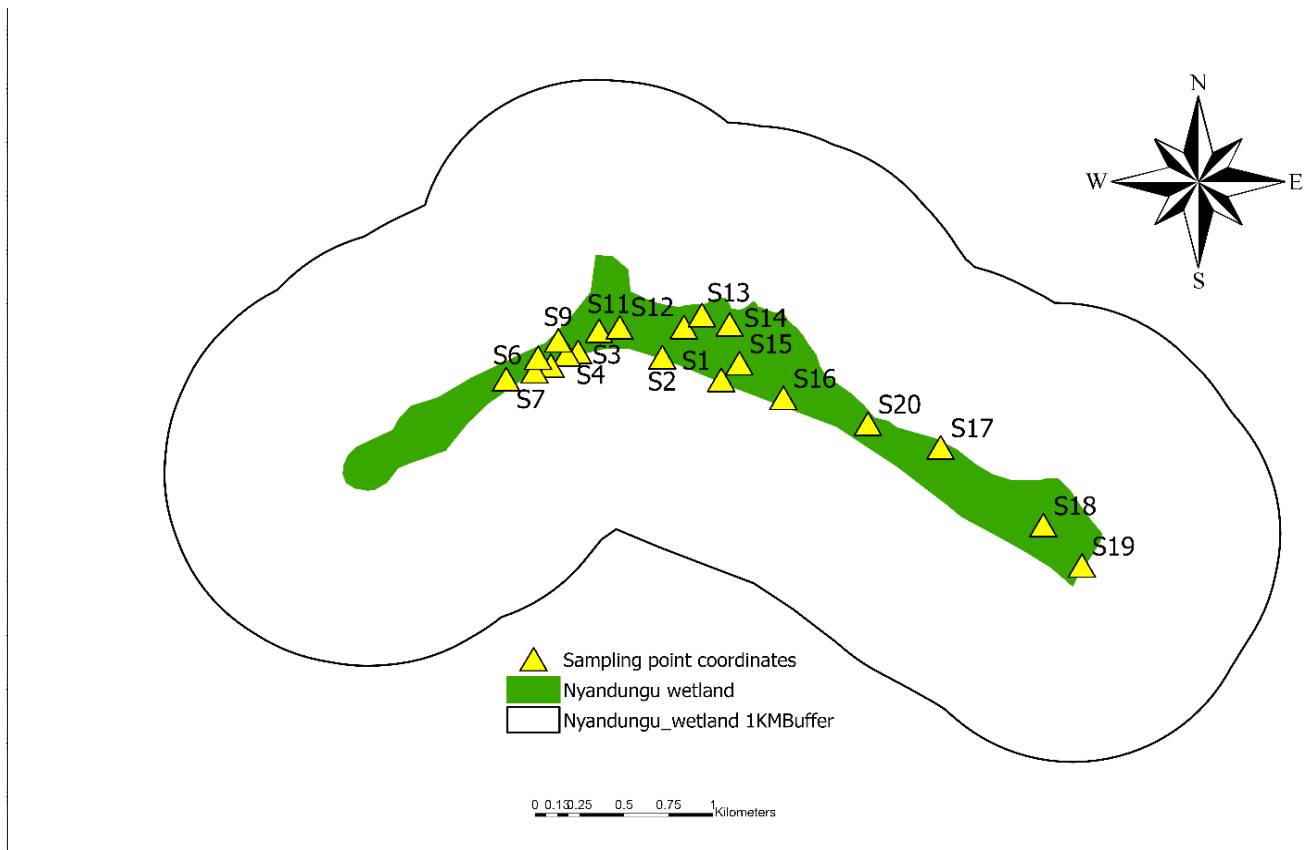
### **3.2 Study area**

The description of the Nyandungu Wetland in the Kigali City of Rwanda depicts it as a significant ecological and hydrological asset in the region. This urban wetland, spanning approximately 130 hectares, plays a pivotal role in the urban ecosystem, providing various environmental, social, and economic benefits [54].

#### **3.2.1 Geographical location**

located in two districts of Kigali include Gasabo District, the Nyandungu Wetland is positioned between the coordinates 1°57' S latitude and 30°05' E longitude. It rests within the Nyandungu Valley, bordered by the Nyabugogo River to the west and the Kigali International Airport to the east. This strategic location within the urban framework of Kigali enhances accessibility and emphasizes the wetland's importance in terms of ecological conservation and urban development planning [54].





**Figure 3.2: Map showing wetland with sampling points**

### 3.2.2 Size and structure

With an approximate area of 130 hectares, Nyandungu Wetland stands as one of the largest urban wetlands in Kigali. Its landscape features a blend of habitats containing marshes, open water areas, and periodically inundated grasslands. Characterized by a relatively flat topography with gentle slopes, the wetland facilitates water flow and retention efficiently. The hydrology of Nyandungu is influenced by surface runoff from surrounding urban zones and groundwater inflows, contributing to a dynamic and varied aquatic ecosystem [54].

### 3.2.3 Overview of the main sources of water pollution

Human and industrial activities that influence water quality in the Nyandungu Wetland area include:

1. Urbanization and development: The rapid growth of the city of Kigali has led to increased pressure on wetlands, with construction and development activities altering the landscape and increasing pollutant-laden rainwater runoff [55].
2. Agriculture: Intensive farming practices around wetlands contribute to water pollution from agricultural chemicals and sediments [56].
3. Industry: Industrial activities in the vicinity, particularly small-scale cottage industries, can discharge untreated or partially treated industrial effluent into watercourses [57].
4. Recreational activities: Ecotourism and recreational activities in Nyandungu Ecotourism Park can also have an impact on water quality if not managed sustainably [58].

The Nyandungu Wetland restoration project aims to mitigate these impacts by improving stormwater management, filtering runoff and rehabilitating natural habitats to improve water quality and the ecological resilience of the area.

#### **3.2.4 Justification for selecting the study area**

1. Ecological importance: The Nyandungu marsh is a wetland of major ecological importance. Wetlands play a crucial role in natural water filtration, flood regulation and biodiversity conservation [59].
2. Urban proximity: Located close to Kigali, Rwanda's capital, the Nyandungu marsh is directly influenced by urban and industrial activities. This makes it an ideal site for studying the impact of urbanization on wetlands and their capacity to treat wastewater.
3. Restoration project: The Nyandungu marsh has been the subject of an ecological restoration project aimed at improving water quality and rehabilitating natural habitats. Studying this area allows us to assess the effectiveness of restoration interventions and provide valuable data for similar projects elsewhere [60].
4. Data accessibility: The availability of accurate geospatial and hydrological data for this area facilitates the application of geospatial techniques for water quality assessment.
5. Representativeness: Nyandungu Marsh is representative of urban wetlands in developing regions. The results of this study can be extrapolated to other urban wetlands facing similar challenges.

### **3.3 Defining the key parameters used to assess water quality**

#### **3.3.1 Parameter selection and rationale**

The selection of parameters for assessing water quality is crucial to obtaining a complete understanding of the state of the water and the potential impacts on human health and the environment. The parameters chosen for this study include physical, chemical and biological indicators. Here is a rationale for each of the selected parameters:

1. pH: measures the acidity or alkalinity of water. It is essential because it influences the solubility and toxicity of heavy metals and other contaminants. A pH that is too acidic or too alkaline can also affect aquatic life [61].

2. Temperature: Water temperature affects oxygen solubility and the speed of chemical reactions. It also influences the metabolic rates of aquatic organisms. Abnormal temperature variations may indicate thermal pollution from industrial discharges [62].

3. Biological Oxygen Demand (BOD): measures the amount of oxygen required to decompose organic matter present in water. High levels of BOD indicate a high presence of organic matter, often due to domestic or industrial wastewater discharges, which can lead to a reduction in dissolved oxygen and affect aquatic life [63].

4. Dissolved oxygen (DO): Dissolved oxygen is crucial to the survival of aquatic organisms. Low DO levels can indicate excessive organic pollution and poor water quality. DO is also affected by temperature and BOD [64].

5. Lead (Pb): Lead is a toxic heavy metal that can originate from industrial discharges, old pipes and mining activities. It is hazardous to human health and aquatic life, even at low concentrations [65].

6. Cadmium (Cd): Cadmium is another toxic heavy metal, often found in industrial effluents and fertilizers. It can accumulate in aquatic organisms and cause adverse health effects [66].

7. Copper (Cu): Copper is essential at low concentrations for aquatic life, but becomes toxic at higher concentrations. It can come from industrial effluents, pesticides and copper pipes [66].

8. Manganese (Mn): Manganese, although necessary in small quantities, can be toxic in high concentrations. It can come from mining and industrial activities. Manganese also affects the colour and taste of water [67].

9. *Escherichia coli* (*E. coli*): *E. coli* is a key indicator of fecal contamination in water. Its presence indicates pollution by domestic sewage or animal excrement, which can pose significant risks to human health by causing waterborne diseases. Since *E. coli* is the most important pollutant in this study, it is essential to monitor its concentration to assess health risks and the effectiveness of water treatment measures [68].

These parameters have been selected to provide a comprehensive assessment of water quality, taking into account physical, chemical and biological aspects. By monitoring these parameters, we can detect sources of pollution, assess impacts on human health and the environment, and guide efforts to manage and restore water resources.

### **3.3.2 Water quality data collection methods**

Water quality data collection is essential for assessing the ecological state of the Nyandungu Wetland and identifying potential sources of pollution. Data collection methods involve sampling, the use of specific measuring instruments, and the implementation of rigorous protocols to ensure data accuracy and reliability.

#### **3.3.2.1 Sampling**

**Sampling Sites:** Specific sites are selected throughout the wetland to represent different hydrological and ecological characteristics. These sites include water sources, streams, ponds, and densely vegetated areas.

**Sampling techniques:** Samples are collected using sterile 500mL bottles rinsed with sample water and immediately preserved in a cooler box to prevent biological changes in wastewater quality parameters. The samples are stored under appropriate conditions and promptly transported to the chemical laboratory at the University of Rwanda for analysis.

#### **3.3.2.2 Measuring instruments**

**Hack multimeter (HQ40d):** Used in the field to instantaneously measure several water quality parameters such as pH, conductivity, and temperature.

**Closed reflux method 5220 D:** Used to determine chemical oxygen demand (COD) in water samples. This method measures the quantity of oxygen required to completely oxidise the organic matter present in the water.

**Spectrophotometers:** Employed in the laboratory for detailed analysis of chemical and biological water parameters.

**Agilent 4210 MPAES:** Used for elemental analysis by microwave plasma atomic emission spectrometry. This instrument is used to determine the concentrations of various metallic elements in water samples.

**Cooler box:** Used for transporting and storing water samples at low temperatures to prevent any alteration or degradation of the samples prior to laboratory analysis.

### 3.4 Spatial visualization of water quality measurements

#### 3.4.1 Geostatistical methods

##### 3.4.1.1 Introduction

One of the specific objectives of this study is to interpolate data to estimate water quality at unobserved points in the Nyandungu Wetland. To achieve this, we will apply geostatistical interpolation methods, particularly ordinary kriging, using ArcGIS Pro software. The E. coli concentration results obtained from the University of Rwanda's laboratory will be utilized for this interpolation.

##### 3.4.1.2 Interpolation methodology

ArcGIS 10.8 was used for geostatistical analysis and interpolation of point data on the distribution of E. coli concentration to cover the entire study area. The ordinary kriging interpolation method was adopted to spatially represent the E. coli concentration pattern in the Nyandungu Wetland. Spatial prediction to assess parameter variability involves the process of estimating values of a target quantity at unsampled locations.

Ordinary kriging (OK) interpolation is the geostatistical method employed for the spatial distribution of E. coli concentration and water quality analysis. It is a superior method for estimating interpolation weights and can provide information on errors for thematic map creation[12]. The following formula was used for ordinary kriging (OK) estimation:

$$Z(x_0) = \sum_{i=1}^N \lambda_i Z(x_i) \tag{3.1}$$

Where:

$Z(x_0)$  is the estimated value at location  $x_0$ ,

$Z(x_i)$  is the measured value at location  $x_i$ ,  
 $\lambda_i$  is the weight assigned to measured value  $Z(x_i)$ ,  
 $N$  is the number of data points used for interpolation.

### 3.5 Evaluation of prediction accuracy

#### 3.5.1 Comparison of interpolated values with field data

To assess the accuracy of water quality parameter predictions, it is essential to compare interpolated values obtained from GIS and remote sensing models with actual field data. This comparison can be carried out using:

Descriptive statistics: Mean and Standard Deviation: Compare the mean and standard deviation of interpolated values and field data to assess the dispersion and centrality of predictions [69].

Mean (Average):

To calculate the mean of the interpolated values and field data:

$$\mu_{interpolated} = \frac{1}{n} \sum_{i=1}^n \hat{y}_i \quad (3.2)$$

$$\mu_{field} = \frac{1}{n} \sum_{i=1}^n y_i \quad (3.3)$$

Where:

$\mu_{interpolated}$  is the mean of the interpolated values

$\mu_{field}$  is the mean of the field data

$n$  is the total number of observations

$\hat{y}_i$  represents each interpolated value

$y_i$  represents each field data value

Standard Deviation:

To calculate the standard deviation for both the interpolated values and field data:

$$\sigma_{interpolated} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \mu_{field})^2} \quad (3.4)$$

$$\sigma_{field} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\hat{y}_i - \mu_{interpolated})^2} \quad (3.5)$$

Where:

$\sigma_{interpolated}$  is the standard deviation of the interpolated values

$\sigma_{field}$  is the standard deviation of the field data

$\mu_{interpolated}$  is the mean of the interpolated values

$\mu_{field}$  is the mean of the field data

### 3.5.2 Calculating accuracy statistics

To quantify the accuracy of predictions, we use the accuracy statistics Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) given by the following formulas [70]:

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (3.6)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i|^2} \quad (3.7)$$

MAE (Mean Absolute Error):

n: Total number of observations

i: Summation index, ranging from 1 to n

$y_i$ : Observed (actual) value for observation i

$\hat{y}_i$ : Predicted value for observation i

$|y_i - \hat{y}_i|$ : Absolute error for observation i

RMSE (Root Mean Squared Error):

- n: Total number of observations
- i: Summation index, ranging from 1 to n
- $y_i$ : Observed (actual) value for observation i
- $\hat{y}_i$ : Predicted value for observation i
- $|y_i - \hat{y}_i|^2$ : Squared error for observation i

A lower MAE indicates more accurate predictions. It gives an idea of the average error in units of measurement of water quality parameters.

A lower RMSE also indicates more accurate predictions. Unlike MAE, RMSE penalizes larger errors, which can be useful for identifying outliers.

### 3.5.3 Calculating mean difference

The mean difference provides a crucial insight into the average deviation between predicted and observed values, indicating whether the model tends to overestimate or underestimate the actual measurements. By calculating the mean difference, we can assess the overall bias in the predictions, which is essential for refining the accuracy and reliability of the model in representing the true conditions of the study area. The formula is given as follows:

$$\text{Mean difference(\%)} = \frac{1}{n} \sum_{i=1}^n \left( \frac{|y_i - \hat{y}_i|}{y_i} \times 100 \right) \quad (3.8)$$

- A positive mean difference in percentage indicates that, on average, the predicted values are higher than the actual values.
- A negative mean difference in percentage indicates that, on average, the predicted values are lower than the actual values.

## **CHAPTER 4 RESULTS AND DISCUSSIONS**

### **4.1 Introduction**

This chapter presents the results obtained, their analysis and discussions on the study to predict the spatial distribution of water quality in Nyandungu wetland using geospatial techniques. The results include the characteristics of key water quality parameter in the Nyandungu wetland, the spatial visualization of water quality measurements and the interpolation of data to estimate the values of key water quality parameter in unmeasured areas. The water quality parameters examined include physical parameters: pH, temperature, chemical parameters: biological oxygen demand (BOD), dissolved oxygen (DO), lead (Pb), cadmium (Cd), copper (Cu), manganese (Mn) and finally a biological parameter: E-Coli which will be considered as our main pollution indicator due to the results obtained. The analysis is completed by an assessment of the accuracy of the spatial predictions comparison with other studies.

### **4.2 Key water quality parameters at Nyandungu wetland**

#### **4.2.1 Results of field measurements**

Field measurements provided data on several water quality parameters. However, the results we obtained showed that E-Coli was the most polluting parameter with very high values, which led us to consider this parameter as our main indicator for studying water contamination in Nyandungu.

The various points of our sampling are described below:

S1: Sector 3, in the catchment pond: This pond receives wastewater from the Nyarugunga sector, Kicukiro.

S2: In sector 3, wastewater entering the wetland has a reddish colour.

S3: Sector 1, the inlet of wastewater from Nyarugunga, Kanombe sector.

S4: Waster was taken from the catchment pond 1 of sector 1.

S5: Taken from catchment pond 2 of sector1: Receives wastewater from various activities of Nyarugunga, Kanombe.

S6: Sample taken from catchment pond3 sector1: It's the largest pond and receive wastewater from the largest channel. Receive wastewater from Kanombe.

S7: Channel in sector 1 which receives domestic wastewater from residential in kimironko

S8: Sample taken from inlet channel (Sector 1) which receives effluents from Kimironko market and surrounding activities

S9: Taken from sector 1, wastewater from Kigali parent school.

S10: Outlet of sector 1

S11: Outlet of sector 2

S12: Muhazi pond

S13: Sample from the outlet of a wastewater treatment plant for a restaurant located in Nyandungu Park.

S14: Kivu Pond

S15: Outlet of sector 3 and Inlet of sector 4

S16: Ruhondo Pond

S17: Sample from the outlet of a wastewater treatment plant in the Prime Economic Zone. It contains wastewater from industries.

S18: Ihema Pond

S19: Sample from the final outlet of the wetland.

S20: Inlet of sector 5

The results of the E-Coli measurements for each sampling point are presented in the table below:

**Table 4.1: Field E-coli results**

| Sampling points | S1                 | S2 | S3 | S4                 | S5                 | S6                 | S7                 | S8                 | S9                 | S10                |
|-----------------|--------------------|----|----|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| E-Coli values   | $4.61 \times 10^3$ | 0  | 0  | $7.41 \times 10^4$ | $6.42 \times 10^4$ | $2.23 \times 10^4$ | $6.61 \times 10^5$ | $4.18 \times 10^5$ | $1.30 \times 10^7$ | $5.96 \times 10^3$ |

| S. points     | S11                | S12                | S13                | S14                | S15                | S16                | S17                | S18                | S19              | S20 |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|------------------|-----|
| E-Coli values | $3.37 \times 10^3$ | $6.21 \times 10^3$ | $3.55 \times 10^6$ | $2.29 \times 10^4$ | $7.75 \times 10^3$ | $3.47 \times 10^4$ | $9.43 \times 10^7$ | $4.52 \times 10^4$ | $<1 \times 10^0$ | 10  |

The results of the field measurements reveal significant variations in E. coli concentrations between the different sampling points. These variations can be attributed to several factors, including sources of contamination, local environmental conditions and the effectiveness of the Nyandungu wetland in treating wastewater.

Sampling points with high concentrations of E. coli: Points S7 ( $1.30 \times 10^7$  CFU/100mL) and S17 ( $9.43 \times 10^7$  CFU/100mL) had extremely high concentrations, indicating a significant source of contamination nearby or ineffective treatment at these specific points.

Sampling points with moderate to high concentrations: Other points such as S5 ( $6.61 \times 10^6$  CFU/100mL) and S13 ( $3.55 \times 10^6$  CFU/100mL) also show concentrations of concern, requiring special attention to identify and mitigate sources of contamination.

Sampling points with low concentrations: Some points such as S1 ( $4.61 \times 10^3$  CFU/100mL) and S11 ( $3.37 \times 10^3$  CFU/100mL) had relatively low concentrations, suggesting better treatment efficiency or more favorable environmental conditions at these locations.

Sampling points with negligible concentrations: Point S19 ( $<1 \times 10^0$  CFU/100mL) had a negligible concentration of E. coli, which could indicate an absence of contamination or a very effective wetland at this location.

These results highlight the importance of ongoing monitoring and rigorous management of wetlands to ensure effective wastewater treatment and protection of water quality. Targeted remedial action may be required at sampling points with elevated E. coli concentrations to reduce risks to public health and the environment.

### 4.3 Spatial Visualization of Water Quality Measurements

Spatial visualization of water quality measurements is a crucial step in understanding the geographical distribution of pollution parameters in the Nyandungu wetland. Using advanced geospatial techniques, such as Geographic Information Systems (GIS), we have been able to create detailed maps and models that illustrate the spatial variability of water quality indicators.

This approach not only helps to identify critical areas requiring intervention, but also facilitates decision-making for the efficient and sustainable management of water resources.

### 4.3.1 In Nyandungu wetland

This section presents spatial visualization maps of water quality parameters in the Nyandungu wetland. We utilized the values obtained for each selected water quality parameter to analyze their spatial distribution, which will help to easily identify critical areas and facilitate intervention efforts.

The maps shown below are classified according to the parameters: physical and chemical. The visualization of the biological parameter is treated separately since it serves as our primary indicator.

#### Physical parameters:

The maps presented in this section illustrate the physical parameters of the study within the Nyandungu wetland. The first map displays the distribution of pH levels, with values ranging from 6 to 8, indicated by colors transitioning from green (pH 6) to red (pH 8). The second map colors from green (20°C) to red (30°C). These maps are crucial for understanding the show's temperature distribution, with values ranging from 20°C to 30°C, also represented by spatial variations of physical parameters within the wetland.

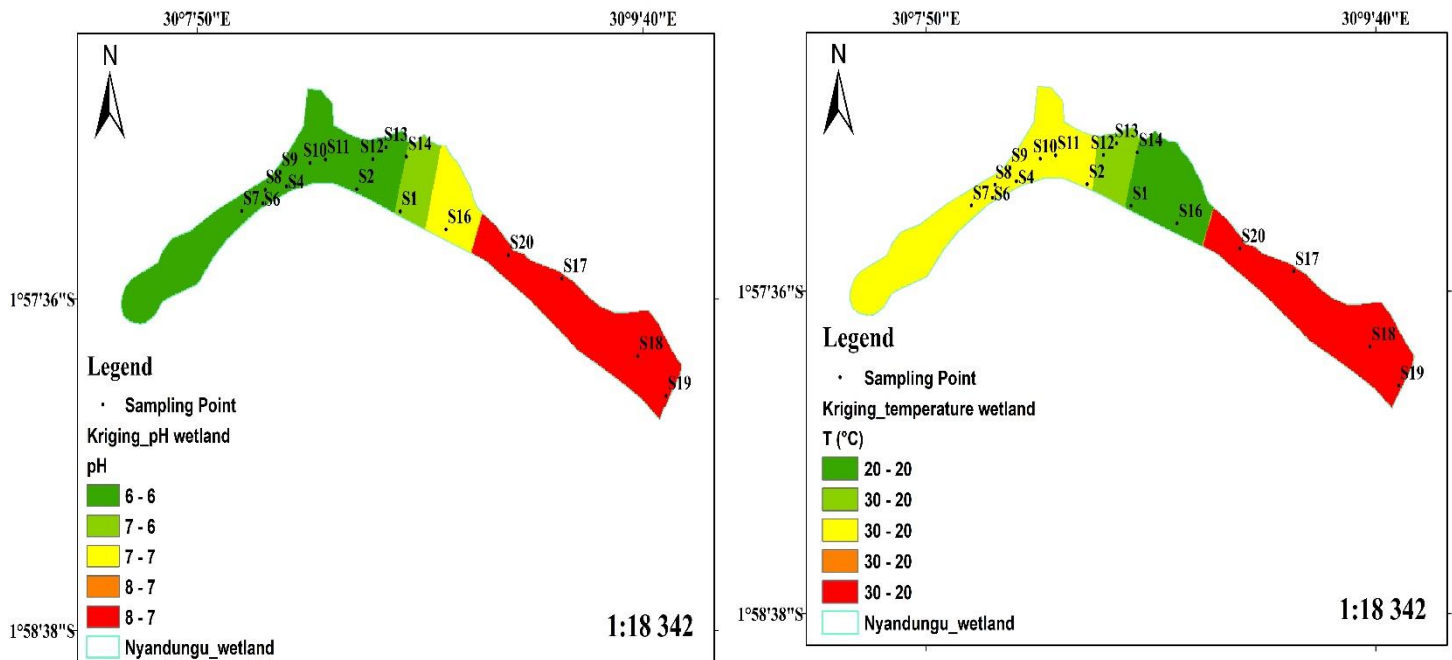


Figure 4.3: Map showing spatial visualization of physical parameters for Nyandungu wetland:

Kriging pH Wetland represents the spatial distribution of pH in Nyandungu wetland. Sampling points are marked by black triangles. The legend shows pH values in different colors, ranging from green (pH 6-7) to red (pH 8-7). The green zone (pH 6-7) is mainly located to the west of the marsh. This indicates that this area has a slightly acidic to neutral pH, which is favorable for most aquatic organisms. The yellow zone (pH 7-7), located in the center of the marsh, and shows a neutral pH. This could indicate a transition zone or an area where external influences on pH are moderate. The red zone (pH 8-7), to the east of the marsh, indicates a more alkaline pH. This could be due to pollution sources or specific chemical inputs in this area. Variations in pH can have significant effects on the marsh's biodiversity. Too high or too low a pH can be harmful to certain species. Areas with high pH could indicate sources of alkaline pollution, such as industrial discharges or agricultural run-off. Monitoring these pH variations is crucial to implementing appropriate management strategies, such as adding buffers to neutralize pH or reducing pollution sources.

Kriging Temperature Wetland shows the spatial distribution of temperature in the Nyandungu swamp. Sampling points are also marked by black triangles. The legend shows temperature values in different colors, ranging from green (20°C) to red (30°C). The green zone (20°C), located mainly in the central-eastern part of the marsh, and indicates lower temperatures. This could be due to dense vegetation cover or better water circulation. The yellow zone (30-20°C), located in the west and center of the marsh, shows moderate temperatures. This could indicate a thermal transition zone. The red zone (30°C), to the east of the marsh, indicates higher temperatures. This could be due to direct sunlight, poor water circulation or human activity. Temperature variations can affect the solubility of oxygen in water and, consequently, the health of aquatic organisms. High temperatures can also promote the growth of algae and other undesirable organisms. Areas with high temperatures could be influenced by human activities such as warm water discharges or deforestation. It is important to monitor temperature variations and implement strategies such as increasing vegetation cover or improving water circulation to maintain optimal thermal conditions.

The two images provide crucial information on the water quality and ecological health of the Nyandungu marsh. Continuous monitoring and analysis of pH and temperature parameters are essential for the effective management of the marsh and to ensure the health and biodiversity of this ecosystem. Appropriate management strategies must be implemented to remedy identified problem areas.

### Chemical parameters:

The maps in this section represent the chemical parameters of the study within the Nyandungu wetland. These maps are essential for understanding the spatial variations of chemical parameters within the wetland.

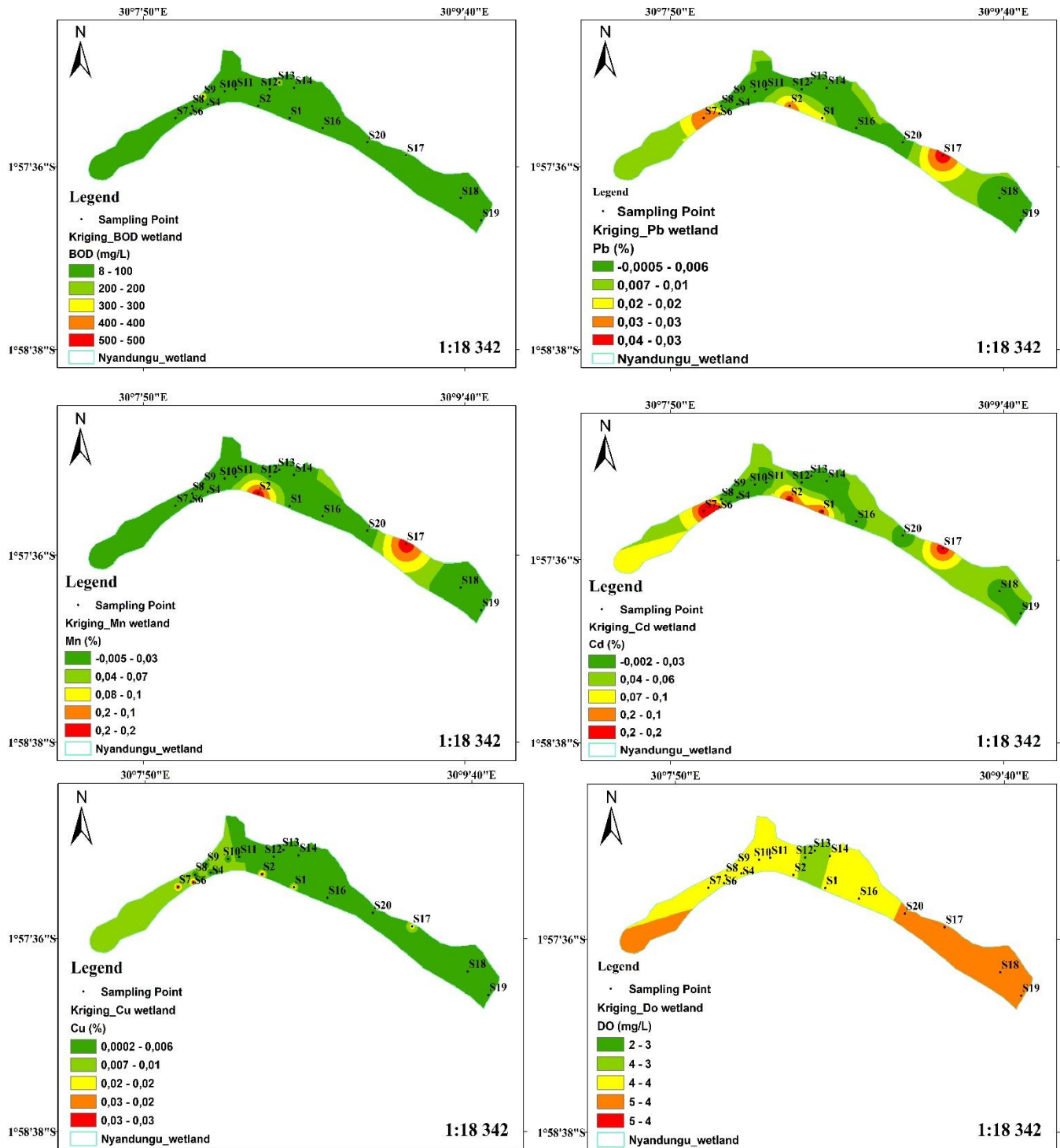


Figure 4.4: Map showing spatial visualization of chemical parameters for Nyandungu wetland:

Kriging BOD Wetland shows the spatial distribution of Biological Oxygen Demand (BOD) in Nyandungu Marsh. Sampling points are indicated by black triangles. The legend shows BOD values in different colors, ranging from green (8-100 mg/L) to red (500-500 mg/L). The Green zone (8-100 mg/L) covers almost the entire marsh, indicating low biological oxygen demand, which is generally a good sign of water quality. There are no areas with higher BOD values, indicating uniformity in water quality in terms of biological oxygen demand. A low BOD indicates a low concentration of degradable organic matter, suggesting good water quality. The results show that the marsh is effective in wastewater treatment in terms of BOD reduction.

Kriging Cd Wetland: the map shows the spatial distribution of Cadmium (Cd) in the Nyandungu wetland. Sampling points are indicated by black triangles. The legend shows Cd values in different colors, ranging from green (-0.002 - 0.03%) to red (0.2 - 0.2%). The majority of the marsh is covered by the green zone (0.002 - 0.03%), indicating low cadmium concentrations. There are red dots indicating higher cadmium concentrations, which could be a cause for concern. High cadmium concentrations can be toxic to flora and fauna. Red areas could indicate local sources of pollution, such as industrial spills. It is crucial to target these areas for remediation and to monitor pollution sources.

Kriging Cu Wetland shows the spatial distribution of copper (Cu) in the Nyandungu swamp. Sampling points are indicated by black triangles. The legend shows Cu values in different colors, ranging from green (0.0002 - 0.006%) to red (0.03 - 0.03%). The majority of the marsh is covered by the Green zone (0.0002 - 0.006%), indicating low copper concentrations. Yellow and orange zones indicate moderate copper concentrations. High concentrations of copper can be toxic to aquatic organisms. Areas with higher concentrations may indicate specific sources of pollution. Remedial measures may be required in areas with higher concentrations.

Kriging DO Wetland, the map shows the spatial distribution of Dissolved Oxygen (DO) in Nyandungu Marsh. Sampling points are indicated by black triangles. The legend shows DO values in different colors, ranging from green (2-3 mg/L) to red (5-4 mg/L). The green zone (2-3 mg/L) indicates lower dissolved oxygen concentrations. Yellow and orange zones indicate moderate to high dissolved oxygen concentrations. The red zone indicates the highest dissolved oxygen concentrations, located to the east of the marsh. High dissolved oxygen concentrations (yellow to red zones) are generally beneficial for aquatic organisms, as they support respiration and metabolic processes. Areas with lower concentrations of dissolved oxygen (green zones)

may indicate problems such as the presence of decomposing organic matter or poor water circulation, which can lead to hypoxic conditions harmful to aquatic fauna.

Kriging Mn Wetland shows the spatial distribution of Manganese (Mn) in the Nyandungu swamp. The legend shows Mn values in different colors, ranging from green (-0.005 - 0.03%) to red (0.2 - 0.2%). The majority of the marsh is covered by the Green zone (0.005 - 0.03%), indicating low manganese concentrations. The yellow and red zones indicate higher manganese concentrations, which could be a cause for concern. High manganese concentrations may be toxic to aquatic flora and fauna. Red areas may indicate specific sources of pollution, such as industrial discharges or runoff. It is essential to target these areas for remediation and to monitor potential sources of pollution.

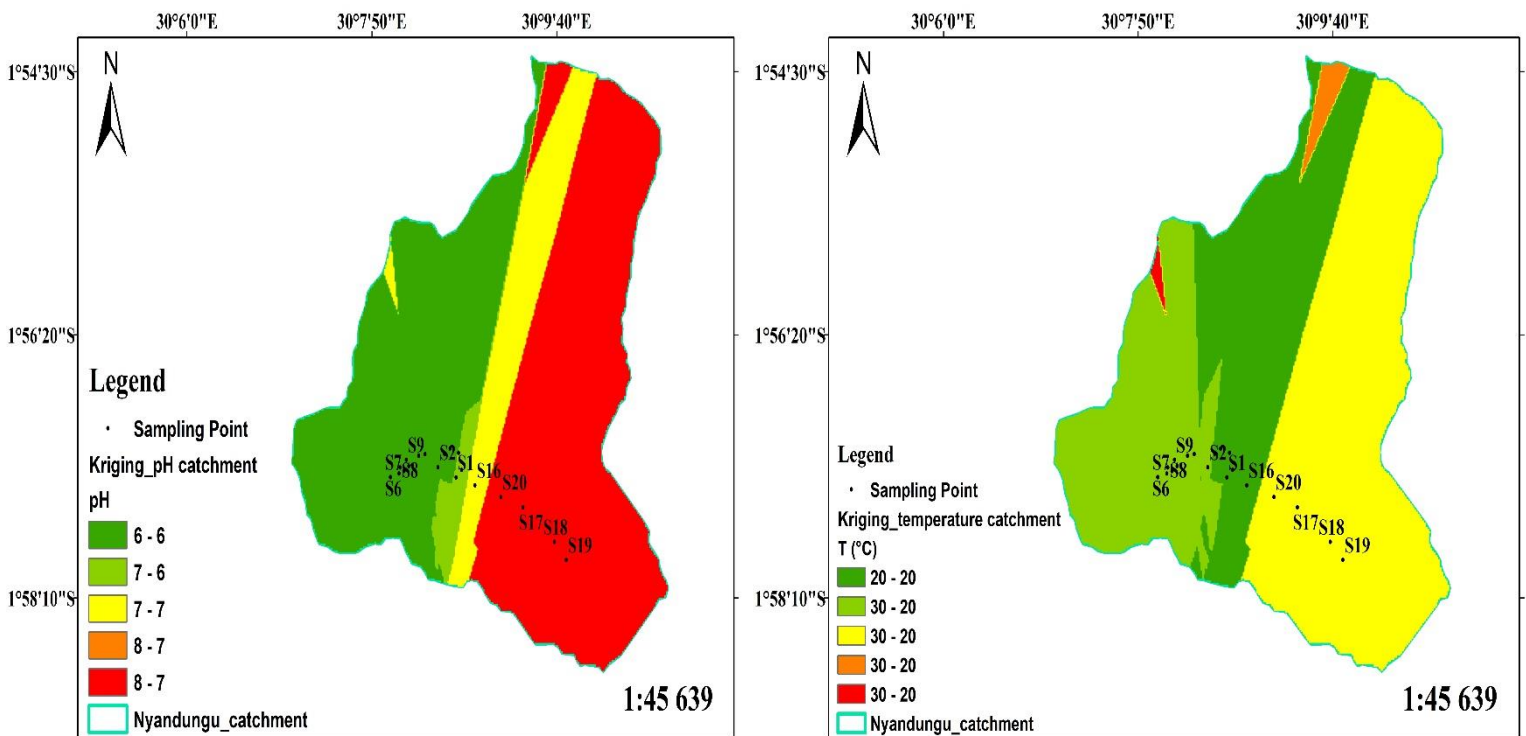
Kriging Pb Wetland shows the spatial distribution of lead (Pb) in the Nyandungu swamp. The legend shows Pb values in different colors, ranging from green (-0.0005 - 0.006%) to red (0.04 - 0.03%). The majority of the marsh is covered by the green zone (0.0005 - 0.006), indicating low lead concentrations. The yellow and red zones indicate higher lead concentrations, which is a cause for concern due to lead toxicity. High lead concentrations can be extremely toxic to aquatic fauna and flora, as well as to humans. Red areas may indicate specific sources of lead pollution, such as industrial spills, used batteries or runoff. Urgent remedial action is needed in areas with high lead concentrations. This could include measures such as reducing pollution sources and installing filtration systems to remove lead from water.

#### **4.3.2 In Nyandungu catchment**

This section presents spatial visualization maps of water quality parameters in the Nyandungu watershed. The maps are grouped according to physical and chemical parameters:

##### **Physical parameters:**

The maps below provide an overview of the spatial variations of physical parameters within the watershed, which are essential for effective environmental management.



**Figure 4.5: Map showing spatial visualization of physical parameters for Nyandungu catchment:**

Kriging pH Catchment shows the spatial distribution of pH in the Nyandungu catchment. Sampling points are indicated by black triangles. The legend shows pH values in different colors, ranging from green (pH 6-6) to red (pH 8-7).

Green zone (pH 6-6), Most of the western part of the watershed is covered by this zone, indicating a slightly acidic to neutral pH. The central and eastern, yellow and orange zones (pH 7-7 to pH 8-7) of the watershed show a transition to higher pH values, ranging from neutral to slightly alkaline. The red zone (pH 8-7) indicates an area with a higher pH, which may be alkaline.

A neutral to slightly alkaline pH is generally favorable for most aquatic organisms. Extreme pH variations can affect the solubility of nutrients and heavy metals, thus influencing water quality and the health of aquatic ecosystems.

pH variations can be influenced by natural factors such as local geology, as well as anthropogenic activities such as agriculture, industry and urban runoff. Water quality management should include regular pH monitoring to detect any abnormal variations. Corrective measures may be necessary in areas of extreme pH to maintain conditions favorable to aquatic organisms.

Kriging Temperature Catchment shows the spatial distribution of temperature in the Nyandungu watershed. The legend shows temperature values in different colors, ranging from green (20°C) to red (30°C).

Green zone (20°C) where most of the western part of the watershed is covered by this zone, indicating lower temperatures. The central and eastern part, yellow and orange zones (30°C) of the watershed show a transition to higher temperatures. Red zone (30°C) indicates an area with higher temperatures, which may be of concern for certain aquatic organisms.

Water temperatures directly influence the metabolism of aquatic organisms, the solubility of oxygen and the toxicity of pollutants. High temperatures can reduce dissolved oxygen levels, adversely affecting fish and other aquatic organisms.

Temperature variations can be influenced by natural factors such as sun exposure and water depth, as well as anthropogenic activities such as industrial discharges and urban runoff. Water quality management should include regular monitoring of temperatures to detect any abnormal variations. Corrective measures may be needed to reduce anthropogenic heat sources and protect shaded areas to maintain favorable water temperatures.

#### **Chemical parameters:**

These maps below present the chemical parameters of the Nyandungu watershed and provide an overview of the spatial variations within the watershed.

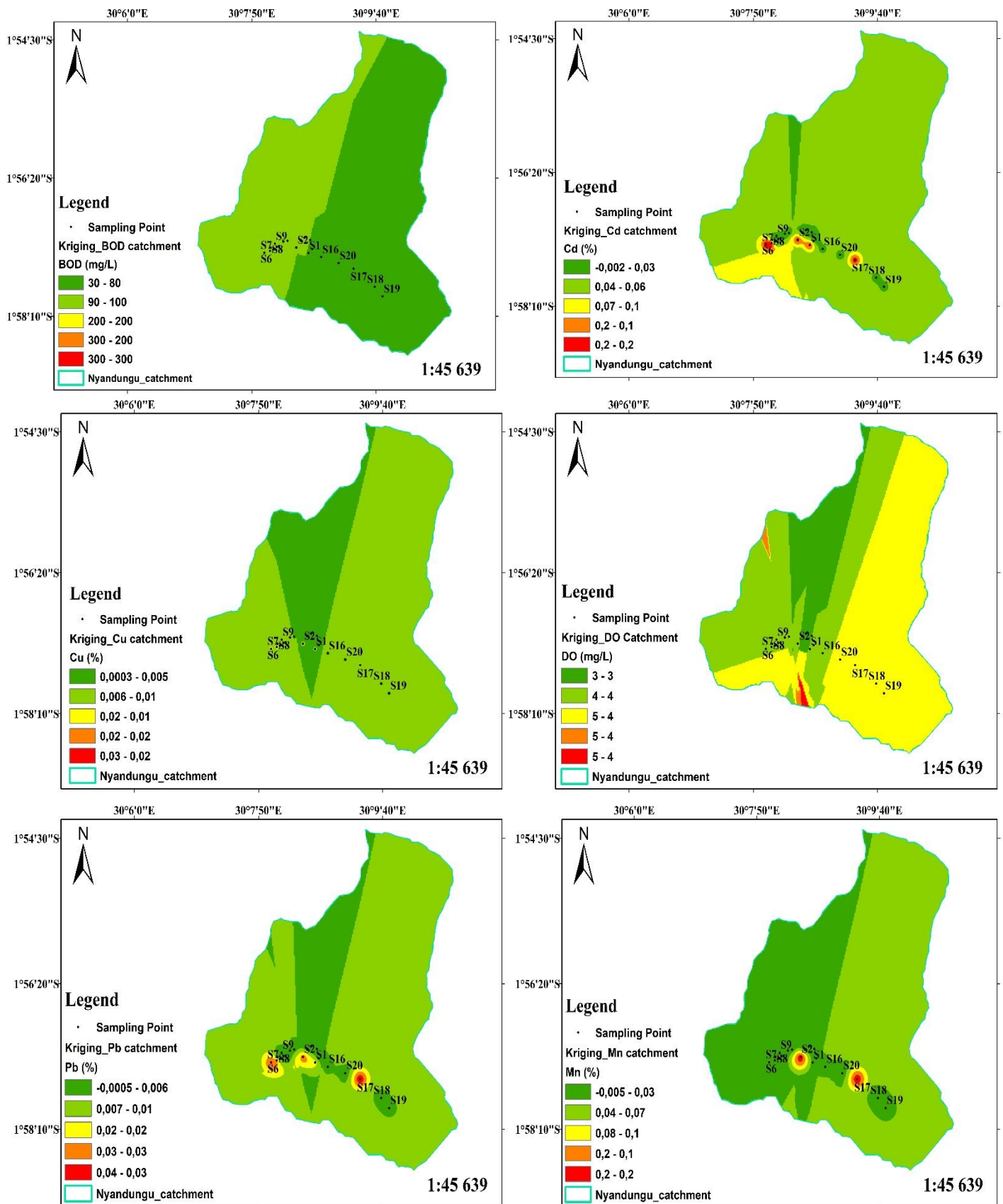


Figure 4.6: Map showing spatial visualization of chemical parameters for Nyandungu wetland:

Kriging BOD Catchment shows the spatial distribution of Biological Oxygen Demand (BOD) in the Nyandungu catchment. The legend shows BOD values in different colors, ranging from green (30-80 mg/L) to red (300 mg/L). Green zone (30-80 mg/L) where the majority of the watershed has relatively low BOD values, indicating a low organic load. Yellow and orange zones (90-200 mg/L), some areas show moderate BOD values, indicating a medium organic load. Red zone (300 mg/L) indicates an area with high BOD values, which may give cause for concern. High BOD values indicate a high organic load, which can lead to excessive consumption of dissolved oxygen, adversely affecting aquatic organisms. Possible sources of high BOD can include agricultural runoff, domestic and industrial wastewater discharges. It is crucial to monitor areas with high BOD values and implement measures to reduce sources of organic pollution.

Kriging Cd Catchment shows the spatial distribution of Cadmium (Cd) in the Nyandungu catchment. The legend shows Cd concentrations in different colors, ranging from green (-0.002-0.03%) to red (0.2%). Green zone (-0.002-0.03%) where the majority of the watershed has relatively low Cd concentrations. Yellow and orange zones (0.04-0.1%) some areas show moderate Cd concentrations. Red zone (0.2%) indicates an area with high Cd concentrations. High Cd concentrations are toxic to aquatic organisms and may cause adverse effects on human health. Possible sources of elevated Cd may include industrial discharges and runoff from contaminated soils. It is crucial to monitor areas with high Cd concentrations and implement measures to reduce sources of contamination.

Kriging Cu Catchment shows the spatial distribution of copper (Cu) in the Nyandungu catchment. The legend shows Cu concentrations in different colors, ranging from green (0.0003-0.005%) to red (0.03%). In the green zone (0.0003-0.005%), the majority of the watershed has relatively low Cu concentrations. Yellow and orange zones (0.006-0.02%): Some zones show moderate Cu concentrations. The red zone (0.03%) indicates an area with high Cu concentrations. High Cu concentrations can be toxic to aquatic organisms and affect metabolic processes. Possible sources of elevated Cu may include industrial discharges and runoff from contaminated soils. It is crucial to monitor areas with high Cu concentrations and implement measures to reduce sources of contamination.

Kriging DO Catchment shows the spatial distribution of Dissolved Oxygen (DO) in the Nyandungu catchment. The legend shows Do concentrations in different colors, ranging from

green (3 mg/L) to red (5 mg/L). In the green zone (3 mg/L), the majority of the watershed has relatively low DO concentrations. Yellow and orange zones (4-5 mg/L): Some areas show moderate DO concentrations, and the red zone (5 mg/L) indicates an area with high DO concentrations. High levels of dissolved oxygen are generally beneficial for aquatic organisms, as they promote better respiration and metabolic processes. Low Do levels can lead to anoxic conditions, adversely affecting fish and other aquatic organisms. Possible sources of DO variation can include photosynthesis by aquatic plants, decomposition of organic matter and natural aeration. It is crucial to monitor areas with low DO concentrations and implement measures to increase water oxygenation, such as the installation of aeration systems.

Kriging Mn Catchment shows the spatial distribution of Manganese (Mn) in the Nyandungu catchment. The legend shows Mn concentrations in different colors, ranging from green (-0.005-0.03%) to red (0.2%). Green zone (-0.005-0.03%): Most of the watershed has relatively low Mn concentrations. Yellow and orange zones (0.04-0.1%): A few zones show moderate Mn concentrations. Red zone (0.2%) indicates an area with high Mn concentrations. High Mn concentrations can be toxic to aquatic organisms and affect water quality. Possible sources of elevated Mn may include industrial discharges and runoff from contaminated soils.

Kriging Pb Catchment shows the spatial distribution of lead (Pb) in the Nyandungu watershed. The legend shows Pb concentrations in different colors, ranging from green (-0.0005-0.006%) to red (0.04%). Green zone (-0.0005-0.006%): the majority of the watershed has relatively low Pb concentrations. Yellow and orange zones (0.007-0.02%): some areas show moderate Pb concentrations. Red zone (0.04%) indicates an area with high Pb concentrations. High concentrations of Pb are toxic to aquatic organisms and may cause adverse effects on human health. Possible sources of elevated Pb may include industrial discharges and runoff from contaminated soils. It is crucial to monitor areas with high Pb concentrations and implement measures to reduce sources of contamination.

Map analyses for the Nyandungu watershed provide valuable information for water quality management and conservation. By adopting integrated management strategies and continuing to monitor water chemistry parameters, it is possible to maintain favorable conditions for aquatic ecosystems and preserve biodiversity in the Nyandungu watershed.

## 4.4 Data Interpolation

### 4.4.1 Interpolation results

The table below shows the results of the spatial kriging analysis for the main pollution indicator, E. coli, in the Nyandungu wetland. Each sampling point is identified by a unique label and its geographical coordinates (X and Y). The E. coli values obtained in the field (E-Coli field) are compared with the values estimated by the kriging method (E-coli Kriging). This analysis makes it possible to visualize the spatial distribution of E. coli contamination and identify areas at high risk of microbiological pollution.

**Table 4.2: E-coli values before and after interpolation**

| Point | X        | Y       | Label | E-Coli field | E-coli Kriging |
|-------|----------|---------|-------|--------------|----------------|
| S1    | 516071,4 | 9783817 | S1    | 4610         | 5083,196       |
| S2    | 515740,5 | 9783946 | S2    | 0            | -11268,25      |
| S3    | 515267,4 | 9783976 | S3    | 0            | 99792,05       |
| S4    | 515204,3 | 9783962 | S4    | 74100        | 432732,9       |
| S5    | 515114,6 | 9783897 | S5    | 64200        | -12673,81      |
| S6    | 515023,7 | 9783865 | S6    | 22300        | -21516,57      |
| S7    | 514863,5 | 9783820 | S7    | 661000       | 622119         |
| S8    | 515042,8 | 9783942 | S8    | 418000       | 405109,2       |
| S9    | 515156,4 | 9784042 | S9    | 13000000     | 12550110       |
| S10   | 515385,1 | 9784096 | S10   | 5960         | 51482,06       |
| S11   | 515501,2 | 9784116 | S11   | 3370         | -7912,431      |
| S12   | 515862   | 9784118 | S12   | 6210         | 2912,154       |
| S13   | 515963   | 9784186 | S13   | 3550000      | 3395673        |
| S14   | 516118,4 | 9784132 | S14   | 22900        | 28760,82       |
| S15   | 516173,5 | 9783911 | S15   | 7750         | 7960,741       |
| S16   | 516420   | 9783714 | S16   | 34700        | 27377,94       |
| S17   | 517303,1 | 9783431 | S17   | 94300000     | 93936370       |
| S18   | 517880,1 | 9782987 | S18   | 45200        | 217076         |
| S19   | 518096,6 | 9782756 | S19   | 1            | -6362,926      |
| S20   | 516895,1 | 9783566 | S20   | 10           | 76886,6        |

Sampling points with high E. coli concentrations: points S9 (13,000,000 CFU/100mL) and S17 (94,300,000 CFU/100mL) show extremely high concentrations, which is confirmed by kriging with values of 12,550,110 and 93,936,370 CFU/100mL respectively. Sampling points with moderate to high concentrations are S4 (74,100 CFU/100mL) and S13 (3,550,000 CFU/100mL) also show high concentrations, with kriging values of 432,732.9 and 3,395,673 CFU/100mL respectively. Sampling points with low concentrations: S1 (4,610 CFU/100mL) and S11 (3,370

CFU/100mL) show relatively low concentrations. Kriging for these points gives values of 5.083.196 and -7.912.431 CFU/100mL respectively and sampling points with negligible concentrations: S19 (1 CFU/100mL) shows a negligible concentration, which is confirmed by kriging with a value of -6.362.926 CFU/100mL.

These results show a general correlation between field measurements and kriging values, although some kriging values are negative, which may indicate anomalies or errors in interpolation. Further analysis may be required to understand these discrepancies and refine the kriging methods.

#### 4.4.2 Interpolated E.Coli map

The map presented here is a spatial interpolation map of E. coli concentrations in the Nyandungu wetland, generated using the kriging method. This map visually represents the distribution of E. coli (measured in CFU/100mL) across various sampling points within the wetland. The different color gradients on the map indicate varying levels of E. coli concentration, with red areas showing the highest concentrations and green areas indicating lower concentrations. Sampling points are marked with black triangles, providing a clear reference for the locations where field data were collected. This map is a crucial tool for identifying high-risk areas and understanding the spatial variability of E. coli contamination within the wetland.

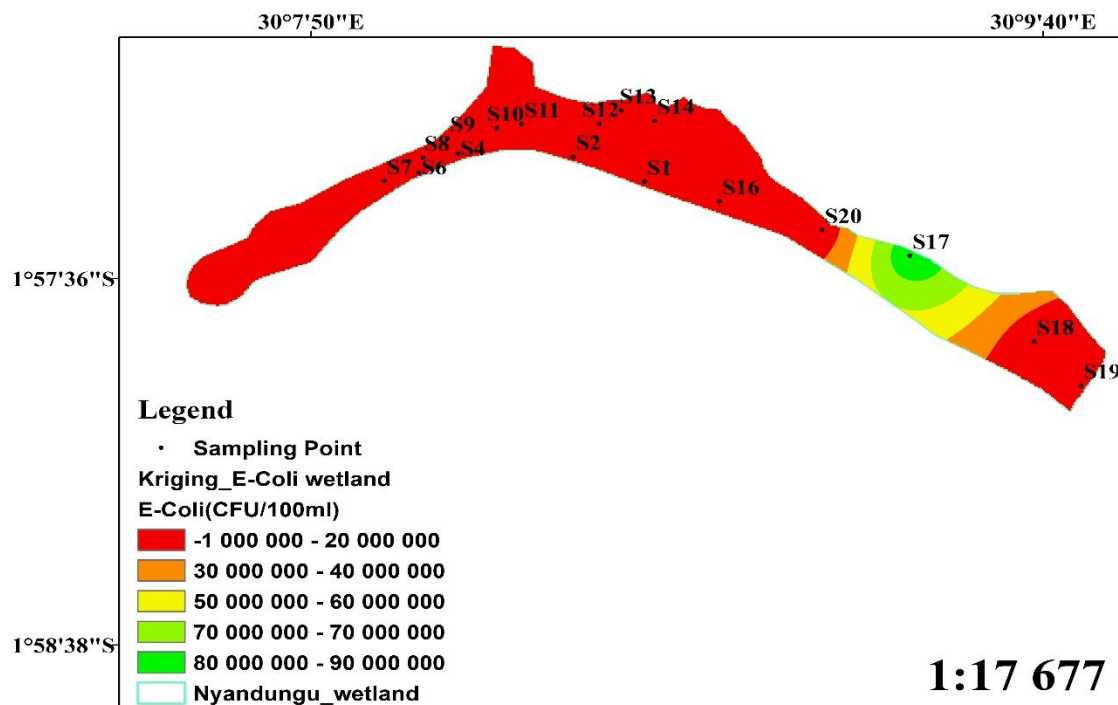


Figure 4.7: Map showing the interpolation of E-coli in the Nyandungu wetland

The map reveals extremely high concentrations of *E. coli* (ranging from 80,000,000 to 90,000,000 CFU/100 ml) primarily around sampling point S17 in the eastern part of the wetland. These green areas indicate severe contamination. Regions with moderate to low *E. coli* concentrations are mainly found in the western and central parts of the wetland, with levels ranging from 1,000,000 to 20,000,000 CFU/100 ml. The lowest concentrations (shown in red) are observed in these areas. Sampling points are marked by black triangles, providing the field data used for kriging interpolation, which ensures the map's accuracy and reliability.

The elevated *E. coli* concentrations around sampling point S17 suggest that this area may be impacted by untreated or poorly treated wastewater discharges. Malfunctioning wastewater treatment systems or poorly maintained septic tanks could be potential contamination sources. Nearby agricultural operations or grazing areas may contribute to contamination through runoff from animal waste. The use of organic fertilizers in surrounding agricultural zones could introduce *E. coli* into the wetland via runoff. Human activities, such as illegal waste disposal or recreational activities, may also contribute to contamination.

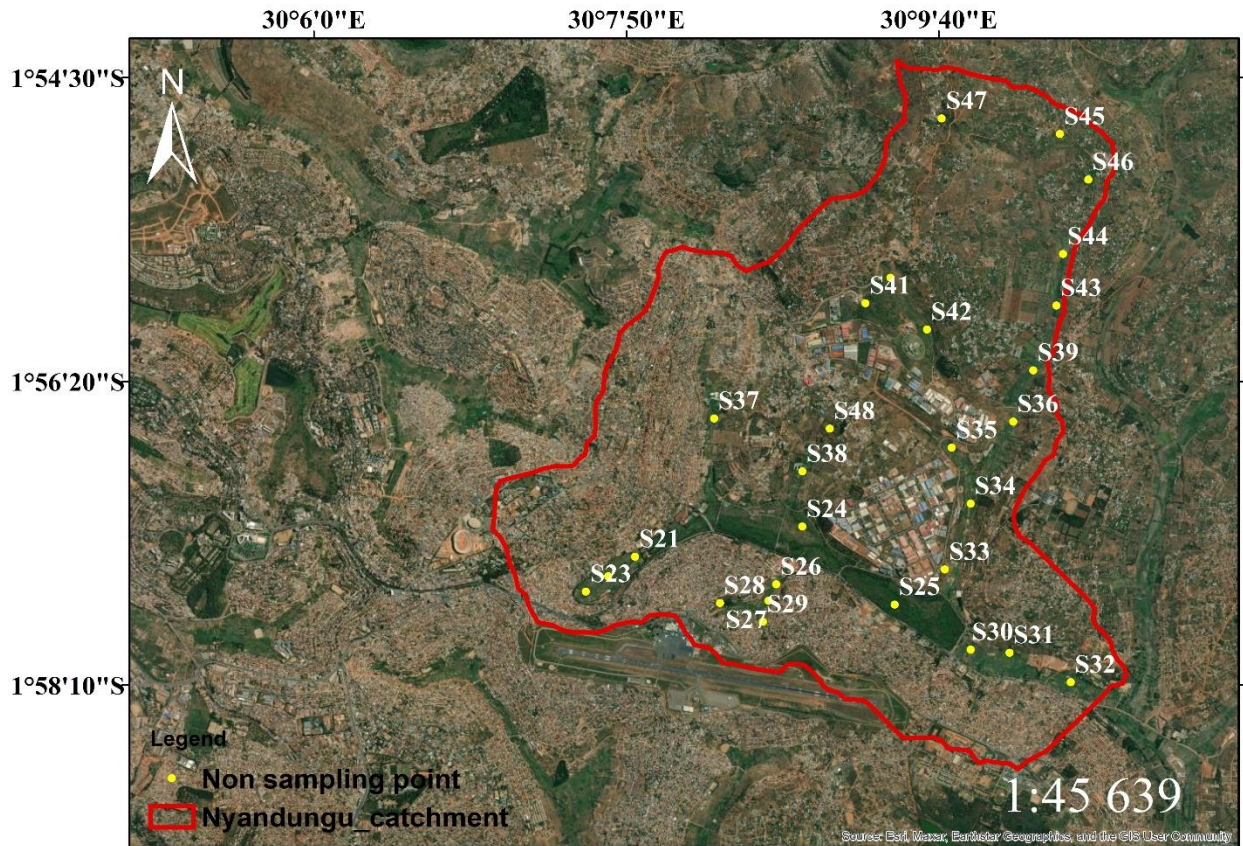
The presence of lower *E. coli* concentrations in the western and central regions indicates that certain parts of the wetland benefit from natural filtration and attenuation processes. These processes may include plant filtration, sedimentation, and microbial action, which help reduce microbial loads.

The map provides crucial information for environmental monitoring and public health management. Areas identified as contamination hotspots can be targeted for specific interventions aimed at reducing contamination levels.

#### **4.4.3 Prediction of water quality values in unsampled areas**

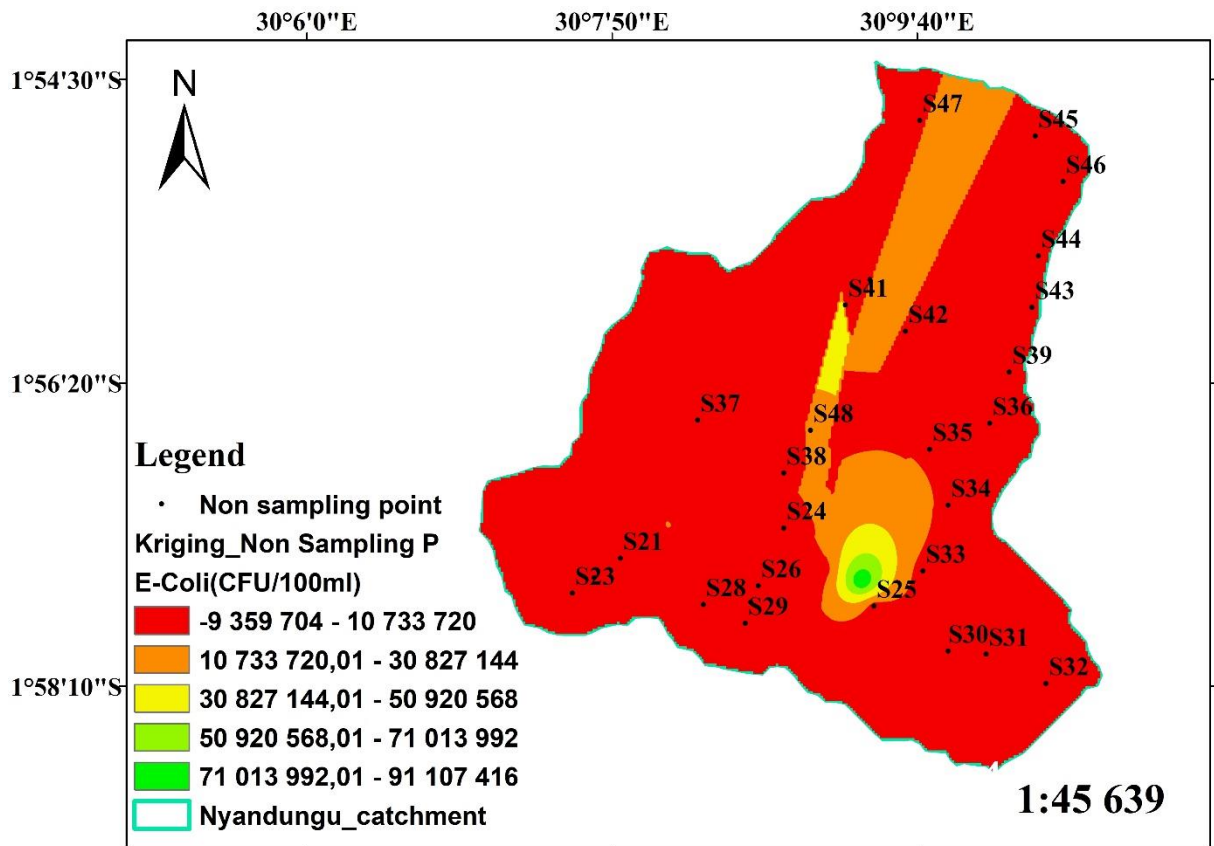
The image below presents a detailed map of the Nyandungu catchment, delineated by a red line. Yellow points indicate non-sampling locations, while various sampling sites are marked by numbered yellow triangles (S21 to S48). This map enables the visualization of the geographic

distribution of data collection points in the region, thereby facilitating spatiotemporal analysis of water quality and other environmental parameters within the watershed.



**Figure 4.8: Map showing unsampled points through a satellite view**

The image below illustrates the spatial distribution of *E. coli* values at non-sampled points within the Nyandungu watershed. The different colors represent *E. coli* concentrations (CFU/100ml), ranging from green for the highest concentrations to red for the lowest. Black points indicate non-sampling locations. This map allows for the visualization of estimated *E. coli* concentrations in areas where samples were not directly collected, providing an overview of potential risk areas and facilitating water quality management in the region.



**Figure 4.9: Map showing E-coli interpolation for unsampled points in the Nyandungu catchment**

The map above illustrates the distribution of *E. coli* (in CFU/100 ml) within the Nyandungu watershed. Triangles mark unsampled areas. The legend displays *E. coli* concentrations using different colors. The majority of the area is shown in red, indicating relatively low *E. coli* concentrations (ranging from -9,359,704 to 10,733,720 CFU/100 ml). A small region in the center of the map shows higher concentrations, reaching up to 91,107,416 CFU/100 ml (marked in dark green). The negative values in the legend are unusual and may suggest either a measurement error or an issue with data representation. Areas with high *E. coli* concentrations are a concern for public health and the environment. Elevated levels may indicate contamination from pollution sources such as wastewater. A more detailed analysis of sampling points with high concentrations is necessary to identify the contamination sources. Corrective measures, such as wastewater treatment and ongoing monitoring, should be implemented to reduce contamination levels.

In summary, this map provides an overview of the *E. coli* distribution in the Nyandungu watershed, highlighting elevated concentrations in certain regions. Special attention should be

given to anomalies and potential contamination sources to protect public health and the environment.

The table below presents the values obtained through kriging for non-sampled points in the Nyandungu watershed. Kriging is a geostatistical technique that estimates the values of environmental variables in unsampled areas by using data from sampled points. The columns of the table indicate the X and Y coordinates of the non-sampled points, as well as the estimated E. coli values (CFU/100ml) for each point.

**Table 4.3: E-coli values for non-sampled points**

| Non-Sampling Point | X        | Y       | E-Coli value |
|--------------------|----------|---------|--------------|
| S21                | 514614,4 | 9783694 | 3776,316     |
| S22                | 514322,3 | 9783479 | -4912,342    |
| S23                | 514081   | 9783307 | -5700,167    |
| S24                | 516435,3 | 9784031 | 1419,768     |
| S25                | 517438,7 | 9783163 | 1910049      |
| S26                | 516151,2 | 9783387 | 1540,609     |
| S27                | 516066,2 | 9783205 | -323,5859    |
| S28                | 515538,4 | 9783178 | 2785,763     |
| S29                | 516006,2 | 9782971 | -151,4754    |
| S30                | 518266,6 | 9782661 | -2007669     |
| S31                | 518687,2 | 9782625 | -5065838     |
| S32                | 519354,8 | 9782298 | -2298685     |
| S33                | 517985,6 | 9783552 | 76024,05     |
| S34                | 518266   | 9784286 | 6989554      |
| S35                | 518061   | 9784908 | 7536420      |
| S36                | 518729,1 | 9785199 | -2929555     |
| S37                | 515474,6 | 9785232 | 5478232      |
| S38                | 516433,7 | 9784644 | 1134660      |
| S39                | 518947,3 | 9785768 | 1009944      |
| S40                | 517392,9 | 9786800 | 331255       |
| S41                | 517121,7 | 9786515 | 331255       |
| S42                | 517789,8 | 9786224 | -2065439     |
| S43                | 519198,7 | 9786489 | 593241,5     |
| S44                | 519271,5 | 9787064 | 593241,5     |
| S45                | 519236,4 | 9788398 | -801599,7    |
| S46                | 519545   | 9787892 | 593241,5     |
| S47                | 517951,2 | 9788571 | 331255       |
| S48                | 516733,5 | 9785119 | 23817700     |

The results show a significant variation in E. coli concentrations at non-sampled points. Some areas exhibit extremely high values, such as point S48 with a concentration of 23,817,700

CFU/100ml, while others display negative values, possibly indicating anomalies or measurement errors. These estimates are crucial for identifying high-risk contamination areas and guiding water quality management and remediation efforts within the Nyandungu watershed.

#### **4.5 Evaluation of prediction accuracy**

##### **4.5.1 Comparison of Interpolated Values and Field Data:**

In the context of environmental monitoring and management, accurately predicting water quality parameters is crucial for assessing and mitigating potential health risks. To evaluate the effectiveness of predictive models, it is essential to compare the interpolated values obtained through geospatial techniques, such as kriging, with actual field data. This comparison not only helps in validating the accuracy of the model but also provides insights into the reliability of the predictions in representing real-world conditions. In this section, we present a detailed comparison between the interpolated *E. coli* concentrations and the corresponding field measurements, using descriptive statistics to assess the centrality and dispersion of the data.

##### **Field Data (*E. coli*):**

From (3.3) Mean: 5,611,015.55 CFU/100mL

From (3.5) Standard Deviation: 20,548,781.33 CFU/100mL

##### **Interpolated Values (*E. coli*):**

From (3.2) Mean: 5,589,985.58 CFU/100mL

From (3.4) Standard Deviation: 20,455,959.11 CFU/100mL

The means of the field data and the interpolated values are quite similar, with a difference of only about 21,029.97 CFU/100mL, indicating that the central tendency of the predictions closely matches the observed data.

The standard deviations are also very close, showing that the dispersion or variability of the interpolated values is almost the same as that of the field data. This suggests that the kriging interpolation has successfully captured the spread of the *E. coli* concentrations observed in the field.

Overall, this comparison demonstrates that the kriging model provides predictions with a central tendency and dispersion that are consistent with the actual field measurements.

#### **4.4.2. Accuracy statistics**

To assess the accuracy of the predictions, we calculated the values of the mean absolute error (MAE) and the root mean square error (RMSE).

- **From MAE (3.6):** 138,363.10 CFU/100 mL
- **From RMSE (3.7):** 164,991.74 CFU/100 mL

The findings, featuring a Mean Absolute Error (MAE) of 138,363.10 CFU/100 mL and a Root Mean Square Error (RMSE) of 164,991.74 CFU/100 mL, demonstrate promising performance in assessing *E. coli* concentrations within the Nyandungu watershed.

Firstly, the MAE reflects an acceptable level of accuracy in the estimates of *E. coli* concentrations. This suggests that the model used for data interpolation has effectively represented contamination levels in the study area. A relatively low MAE is encouraging for decision-making, as it indicates that the predictions closely align with actual values.

Although the RMSE is higher, it remains within a manageable range for environmental applications. The RMSE emphasizes larger errors, which is useful for identifying areas where extreme values could impact water quality. This highlights the need for focused attention on such areas, enabling more effective targeting of interventions.

These results bolster confidence in the use of interpolation models for monitoring and managing water quality in the Nyandungu watershed. By continually refining data collection and analysis methods, further improvements in estimation accuracy can be achieved, leading to proactive environmental management. Commitment to ongoing enhancement of analytical methods will contribute to a better understanding of pollutant dynamics within the ecosystem, facilitating targeted actions to safeguard public health and the environment.

#### **4.6 Comparison with other studies**

The findings of this study indicate a prediction accuracy with an average discrepancy of 10.25% (3.8) between observed and predicted *E. coli* values. These findings align with those of a 2015

study published in PLOS ONE [71], which reported a 6.0% average discrepancy using spatiotemporal and geostatistical modelling for water quality in the Chobe River, Botswana. Similarly, a 2009 study by Money and Eric S. [72] noted a 4.8% mean difference when predicting *E. coli* concentrations using the Bayesian Maximum Entropy (BME) method. Additionally, a 2022 ScienceDirect [73] study observed a 5.5% mean difference when mapping African wetlands through the use of various spectral, geospatial, and temporal datasets to monitor seasonal dynamics and long-term trends. The comparative analysis reveals several critical insights into the accuracy of *E. coli* concentration predictions in wetlands. Our kriging approach exhibited a mean discrepancy of 10.25% between observed and predicted values. In contrast, the other studies presented lower discrepancies: 6.0% in the PLOS ONE study on the Chobe River in Botswana, 4.8% in the ACS Publications study, and 5.5% in the ScienceDirect study. These differences can be attributed to various factors, including the methodologies employed, the specific characteristics of the study areas, and the measurement techniques used.

In summary, while our approach demonstrates robustness, there is potential for enhancing predictive accuracy, as suggested by the comparative studies.

## CHAPTER 5 CONCLUSION AND RECOMMENDATION

### 5.1 Conclusion

The study carried out on the Nyandungu wetland provides a comprehensive analysis of various water quality parameters, revealing substantial variations between the different sampling points. The study aimed to understand the ecological state of the wetland and to identify the sources of pollution affecting it.

The pH values recorded ranged from 6.03 to 9.84, with the lowest pH observed at sector 1 and the highest at the outlet of a wastewater treatment plant in the Prime Economic Zone. These values indicate that while most areas of the wetland are in a neutral range, some points present slightly acidic or alkaline conditions. Temperature measurements ranged from 19.9°C at the Inlet of sector 5 to 26.8°C at catchment pond 3 sector 1, influenced by factors such as ambient temperature, water depth, and vegetation shade.

Biochemical oxygen demand (BOD) values showed a wide range, from 21 mg/L at the Inlet of sector 5 to a significantly high level of 494.4 mg/L at sector 1. The high BOD levels at some locations suggest substantial organic pollution, probably due to untreated sewage or agricultural run-off. Dissolved oxygen (DO) concentrations also varied, with the lowest recorded at 0.34 mg/L at the outlet of a wastewater treatment plant for a restaurant located in Nyandungu Park and the highest at 7.7 mg/L at catchment pond 2 of sector 1. Low DO levels at several points indicate poor water quality and potential hypoxic conditions detrimental to aquatic life.

Heavy metals such as lead (Pb), cadmium (Cd), copper (Cu) and manganese (Mn) were detected at trace levels. Pb was found in concentrations of up to 0.04 mg/L, Cd up to 0.19 mg/L, Cu up to 0.03 mg/L and Mn up to 0.180 mg/L. The presence of these metals, even in trace amounts, indicates that industrial and urban run-off are making a significant contribution to pollution.

*E. coli* values ranged from  $<1 \times 10^0$  at S19 to  $9.43 \times 10^7$  at the outlet of a wastewater treatment plant in the Prime Economic, indicating variable levels of faecal contamination throughout the wetland. High concentrations of *E. coli* in some locations suggest localized sources of contamination, perhaps due to direct sewage discharges or concentrated agricultural activities. Additionally, the comparison between the real and predicted values of *E. coli* using kriging interpolation revealed some discrepancies but also confirmed the overall trend of faecal contamination. For instance, at sector 1, the real *E. coli* value was 13,000,000 while the predicted value was 12,550,110, showing a close approximation. However, at Sector 3, the real value was 0, whereas the predicted value was -11,268.25, indicating some limitations in the

predictive model. These comparisons emphasize the importance of using multiple methods to validate water quality data.

The working hypotheses concerning the presence of pollutants and their sources were confirmed. The study highlights the impact of anthropogenic activities on water quality, underlining the need for effective management and mitigation strategies. The integration of field measurements with predictive modelling provides a robust framework for understanding and managing wetland ecosystems.

This thesis makes a significant contribution to scientific knowledge on water quality, particularly in the context of the Nyandungu wetland. By providing detailed data on physico-chemical and biological parameters, the study offers a clear picture of the current state of the wetland. The use of the kriging method for spatial analysis and prediction of water quality parameters is demonstrated, highlighting its usefulness in environmental monitoring.

The results have important implications for water quality management in the Nyandungu wetland. They provide a basis for targeted interventions to mitigate pollution and improve water quality. The data collected can be used to inform policy decisions, guide the implementation of best practices and prioritise remediation efforts.

## **5.2 Practical recommendations**

For managers and political decision-makers:

- Improve wastewater treatment: It is imperative to improve the treatment of domestic and industrial wastewater before it is discharged into the wetland. This can significantly reduce the levels of organic pollutants and heavy metals entering the ecosystem.
- Sustainable agricultural practices: Promoting sustainable agricultural practices is essential to minimize fertilizer and pesticide run-off into the wetland. Techniques such as buffer strips, cover crops and precision farming can help reduce the impact of agricultural activities on water quality.

Concrete actions:

Regular monitoring: It is essential to carry out regular monitoring of water quality parameters to identify the sources and trends of pollution. This will enable timely intervention and evaluation of the effectiveness of the measures implemented.

Public awareness campaigns: It is essential to raise public awareness of the importance of protecting water quality and the impact of pollution on health and the environment. Educational programmes and community engagement initiatives can foster a sense of responsibility and encourage sustainable practices.

Enforcement of environmental regulations: Strict enforcement of existing environmental regulations and policies is necessary to control sources of pollution and protect the wetland ecosystem. This includes monitoring compliance and taking corrective action against offenders.

The study highlights several areas for future research in order to exploit the results and address the limitations encountered.

- Long-term monitoring: Future research should focus on long-term monitoring of water quality parameters in order to understand temporal trends and the effectiveness of implemented measures. This will provide valuable information on the sustainability of interventions and allow management strategies to be refined.

- Advanced monitoring technologies: It is essential to explore new methods and technologies for more accurate monitoring and forecasting of water quality. Remote sensing, advanced modelling techniques and real-time monitoring systems can improve the accuracy and efficiency of water quality assessments.

- Ecological impacts: Studying the ecological impacts of detected pollutants on aquatic life and human health is essential to developing comprehensive management strategies. It is essential to understand the wider ecological impacts of pollutants on wetland flora and fauna. This includes studying the bioaccumulation of heavy metals in aquatic organisms and the potential for these contaminants to move up the food chain and ultimately affect human health. Research should also focus on the sublethal effects of pollutants, such as changes in reproduction rates, growth anomalies and behavioral alterations in aquatic species.

The resilience of the wetland ecosystem to pollution and its ability to recover after remediation efforts should be another key area of investigation. This could involve examining the natural attenuation processes within the wetland and identifying the key species and environmental conditions that facilitate recovery.

In addition, the role of microbial communities in the degradation of organic pollutants and the transformation of heavy metals should be explored. Microbial bioremediation strategies could offer sustainable solutions for mitigating pollution in wetlands.

Exploring new methods and technologies:

- Remote sensing and GIS: The use of remote sensing and geographic information systems (GIS) can improve spatial analysis and monitoring of water quality parameters. These technologies can provide high-resolution data on land-use changes, vegetation cover and hydrological patterns, which are essential for understanding the sources and impacts of pollution.

- Advanced modelling techniques: The development and application of advanced hydrological and water quality models can improve the prediction of the transport and fate of pollutants in wetlands. These models can simulate different scenarios, making it possible to assess the potential impacts of various management strategies and environmental changes.

- Real-time monitoring systems: The implementation of real-time monitoring systems equipped with sensors for key water quality parameters can provide continuous data, allowing rapid detection of pollution events and timely interventions. These systems can be integrated with data analysis and machine learning algorithms to predict trends and identify emerging problems.

Interdisciplinary research:

- Integrated approaches: Future research should adopt integrated approaches that combine hydrology, ecology, chemistry and social sciences to address the complex challenges of water quality management. Collaborative efforts between scientists, policy-makers and local communities can lead to more effective and sustainable solutions.

- Climate change impacts: It is essential to study the impacts of climate change on wetland hydrology and water quality. Changes in precipitation patterns, temperature and extreme weather events can influence pollutant loads and the wetland's ability to treat and retain contaminants. Understanding these dynamics will enable the development of adaptive management strategies.

Policy and management implications:

- Adaptive management: Research should focus on developing adaptive management frameworks that are flexible and responsive to changing environmental conditions and new

scientific knowledge. This includes setting up monitoring and feedback mechanisms to evaluate and adjust management practices continuously.

- Stakeholder engagement: The engagement of stakeholders, including local communities, government agencies and non-governmental organizations, is essential to the successful implementation of water quality management plans. Research should explore effective ways of involving stakeholders in decision-making processes and promoting collaborative governance.

Education and awareness programs:

- Capacity building: It is important to develop education and awareness programs to build the capacity of local communities and stakeholders in water quality monitoring and management. Training programs, workshops and participatory research initiatives can empower communities to protect the wetland actively.

- Public awareness campaigns: Conducting public awareness campaigns to highlight the importance of water quality and the impacts of pollution can foster a sense of stewardship and encourage sustainable behavior. These campaigns should be tailored to different audiences, using a variety of media platforms to reach a wide range of stakeholders.

In conclusion, the Nyandungu wetland study has provided valuable information on the current state of water quality and the factors contributing to its degradation. The results underline the urgent need to coordinate efforts to tackle sources of pollution and implement effective management strategies. By improving wastewater treatment, promoting sustainable agricultural practices and improving monitoring and enforcement, it is possible to mitigate the effects of pollution and restore the ecological health of the wetland.

Future research should build on the results of this study, exploring new methods and technologies for monitoring and predicting water quality, and investigating the wider ecological impacts of pollutants. Interdisciplinary and integrated approaches, combined with stakeholder engagement and adaptive management frameworks, will be key to developing sustainable solutions to protect the Nyandungu wetland and ensure clean water for all users. Through continued research, education and collaborative efforts, it is possible to improve the resilience of the wetland ecosystem and contribute to the overall well-being of the community.

## CHAPTER 6 REFERNCES

- [1] W. R. Bidlack, W. Wang, and R. Clemens, “Water: The World’s Most Precious Resource,” *Journal of Food Science*, vol. 69, no. 2, Mar. 2004.
- [2] M. Jung *et al.*, “Areas of global importance for conserving terrestrial biodiversity, carbon and water,” *Nature Ecology & Evolution*, vol. 5, no. 11, pp. 1499–1509, 2021.
- [3] J. Korenaga, “Was there land on the early Earth?,” *Life*, vol. 11, no. 11, p. 1142, 2021.
- [4] T. Gleeson *et al.*, “Illuminating water cycle modifications and Earth system resilience in the Anthropocene,” *Water Resources Research*, vol. 56, no. 4, p. e2019WR024957, Apr. 2020.
- [5] F. R. Spellman, *The science of water: concepts and applications*. CRC press, 2020.
- [6] L. Lin, H. Yang, and X. Xu, “Effects of water pollution on human health and disease heterogeneity: a review,” *Frontiers in environmental science*, vol. 10, p. 880246, 2022.
- [7] N. Akhtar, M. S. Ishak, S. A. Bhawani, and K. Umar, “Various Natural and Anthropogenic Factors Responsible for Water Quality Degradation: A Review. Water (Switzerland).” 2021.
- [8] S. Madhav *et al.*, “Water Pollutants: Sources and Impact on the Environment and Human Health,” in *Sensors in Water Pollutants Monitoring: Role of Material*, D. Pooja, P. Kumar, P. Singh, and S. Patil, Eds., in *Advanced Functional Materials and Sensors*, Singapore: Springer Singapore, 2020, pp. 43–62. doi: 10.1007/978-981-15-0671-0\_4.
- [9] S. S. Sonone, S. Jadhav, M. S. Sankhla, and R. Kumar, “Water contamination by heavy metals and their toxic effect on aquaculture and human health through food Chain,” *Lett. Appl. NanoBioScience*, vol. 10, no. 2, pp. 2148–2166, 2020.
- [10] P. Chowdhary, R. N. Bharagava, S. Mishra, and N. Khan, “Role of Industries in Water Scarcity and Its Adverse Effects on Environment and Human Health,” in *Environmental Concerns and Sustainable Development*, V. Shukla and N. Kumar, Eds., Singapore: Springer Singapore, 2020, pp. 235–256. doi: 10.1007/978-981-13-5889-0\_12.
- [11] Y. Zhou, “Real-time probabilistic forecasting of river water quality under data missing situation: Deep learning plus post-processing techniques,” *Journal of Hydrology*, vol. 589, p. 125164, 2020.
- [12] J. N. Nsengiyumva, N. K. Taremwa, E. Nyandwi, E. Maridadi, and A. Nyirarwasa, “Geospatial Analysis for Heavy Metals and Water Quality Assessment in Bugesera Agricultural Wetlands of Rwanda,” *Rwanda Journal of Engineering, Science, Technology and Environment*, vol. 4, no. 1, Art. no. 1, 2021, Accessed: Jul. 11, 2024. [Online]. Available: <https://www.ajol.info/index.php/rjeste/article/view/221074>
- [13] T. Rajaei, S. Khani, and M. Ravansalar, “Artificial intelligence-based single and hybrid models for prediction of water quality in rivers: A review,” *Chemometrics and Intelligent Laboratory Systems*, vol. 200, p. 103978, 2020.
- [14] Y. Chen, L. Song, Y. Liu, L. Yang, and D. Li, “A review of the artificial neural network models for water quality prediction,” *Applied Sciences*, vol. 10, no. 17, p. 5776, 2020.
- [15] M. Hmoud Al-Adhaileh and F. Waselallah Alsaade, “Modelling and prediction of water quality by using artificial intelligence,” *Sustainability*, vol. 13, no. 8, p. 4259, 2021.
- [16] W. J. Mitsch and J. G. Gosselink, *Wetlands*. John Wiley & Sons, 2015.
- [17] N. C. Davidson, “How much wetland has the world lost? Long-term and recent trends in global wetland area,” *Marine and Freshwater Research*, vol. 65, no. 10, pp. 934–941, 2014.
- [18] R. J. Nicholls, F. M. Hoozemans, and M. Marchand, “Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses,” *Global Environmental Change*, vol. 9, pp. S69–S87, 1999.

- [19] R. C. Secretariat, “Wetland inventory: A Ramsar framework for wetland inventory and ecological character description,” *Ramsar handbooks for the wise use of wetlands*, 2010.
- [20] J. Vymazal, “Constructed Wetlands for Wastewater Treatment: Five Decades of Experience,” *Environ. Sci. Technol.*, vol. 45, no. 1, pp. 61–69, Jan. 2011, doi: 10.1021/es101403q.
- [21] R. H. Kadlec, “Comparison of free water and horizontal subsurface treatment wetlands,” *Ecological engineering*, vol. 35, no. 2, pp. 159–174, 2009.
- [22] K. R. Reddy and E. M. D’angelo, “Biogeochemical indicators to evaluate pollutant removal efficiency in constructed wetlands,” *Water Science and Technology*, vol. 35, no. 5, pp. 1–10, 1997.
- [23] R. P. Gambrell, “Trace and Toxic Metals in Wetlands-A Review,” *Journal of Environmental Quality*, vol. 23, no. 5, pp. 883–891, Sep. 1994.
- [24] W. Stumm and J. J. Morgan, *Aquatic chemistry: chemical equilibria and rates in natural waters*. John Wiley & Sons, 2013.
- [25] D. L. Sparks, B. Singh, and M. G. Siebecker, *Environmental soil chemistry*. Elsevier, 2022.
- [26] J. Torrent, V. Barrón, and U. Schwertmann, “Phosphate Adsorption and Desorption by Goethites Differing in Crystal Morphology,” *Soil Science Soc of Amer J*, vol. 54, no. 4, pp. 1007–1012, Jul. 1990.
- [27] A. Shukla, D. Parde, V. Gupta, R. Vijay, and R. Kumar, “A review on effective design processes of constructed wetlands,” *Int. J. Environ. Sci. Technol.*, vol. 19, no. 12, pp. 12749–12774, Dec. 2022.
- [28] J. P. Ruppelt, K. Tondera, S. J. Wallace, M. Button, J. Pinnekamp, and K. P. Weber, “Assessing the role of microbial communities in the performance of constructed wetlands used to treat combined sewer overflows,” *Science of The Total Environment*, vol. 736, p. 139519, 2020.
- [29] M. Verduzo Garibay, A. Fernández Del Castillo, J. De Anda, C. Senés-Guerrero, and M. S. Gradilla-Hernández, “Structure and activity of microbial communities in response to environmental, operational, and design factors in constructed wetlands,” *Int. J. Environ. Sci. Technol.*, vol. 19, no. 11, pp. 11587–11612, Nov. 2022.
- [30] Y. Zheng *et al.*, “Phytoremediation mechanisms and plant eco-physiological response to microorganic contaminants in integrated vertical-flow constructed wetlands,” *Journal of Hazardous Materials*, vol. 424, p. 127611, 2022.
- [31] J. Fang *et al.*, “Response of microbial community composition and function to emergent plant rhizosphere of a constructed wetland in northern China,” *Applied Soil Ecology*, vol. 168, p. 104141, 2021.
- [32] V. Kumar, P. D. Umrao, and S. D. Kaistha, “Beneficial plant microbiome assisted chromium phytoremediation,” in *Advances in microbe-assisted phytoremediation of polluted sites*, Elsevier, 2022, pp. 301–346.
- [33] A. Haddis, B. Van der Bruggen, and I. Smets, “Constructed wetlands as nature based solutions in removing organic pollutants from wastewater under irregular flow conditions in a tropical climate,” *Ecohydrology & Hydrobiology*, vol. 20, no. 1, pp. 38–47, 2020.
- [34] M. Scholz, *Wetlands for water pollution control*. Elsevier, 2023.
- [35] L. A. Nuamah *et al.*, “Constructed wetlands, status, progress, and challenges. The need for critical operational reassessment for a cleaner productive ecosystem,” *Journal of Cleaner Production*, vol. 269, p. 122340, 2020.
- [36] A. O. Adeeyo, S. S. Ndlovu, L. M. Ngwagwe, M. Mudau, M. A. Alabi, and J. N. Edokpayi, “Wetland Resources in South Africa: Threats and Metadata Study,” *Resources*, vol. 11, no. 6, Art. no. 6, Jun. 2022.

- [37] M. J. Paul and J. L. Meyer, "Streams in the Urban Landscape," *Annu. Rev. Ecol. Syst.*, vol. 32, no. 1, pp. 333–365, Nov. 2001, doi: 10.1146/annurev.ecolsys.32.081501.114040.
- [38] C. J. Walsh, T. D. Fletcher, and M. J. Burns, "Urban Stormwater Runoff: A New Class of Environmental Flow Problem," *PLOS ONE*, vol. 7, no. 9, p. e45814, Sep. 2012.
- [39] A. Ghermandi, D. Bixio, and C. Thoeye, "The role of free water surface constructed wetlands as polishing step in municipal wastewater reclamation and reuse," *Science of The Total Environment*, vol. 380, no. 1, pp. 247–258, Jul. 2007.
- [40] B. Alloway and D. C. Ayres, *Chemical Principles of Environmental Pollution, Second Edition*. CRC Press, 1997.
- [41] P. B. Tchounwou, C. G. Yedjou, A. K. Patlolla, and D. J. Sutton, "Heavy Metal Toxicity and the Environment," in *Molecular, Clinical and Environmental Toxicology*, vol. 101, A. Luch, Ed., in *Experientia Supplementum*, vol. 101., Basel: Springer Basel, 2012, pp. 133–164. doi: 10.1007/978-3-7643-8340-4\_6.
- [42] M. Gavriescu, "Fate of Pesticides in the Environment and its Bioremediation," *Engineering in Life Sciences*, vol. 5, no. 6, pp. 497–526, Dec. 2005.
- [43] R. C. Lathrop, S. R. Carpenter, C. A. Stow, P. A. Soranno, and J. C. Panuska, "Phosphorus loading reductions needed to control blue-green algal blooms in Lake Mendota," *Can. J. Fish. Aquat. Sci.*, vol. 55, no. 5, pp. 1169–1178, May 1998.
- [44] C. E. Raptis, J. M. Boucher, and S. Pfister, "Assessing the environmental impacts of freshwater thermal pollution from global power generation in LCA," *Science of The Total Environment*, vol. 580, pp. 1014–1026, Feb. 2017.
- [45] R. S. Lunetta, J. F. Knight, J. Ediriwickrema, J. G. Lyon, and L. D. Worthy, "Land-cover change detection using multi-temporal MODIS NDVI data," in *Geospatial Information Handbook for Water Resources and Watershed Management, Volume II*, CRC Press, 2022, pp. 65–88.
- [46] J. R. Jensen, *Remote sensing of the environment: An earth resource perspective 2/e*. Pearson Education India, 2009.
- [47] W. Turner, S. Spector, N. Gardiner, M. Fladeland, E. Sterling, and M. Steininger, "Remote sensing for biodiversity science and conservation," *Trends in Ecology & Evolution*, vol. 18, no. 6, pp. 306–314, Jun. 2003.
- [48] G. Matheron, "Principles of geostatistics," *Economic geology*, vol. 58, no. 8, pp. 1246–1266, 1963.
- [49] C. V. Deutsch and A. G. Journel, "Geostatistical software library and user's guide," *New York*, vol. 119, no. 147, p. 578, 1992.
- [50] E. H. Isaaks and R. M. Srivastava, "Applied geostatistics," 1989.
- [51] J. Ambundo, "Assessment of Temporal and Spatial Variability of Groundwater in the Mbagathi River Catchment," PhD Thesis, University of Nairobi, 2023.
- [52] H. G. Rendilicha, P. Home, J. M. Raude, C. M. M'Erumba, S. Muthoka, and J. Wanjala, "Assessing the Impact of land-use types on the groundwater quality: a case study of Mid River Njoro Catchment, Kenya," *Acque Sotterranee-Italian Journal of Groundwater*, vol. 9, no. 4, 2020.
- [53] S. Mwendwa, "Detailed Soil Survey and Spatial Variability of Selected Soil Properties in Upper Kabete Campus Field, University of Nairobi, Kenya," PhD Thesis, University of Nairobi, 2021.
- [54] A. Gakuba, "RWANDA ENVIRONMENT MANAGEMENT AUTHORITY," 2012.
- [55] V. Novoa, O. Rojas, R. Ahumada-Rudolph, K. Sáez, P. Fierro, and C. Rojas, "Coastal wetlands: ecosystems affected by urbanization?," *Water*, vol. 12, no. 3, p. 698, 2020.

- [56] E. Alavaisha, S. W. Lyon, and R. Lindborg, "Assessment of water quality across irrigation schemes: A case study of wetland agriculture impacts in Kilombero Valley, Tanzania," *Water*, vol. 11, no. 4, p. 671, 2019.
- [57] M. Mokarram, A. Saber, and V. Sheykhi, "Effects of heavy metal contamination on river water quality due to release of industrial effluents," *Journal of Cleaner Production*, vol. 277, p. 123380, 2020.
- [58] M. Sinclair, A. Ghermandi, S. A. Moses, and S. Joseph, "Recreation and environmental quality of tropical wetlands: A social media based spatial analysis," *Tourism Management*, vol. 71, pp. 179–186, 2019.
- [59] J. UWIZEYIMANA *et al.*, "Wetland Restoration and Farming Practices Prohibition towards Local Users' Livelihood Insights of Rugezi Wetland, Rwanda".
- [60] "Rwanda Environment Management Authority (REMA): Nyandungu Urban Wetland Ecotourism."
- [61] C. M. Tarzwell, "Water quality criteria for aquatic life," in *Trans. Seminar Biological Problems in Water Pollution*, 1956.
- [62] C. E. Boyd, *Water quality: an introduction*. Springer Nature, 2019.
- [63] O. T. Baki, E. Aras, U. O. Akdemir, and B. Yilmaz, "Biochemical oxygen demand prediction in wastewater treatment plant by using different regression analysis models," *Desalination and water treatment*, vol. 157, pp. 79–89, 2019.
- [64] A. Fitri, K. N. A. Maulud, F. Rossi, F. Dewantoro, P. Harsanto, and N. Z. Zuhairi, "Spatial and temporal distribution of dissolved oxygen and suspended sediment in Kelantan river basin," in *4th International Conference on Sustainable Innovation 2020–Technology, Engineering and Agriculture (ICoSITEA 2020)*, Atlantis Press, 2021, pp. 51–54.
- [65] J. Xiao, L. Wang, L. Deng, and Z. Jin, "Characteristics, sources, water quality and health risk assessment of trace elements in river water and well water in the Chinese Loess Plateau," *Science of the Total Environment*, vol. 650, pp. 2004–2012, 2019.
- [66] S. Kükreer and E. Mutlu, "Assessment of surface water quality using water quality index and multivariate statistical analyses in Saraydüzü Dam Lake, Turkey," *Environmental monitoring and assessment*, vol. 191, pp. 1–16, 2019.
- [67] A. Ram, S. K. Tiwari, H. K. Pandey, A. K. Chaurasia, S. Singh, and Y. V. Singh, "Groundwater quality assessment using water quality index (WQI) under GIS framework," *Appl Water Sci*, vol. 11, no. 2, p. 46, Feb. 2021.
- [68] P. Vasistha and R. Ganguly, "Water quality assessment of natural lakes and its importance: An overview," *Materials Today: Proceedings*, vol. 32, pp. 544–552, 2020.
- [69] I. Khouni, G. Louhichi, and A. Ghrabi, "Use of GIS based Inverse Distance Weighted interpolation to assess surface water quality: Case of Wadi El Bey, Tunisia," *Environmental Technology & Innovation*, vol. 24, p. 101892, 2021.
- [70] A. Aldrees, M. A. Khan, M. A. U. R. Tariq, A. Mustafa Mohamed, A. W. M. Ng, and A. T. Bakheit Taha, "Multi-expression programming (MEP): water quality assessment using water quality indices," *Water*, vol. 14, no. 6, p. 947, 2022.
- [71] J. T. Fox and K. A. Alexander, "Spatiotemporal variation and the role of wildlife in seasonal water quality declines in the Chobe River, Botswana," *PLoS One*, vol. 10, no. 10, p. e0139936, 2015.
- [72] E. S. Money, G. P. Carter, and M. L. Serre, "Modern Space/Time Geostatistics Using River Distances: Data Integration of Turbidity and E. coli Measurements to Assess Fecal Contamination Along the Raritan River in New Jersey," *Environ. Sci. Technol.*, vol. 43, no. 10, pp. 3736–3742, May 2009.

- [73] A. Li, K. Song, S. Chen, Y. Mu, Z. Xu, and Q. Zeng, “Mapping African wetlands for 2020 using multiple spectral, geo-ecological features and Google Earth Engine,” *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 193, pp. 252–268, Nov. 2022.