AN ASSESSMENT OF WATER QUALITY, SOIL DEGRADATION AND WATER PURIFICATION ABILITY OF KHUBELU WETLAND IN MOKHOTLONG LESOTHO, AND THE IMPLICATIONS OF CLIMATE CHANGE

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AN ASSESSMENT OF WATER QUALITY, SOIL DEGRADATION AND WATER PURIFICATION ABILITY OF KHUBELU WETLAND IN MOKHOTLONG LESOTHO, AND THE IMPLICATIONS OF CLIMATE CHANGE

by

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Declaration

I, Antoinette Maeti George, hereby declare that this thesis, which I hereby submit for the degree of **DOCTOR OF PHILOSOPHY IN ENVIRONMENTAL MANAGEMENT** at the University of South Africa, is my own work and has not previously been published or submitted by me for a degree at this or any other institution.

I declare that the thesis does not contain any written work presented by other persons whether written, pictures, graphs or data or any other information without acknowledging the source.

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For many of us, water simply flows from a faucet, and we think little about it beyond this point of contact. We have lost a sense of respect for the wild river, for the complex workings of a wetland, for the intricate web of life that water supports. — Sandra Postel

Abstract

Palustrine wetlands in Lesotho are vulnerable to vegetation loss due to overgrazing and the nature of the topography, the latter leading to gully erosion exacerbated by a degraded soil structure. Degraded soils are not able to adsorb pollutants; neither can they support vegetation growth. The presence of degraded soils in wetlands thus contributes towards leaching of pollutants into nearby streams and groundwater resources. Khubelu wetland (which was the focus of this study) is a palustrine wetland that discharges water into the Khubelu stream in Lesotho. The water purification function of this wetland is pertinent since Khubelu River is one of the tributaries at the headwaters of the shared Orange-Senqu basin. This function is threatened by vegetation loss and soil degradation through overgrazing and environmental conditions like extreme climatic variations. Consequently, water released into adjacent streams from the wetland could be of low quality, further putting at risk the health of this ecosystem and users of these streams due to toxicity caused by the polluted water from the wetland. With predicted floods and/or droughts and intense heat, water temperatures may rise by up to 70% in the 21st century according to researchers. It is believed that floods would lead to shorter residence time of water within wetlands, washing away soil with pollutants into surrounding streams before any geochemical processes that would sequester them occurs. Droughts on the other hand would lead to failure of dilution of polluted waters. Excessive evaporation due to intense heat would also leave pollutant-concentrated water behind. Since these wetlands are the headwaters of an international river, the problem of water pollution and deteriorated water resources might be regional.

The main aim of the study was to characterise the extent of soil degradation and water quality in the Khubelu wetland and assess the water purification ability in an endeavour to understand the role the wetland plays in the quality of water in rivers and streams fed by the Khubelu wetland, and also to understand how changes in climate would impact on the wetland characteristics. *In situ* analyses of soil and water were done followed by sampling of the same for further analysis in the laboratory using standard methods. Surface water samples were collected from two sampling points in the Khubelu stream, whereas water in the wetland was sampled from seven piezometers installed in the wetland. Three replicates of water samples were collected from each sampling point monthly over a period of one year. The water properties determined included pH,

Electrical Conductivity (EC), Dissolved Oxygen (DO), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), cations (magnesium, calcium, potassium and sodium), Total Dissolved Solids (TDS), nitrates, phosphates and chlorides. The data generated from these analyses were subjected to various statistical tests and the Water Quality Index (WQI) of the wetland and stream waters determined. The water quality drinking standards were preferred in this study since the major beneficiaries of the stream that emanates from the wetland are human populace. Prediction of water quality in the wetland in light of the changing climate was done using the Water Evaluation and Planning (WEAP) model.

Soil samples were collected from the upper, middle and lower areas of the wetland, referred to as upstream, midstream and downstream of the wetland in the report, at the same sites where the piezometers were installed. At each site, three sampling points were identified two metres apart from each other and samples collected at depths of 15 cm, 30 cm and 45 cm at each site. The soil samples were then characterised for their texture, pH, Electrical Conductivity (EC), Cation Exchange Capacity (CEC), Total Carbon (TC), Total Nitrogen (TN), Organic Matter (OM), exchangeable calcium, magnesium, potassium and sodium, and available phosphorus, using standard procedures. The soil data generated were then subjected to data analyses and the Chemical Degradation Index (CDI) of the wetland soils determined. Determination of the wetland's potential to purify water was done by assessing its ability to retain nutrients, pollutants and sediments.

Results obtained in this study showed that the wetland and stream water had circumneutral pH with values that ranged from 6.32 -7.69. The values for Na, Ca, K, Mg, TDS, NO_3, Cl and DO in the wetland and stream waters were below the WHO drinking water standards thresholds of 200 mg/l for Na and Ca, 12 mg/l for K, 150 mg/l for Mg, 50 mg/l for TDS 50 mg/l for NO_3, 5 mg/l for DO and BOD, and 250 mg/l for Cl. Food and Agricultural Organisation (FAO) water standards for livestock drinking were: EC: <1.5 mS/cm (Excellent); 1.5 – 5.0 mS/cm (very satisfactory); < 250 mg/l of Mg for cows, 400 mg/l for beef cattle, and 500 mg/l for adult sheep. SA Irrigation water quality standards were also used, and it was determined that pH was within the acceptable threshold of 6.5 – 8.4, 70 mg/l for sodium and 0.4 mS/cm for EC. EC of 0.41 mS/cm to 1.12 mS/cm in the wetland and 0.67 mS/cm to 2.11 mS/cm in the stream was above the SA irrigation

water quality standards. Other water properties such as PO_4 (0.06-1.26 mg/l in stream and 0.17-0.61 mg/l in wetland), and COD (10.00 to 55.00 mg/l in stream and 48-140.80 mg/l in the wetland) were above the WHO permissible limits. The water quality in the Khubelu wetland and stream ranged from very poor to unsuitable for drinking, with WQI values of 107 for the stream and 93 for the wetland. Water quality simulation along the Khubelu stream using the WEAP model shows that by the year 2025, BOD as one of the water quality parameters, would be high, with DO declining further especially if temperature increases and precipitation decreases. The wetland had sandy and acidic soils, with the TC and TN content of the soil decreasing with depth. The CDI value for the soil was 3.29. Regarding potential to reduce sediments, nutrients and organic pollutants, the wetland scored 7.09, 5.39 and 7.39 out of 10, respectively. This implies that there is moderate potential for the wetland to purify water that is discharged into the stream.

The study concludes that the stream and wetland water qualities are unsuitable for human consumption and usable for livestock drinking. However, there might be some risks associated with evaporation that would leave the water saline. The wetland water presents a threat to the water quality of the receiving stream. However, the wetland has moderate potential to retain sediments, nutrients and toxic organics. This potential is threatened by a predicted decrease in precipitation and increase in temperature since oxygen-depleting contaminants and other pollutants whose behaviour in the environment are influenced by climate are highly likely to increase in concentrations in both the wetland and the stream. There is therefore a threat to the supply of water of good quality to the Senqu catchment, which supplies neighbouring countries (South Africa, Namibia and Botswana). Similar studies to this one need to be carried out for other wetlands in Lesotho on a regular basis to come up with data that would aid policy development that seeks to protect water resources.

List of Acronyms and Units

AAS	Atomic Absorption Spectrometer
ANOVA	Analysis of Variance
APHA	American Public Health Association
AU	Assessment Unit
BOD	Biochemical Oxygen Demand
CDI	Chemical Degradation Index
CEC	Cation Exchange Capacity
COD	Chemical Oxygen Demand
DEM	Digital Elevation Model
DIC	Dissolved Inorganic Carbon
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DRRM	Department of Range Resources Management
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
ENSO	El Nino, Southern Oscillation Index
ETo	Evapotranspiration
FAO	Food and Agriculture Organisation
GCM	General Circulation Model
GHGs	Green House Gases
GIS	Geographical Information System
GoL	Government of Lesotho
DNRA	Dissimilatory Nitrate Reduction to Ammonium
GPS	Geographic Positioning System
GTZ	German Technical Cooperation
GW	Ground Water
HSD	Honest Significance Difference
IPCC	Intergovernmental Panel on Climate Change
KMO	Kaiser-Meyer-Olkin
LHDA	Lesotho Highlands Development Authority
LHWP	Lesotho Highlands Water Project

LMS	Lesotho Meteorological Services
LOI	Loss-on-ignition
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Productivity
NSE	Nash-Sutcliffe Efficiency
NRCS	Natural Resources Conservation Service
NUL	National University of Lesotho
OC	Organic Carbon
OM	Organic Matter
ORASECOM	Orange-Senqu River Commission
OS	Oxygen saturation
P_{act}	Index of actual phosphate accumulation
PC	Principal Components
PCA	Principal Component Analysis
POC	Particulate Organic Carbon
POP	Particulate Organic Phosphorus
RCP	Representative Concentration Pathways
SADC	South African Development Corporation
SFI	Soil Form Indicator
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SOP	Soluble Organic Phosphorus
SPSS	Statistical Package for Social Sciences
SRS	Satellite Remote Sensing
SWI	Soil Wetness Indicator
TC	Total Carbon
TDS	Total Dissolved Solids
TN	Total Nitrogen
TUI	Terrain Unit Indicator
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
VI	Vegetation Indicator
WEAP	Water Evaluation and Planning

WHO	World Health Organisation
WQI	Water Quality Index

Table of Contents

List of Appendices

List of Figures

List of Tables

CHAPTER 1
INTRODUCTION

1.1 Background to the study

The definition of wetlands is not straightforward due to the wide spectrum of locations (inland or within deep waters) within which they are found, the hydraulic functions they provide, the period within which they are saturated with water, the species that may have adapted to living in the wetland, and other features that may be cross-cutting. Resulting from these, the Ramsar Convention in 1971 defined wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six meters" (Finlayson & Moser, 1991). This definition falls short of the regulatory definition, and so the U.S Army of Corps of Engineers (1984) came up with a regulatory definition which describes wetlands as: "those areas that are inundated with or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support a prevalence of vegetation typically adapted for life in saturated soil conditions". Wetlands generally include swamps, marshes, bogs and similar areas. With the two inadequate definitions above, Tiner (2016) came up with another definition that specified the extent of wetlands from the surface as "areas that are saturated with water within at least 30 cm of their ground surface for at least two weeks or more". According to the MEA (2005), wetlands can be classified as marine/coastal wetlands (saline and freshwater lagoons, and coral reefs), inland wetlands (streams, lakes and rivers), and manmade wetlands (canals and constructed wetland).

Though wetlands differ in their species composition and habitat types, they must all have the following characteristics in order to be considered wetlands: wetland hydrology, hydric soils (soils that during the growing season are saturated and render anaerobic conditions in the upper part of their soil substrate (NRCS, 1998) or soils formed under anaerobic conditions), and hydrophytic vegetation (Soil Survey Staff, 1994). Wetlands generally serve several functions including the improvement of water quality, influencing hydrology of the area where they are found, and provision of habitats for plants and animals. They also dissipate water that runs through them, assist in flood attenuation, and thus preventing soil erosion. In addition, other wetland hydrological functions are recharge of groundwater and discharge of streams. Wetlands have thus sustained downstream users through clean water provision, vegetation provision and ecological balance (Tong *et al.,* 2014). These ecosystems act as sources, sinks and transformers of chemicals and nutrients (Xiuzhen, 2000; Mitsch & Gosselink, 2007). They can perform water purification functions because some wetland vegetation is able to absorb pollutants, nutrients and salts through their roots, and wetland soils are also known to adsorb pollutants. Soil, biota, and wetland water all act as media for transformation of nutrients including nitrogen, carbon and phosphorus and therefore play a key role in biogeochemical cycling (Mitsch & Gosselink, 2007; Reddy *et al.,* 2010). They also sequester carbon through their conversion of carbon dioxide into biomass.

Globally, wetlands are threatened by climate change (Wilby *et al.,* 2010), especially through variations in temperature and precipitation. Studies by Senhorst & Zwolsman (2005) and Delpla *et al.* (2009) have signified the possibility of compromised water quality of some water resources as a result of increased frequency and intensity of extreme temperature, flood and drought events. An increase in air temperature from 1.5ºC to 4.8ºC would bring about an increase in water temperature by 70% (for example from 30ºC to 51ºC) (Harris & Roach, 2017). Generally, temperature is the main driver of most physico-chemical and biological reactions in the environment including wetlands (Bates *et al*., 2008; Prathumratana *et al.,* 2008; Delpla *et al*., 2009). A study by Meyer and Sale (1999) has shown that there is accelerated growth of phytoplankton and primary production in rivers due to increased water temperature (Bates *et al.,* 2008), leading to depletion of Dissolved Oxygen (DO) as the plants die and decompose. Biogeochemical reactions in wetlands, which contribute towards water purification, are affected by precipitation, interaction with groundwater, reaction with Organic Carbon (OC) and evapotranspiration rates (Waiser, 2006; Gerla, 2013).

In their study, Chen *et al.* (2002) have shown that recharge processes of groundwater may be affected by climate change. Reference was made to Western Australia (Smith & Pollock, 2010) and south-western Unites States (Thomas *et al.,* 2016), where decreases in groundwater recharge were as a result of slow recharge from surface water. Extremes in precipitation however are envisaged to affect wetland water quality due to sedimentation during rain storms, Dissolved Organic Carbon (DOC) and salts (IPCC, 2008). Other authors pronounced the likelihood that wetland water quality may also decline due to poor dilution of pollutants caused by low precipitation and high temperatures (Meyer & Sale, 1999; Delpla *et al.,* 2009; Grochowska & Tandyrak, 2009). In Africa, rainfall is projected to increase, but for southern Africa, projections show a general reduction in precipitation (Bates *et al*., 2008) with Chapman (2012) emphasising that this would be the case in winter. Further projections to the year 2100 reveal a reduction in precipitation in winter (May to July), with first summer rains of more intensity being experienced much later than what prevails presently. These may have consequences for wetland functions.

Wetland soils have several functions ranging from attenuation of floods and being a habitat for animals. Wetland soils have also been useful in the removal of contaminants (Huang *et al*., 2012) and nutrients like phosphorus (Schoumans, 2015) from wetland water that would otherwise pollute rivers downstream. Soil can retain exchangeable cations that are introduced into wetlands through exchange reactions with plant roots (Mulder & Cresser, 1994). With high temperatures, wetland soils will likely dry up, a process that would consequently lead to oxidation or reduction of the solute and solid-phase soil species (Shand *et al.,* 2017). High temperatures are also associated with high pollutant and nutrient concentration in streams (Alam *et al.,* 2013) due to high evaporation that leaves behind these pollutants. In general, low temperatures are not suitable for soil microbial activities that are responsible for denitrification, and hence low temperatures may lead to a failure of wetlands to remove nitrates by denitrification. Extreme rain does not allow water to settle or be retained in wetlands and thus adsorption of pollutants and nutrients that water may be carrying with it onto wetland soils is reduced (Hosseini *et al.,* 2017). Saturated soils, coupled with high temperature, lead to increased microbial activity that ensures decomposition of OM and hence less stored OC in such soils (Hoorman & Islam, 2010). When low precipitation is experienced, low dilution of salts will be experienced leading to their high concentrations, whereas microbial activity will be low owing to unfavourable moisture conditions leading into low rate of OM decomposition (Hoorman & Islam, 2010). Organic carbon is expected to be high in such environments, as well as increased water-holding capacity. However, unsaturated soil conditions may be favoured by aerobic micro-organisms, which would decompose OM. The performance of micro-organisms that are responsible for OM decomposition and nutrient recycling is also regulated by other factors like pH (with pH of 6 to 8 for bacteria (Brady, 1990) and 4 to 6 for fungi (Paul & Clark, 1996)). In a study by Higashida and Takao (1986), low soil pH was found to suppress microbial activity, and hence contribute to high soil OM accumulation. The quality of OM also plays a role as sugars and amino acids decompose much faster than cellulose and hemicellulose (Paul & Clark, 1996), the latter being constituents of wetland OM.

Future climate predictions for Lesotho show both an increase (between 150 mm and 900 mm annually) and a decrease (between 150 mm and 600 mm) in precipitation for the year 2030-2050 (World Bank, 2016). However, 64 General Circulation Model (GCM) projections indicate drier conditions, with 57 GCM projections pointing to wetter conditions in Lesotho (World Bank, 2016). In Lesotho, previous studies relate compromised water purification function of wetlands to other activities such as overgrazing and overharvesting of some wetland resources (DWA, 2005). The relationship between this important wetland function and climatic variations, especially changes in precipitation, temperature, and evaporation (Tong *et al.,* 2014) has not been studied closely, and could ultimately lead to their mismanagement and loss of water resources' functions and values. This study focuses on Khubelu wetland, a palustrine wetland in Mokhotlong district, Lesotho. The Khubelu wetland feeds several rivers, including shared and transboundary rivers. It is known to sustain these rivers with pure water, control soil erosion, and recharge groundwater (DWA, 2005).

1.2 Statement of the problem

Sustained provision of water of good quality is the basis for healthy ecosystems and human survival. It is therefore worthwhile to know potential threats to water systems to minimise or stop their deterioration. Lesotho, like other countries, has been experiencing high temperatures and low precipitation; a phenomenon associated with global climate change. Currently, focus on wetland degradation in the highlands of Lesotho is related to steep slopes that exacerbate soil erosion, rat invasion, sparse vegetation and low organic carbon (Olaleye, 2013) while the assessment of water quality and how it may be impacted upon by climate change has received little attention (Bates *et al.,* 2008).

The effects of climate change on wetlands are not usually evident immediately when they occur, resulting in wetland managers not being enthusiastic to develop strategies that would be employed to alleviate climate change effects on water bodies. It is therefore significant that prediction of the likely effects of climate change on wetlands be done on time. In the light of the projected temperatures, it can be assumed that prolonged hot summers will contribute towards high Electrical Conductivity (EC) (Gerla, 2013; Herbert *et al.,* 2015), and high levels of nutrients and dissolved salts (Burkett & Kusler 2000) in wetlands due to processes like evapotranspiration (Reddy *et al.,* 2010). Extremes in temperatures will also lead to degradation of soil, and hence its inability to retain pollutants. It has been found by Xu *et al*. (2016) that low temperatures are associated with low activity of micro-organisms responsible for denitrification and hence failure of wetlands to remove nitrate by denitrification (Hoorman & Islam, 2010). This will subsequently lead to threatened quality of streams that run from such wetlands, whereby in this case, eutrophication may result from excessive supply of nutrients to the Khubelu stream.

Eutrophication in streams emanating from wetlands is a sign that the wetland is not able to purify water. Water supplied by the stream to the surrounding areas as a result may be of poor quality. Due to a decline in precipitation, there is also a likelihood of a change in Khubelu wetland vegetation cover. The wetland will subsequently be unable to trap sediments, pollutants and nutrients, and hence not be able to purify water that runs into the Khubelu stream. Vegetation does not only trap sediments but it also helps in soil development and erosion prevention. With the foreseen loss of wetland vegetation, degradation of soil and resultant failure of the wetland to trap sediments, organic pollutants and nutrients, the Khubelu stream that is fed by the Khubelu wetland would have water of low quality.

With expected low flows due to decrease in precipitation, it can also be assumed that there will be less contaminant and salt dilution, followed by high concentrations in wetland waters and their associated streams (Kileen, 2008). Excessive precipitation that does not allow long residence time of water in wetlands would subsequently lead to them being washed into the nearby streams, and this will further stress the Lesotho palustrine wetlands that sustain river flows. Lesotho supplies clean water to rivers that are shared with South Africa, Namibia and Botswana (DWA, 2005). Wetlands are at the headwaters of these water sources and, with the envisaged decline in water quality from the headwaters of the country, this supply and the economic benefit derived from this resource by the country are threatened. The impact of climate change is determined by how sensitive a system is and the degree of exposure to such climatic variations (Dejene *et al*., 2011). It is currently not clear how climate change (extreme drought and flood events) may affect the effectiveness of wetlands such as Khubelu to purify water prior to its water discharge into streams. This study intends to address this gap.

1.3 Research questions

The study addresses the following questions:

i. What is the quality of water in Khubelu wetland and stream?
ii. What are the characteristics of soils in the Khubelu wetland?
iii. Is the Khubelu wetland still performing its water purification function?
iv. What is the effect of climate change on water quality of the Khubelu stream?

1.4 Research Aim

The main aim of the study is to determine how climate change may affect water quality in Khubelu wetland and to understand how these effects may impact on the wetland's water purification ability. In order to address the aim and answer the research questions above, the following specific objectives have been designed:

i. To determine the quality of water in Khubelu wetland and stream.
ii. To characterise the soil quality of Khubelu wetland.
iii. To assess the water purification function of the Khubelu wetland.
iv. To determine the effect of climate change on water quality of the Khubelu stream.

1.5 Conceptual framework of the study

Figure 1.1 shows how high temperatures and drought would affect a wetland's ability to purify water. When precipitation is high, pollutants have a good chance of being diluted, but anoxic conditions may develop leading to a slow rate of organic matter (OM) decomposition and hence their accumulation, supporting vegetation growth. Good vegetation slows down the velocity of runoff, while supporting nutrient retention, pollutants adsorption and enabling trapping of sediments. When the water flow velocity in the wetland is reduced, there will be a longer residence time of the water within the wetland, enabling the exchange of cations between wetland water, soil and plant roots. This also results in the creation of anoxic conditions within the wetland that slows down the rate of organic matter decomposition. This ensures release of purified water into nearby streams. On the other hand, low precipitation is accompanied by oxic conditions that enhance OM decomposition, and poor vegetation cover. There may, as a result be low sediment trapping, pollutant and nutrient retention. The wetland water may not be adequately purified. High temperatures lead to high evapotranspiration and evaporation, while speeding up microbial activities. This in turn leads to low OM accumulation due to its high rate of decomposition, and hence poor vegetation growth. Low temperatures, on the other hand, favour low OM decomposition and good vegetation cover due to high accumulation of OM. There will be high pollutant retention, sediment trapping and nutrient retention. All these lead towards discharge of water purified water into the nearby stream. From the conceptual framework, it is evident that wetlands release pure water with the assistance of their soil and vegetation. Vegetation like grasses reduce water speed, thus minimising the erosive power of water. The vegetation absorbs pollutants, salts and nutrients so that water leaving the wetland has low concentration of these components.

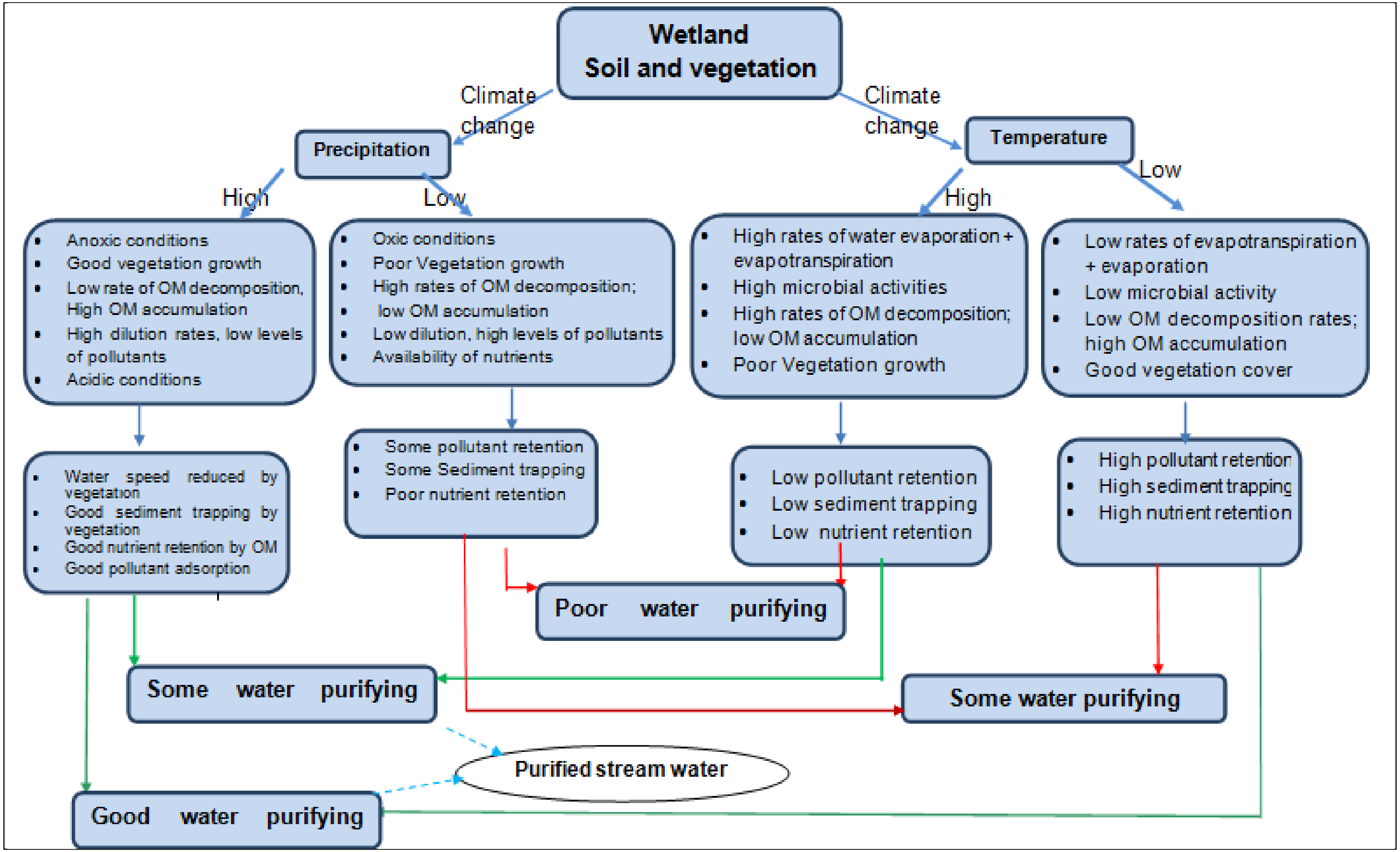


Figure 1.1: Conceptual Framework of the study

1.6 Rationale and significance of the study

Wetlands are threatened by changing climate globally. Climate change is expected to change precipitation patterns, increase air and water temperature, and increase storm intensity (IPCC, 2008), with some regions likely to experience low precipitation resulting in adverse effects on wetland functions (Kim *et al.,* 2012) like water purification. It is necessary therefore to determine whether temperature and precipitation variations may affect soil quality, wetland vegetation cover, and ultimately wetlands' pollutant and nutrient removal capacity (Reddy *et al.,* 2010).

Palustrine wetlands are believed and expected to purify water, rendering stream water emanating from them of good quality. It is pertinent that water and soil quality of the wetland are determined as these two wetland components play a significant role in the wetland's ability to purify water. With predicted variations in precipitation and temperature of the Oxbow area, there is a possibility that this function of the Khubelu wetland will be affected. The results of this study provide valuable information that could be utilised to manage the wetland to ensure that it is still able to perform this function.

Water pollution is becoming a global concern for both water-abundant and water-scarce countries. Lesotho is one of those water-abundant countries and hence one of the reasons why issues around water pollution are being overlooked. The highlands of Lesotho are also the headwaters of many rivers including Senqu River, which explains why Khubelu has been listed as an under-protected area (GoL, 2006). Water scarcity and continued degradation of wetlands are, globally, putting communities in developing countries at health risk (MEA, 2005). Communities in Lesotho are among those facing these challenges and research is needed to protect public health and the health of ecosystems in the country in the face of a changing climate. Focus must be on modelling climate-affected water contaminants such as nutrients, oxygen depleting contaminants, and other related pollutants that are driven by climate. Results from this study add to the limited information and data available for policy and decision makers in Lesotho and in the Southern African Development Community (SADC) region regarding effective management of wetlands and other natural ecosystems (National Academies of Sciences, 2016). Lesotho is amongst the southern African countries without climate change prediction models and the study intends to address this gap. The study is also expected to inform whether wetlands may be resilient to changes that are envisaged as a result of climatic variations. This will benefit Orange-Senqu River Commission (ORASECOM), Lesotho and South Africa in terms of sustained water supply of good quality.

This study also serves as a baseline for other wetland studies especially those wetlands that are sources of major rivers in Lesotho, since all these catchments eventually have their streams running into South Africa. It is hoped that the study outcomes will strengthen climate change adaptation strategies and enable policymakers and other decision makers make scientifically informed decisions in managing Khubelu wetlands and the Orange-Senqu basin.

1.7 Delimitation of the study

The study was conducted on Khubelu wetland, in the Phapong sub-catchment. This catchment is in the northern highlands of Lesotho in the Mokhotlong district. Water quality parameters that were analysed were chosen based on their importance in determining Water Quality Index (WQI), whereas those selected for soil quality were those that contribute significantly to wetland’s ability to purify water.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

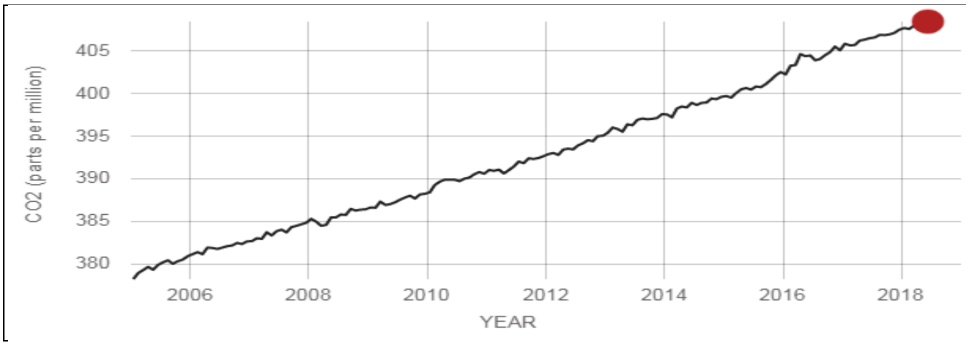
Wetlands play a significant role in the communities where they are found. As a result of their importance, several studies have been carried out to understand different aspects about wetlands. This study focuses on a palustrine wetland. In this chapter, existing empirical studies on wetlands, the kinds of water and soils that make up this unique ecosystem as well of its water quality are presented. Information on challenges that palustrine wetlands are facing in the light of variations in temperature and precipitation have also been presented. The effects that climate change may have on these wetland components, and how these climatic changes may influence the water purification function of wetlands, are also discussed.

2.2 Climate change and its causes

Climate change is described by Inter-governmental Panel on Climate Change (IPCC) (2007) as a significant change in climatic conditions such as temperature and hydrological systems (like fluctuating precipitation patterns, increase in water vapour and soil moisture) as a result of natural causes or human activities (IPCC, 2007, 2008; Cook *et al*., 2016). Other definitions say it is a period of ten years and above, where there is a digression in climatic state statistically (Wei-hong, 2009). These definitions point towards the significance of variations in climatic conditions over time. The phenomenon dates back to the 1800s when it was associated with temperature changes in the equator-pole distributions and not in the equatorial ones (Lindzen, 1994). The major contributor to climate change was then water vapour, followed by clouds and then carbon dioxide (Goody & Yung, 1989). It must be acknowledged that there were not enough data back in the 1800s to fully support or align global warming with anthropogenic activities (Lindzen, 1994).

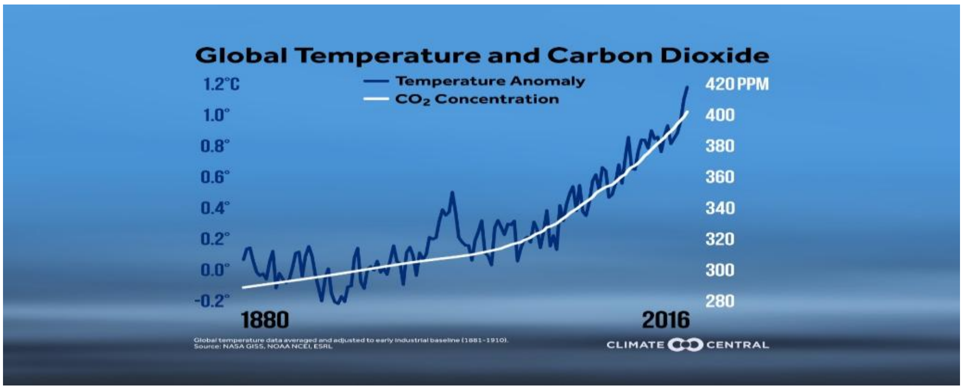
Climate change has been experienced globally but the rate at which the planet earth is heating is extraordinary. It is mostly an anthropogenic phenomenon (Qin *et al*., 2014; Choi *et al.,* 2017), resulting from excessive emission of Green House Gases -GHGs (IPCC, 2014) that trap long wave radiation from the earth's surface thus increasing

Earth's temperatures (Mitsch & Gosselink, 2007). Greenhouse gases include methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), ozone (O_3) and water vapour (Mitsch & Gosselink, 2007; Barros & Albernaz, 2014), with the main contributor being carbon dioxide. Activities contributing towards increased levels of carbon dioxide include deforestation, desertification, industrialisation (National Academies of Sciences, 2016) and forest fires. Scientists refer to the problem of increased CO_2 as a global change (Fig. 2.1) due to the varied responses observed in different areas with some areas showing a warming effect, and others a cooling effect (Harris & Roach, 2017). Figure 2.2 shows a direct link between increases in atmospheric CO_2 levels with global temperature, with a forecast made up to the year 2020. There has also been an observation that a rise in global carbon dioxide is directly proportional to a rise in global temperatures, as in Figure 2.2 and 2.3. Global average surface temperatures have increased by 1.4 - 5.8ºC since the industrial revolution (Houghton, 2003). The 2030 projections show that there will be global temperature increase of 0.3 to 2.5ºC (Daron, 2014), whereas the 2100 projections show an increase of 2 to 5.4ºC (Chapman, 2012).



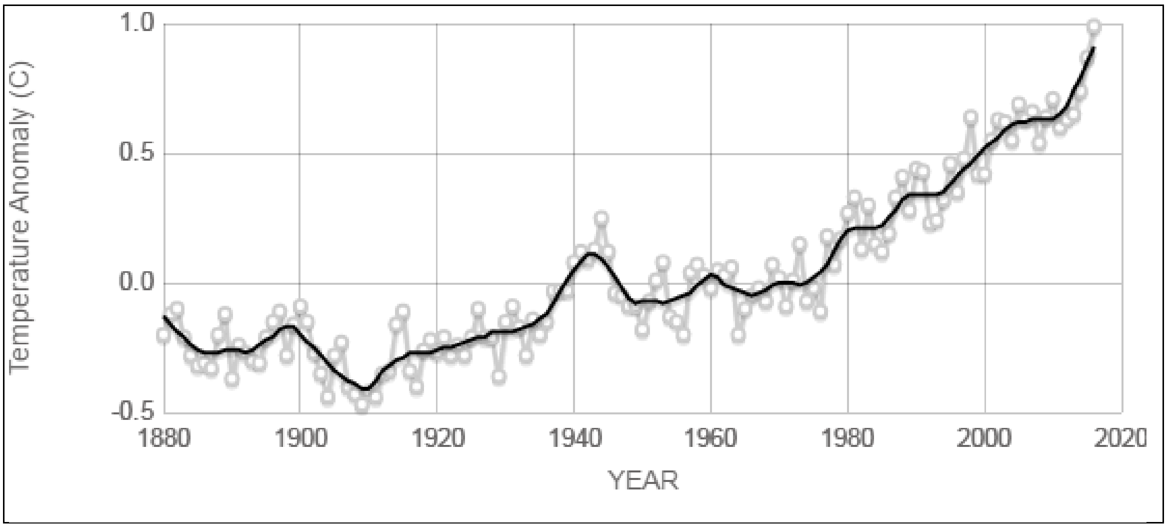
(Source: climate.nasa.gov- June 2018)

Figure 2.1: Global CO_2 trends from 2005 to 2018



(Source: Global Central, 2017)

Figure 2.2: Global temperature and CO_2 trends



(Source: Climate.nasa.gov- 2017)

Figure 2.3: Global temperature rise from the year 1800 to 2020

Climate change is likely to have an effect on several ecosystems including wetlands. In wetlands, water, soil, fauna and flora function together in a healthy ecosystem and a shift in one component may affect the way that one or more of the others may behave or operate. Nutrient availability, soil quality, DO, and anaerobic bacteria are examples of components and characteristics that operate together to sustain wetlands. Wetland functions and biogeochemical processes may be altered by varying climatic conditions.

2.3 Wetland ecosystems

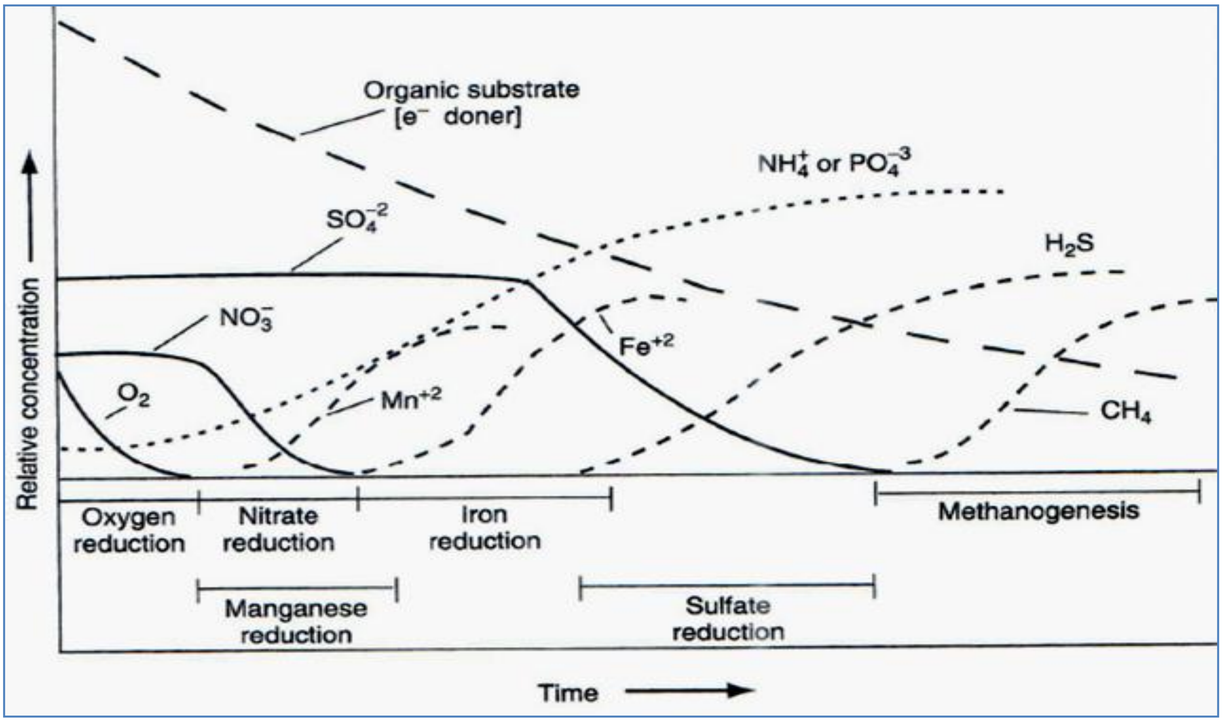
Wetlands are located in between terrestrial and aquatic environments, and hence in transition between these two distinct ecosystems. Wetland functions are attributable to their forms and their hydrological processes, as well as biogeochemical interactions taking place within them (Mitsch & Gosselink, 2007; Maltby, 2009). These functions also depend on soil types (Jackson *et al.,* 2014), which are associated with wetland hydrology and vegetation cover (Ballantine *et al.,* 2011).

2.3.1 Wetland types

Five wetland systems: estuarine, marine, lacustrine, riverine and palustrine wetland systems have been commonly described (Cowardin *et al*., 1979). Estuarine wetlands are semi-enclosed by land, but open enough for ocean water to access them. They therefore have saline water diluted by water from terrestrial surface runoff. Marine wetlands are open oceans with high-energy coastline. Wetlands that are associated with deep water depressions or dammed channels are referred to as lacustrine wetlands and are usually lakes. Riverine wetlands are those that are found within channels or river systems that may be perennial, intermittent or annual but are not dominated by trees and shrubs. Palustrine wetlands, also called sponges due to their ability to retain water during rainy seasons and release it in the dry season, are non-tidal in nature and are dominated by trees, shrubs and emergent vegetation and contain ocean derived salts in concentrations lower than 0.5 ppm (Barnes *et al.,* 2002; Seelig & DeKeyser, 2006; Mitsch & Gosselink, 2007). The ability of wetlands to retain water allows them to remove pollutants, salts and nutrients that would compromise the receiving stream water quality (Hammer & Bastian, 1988; Dugan, 1990; Spellman & Bieber, 2012; Amacha *et al*., 2017). Palustrine wetlands, like most other wetlands, have a variety of functions such as water purification, pollution control (Adhikari *et al.,* 2009), flood attenuation, erosion control, groundwater recharge, and discharge/sustenance of surface water bodies, biogeochemical processes and nutrient assimilation (Hermandez & Mitsch, 2007; Faithful, 2015). Of the five wetland types described, only three: Lacustrine (impoundments that are mainly utilised for water supply and soil conservation), riverine - being rivers and streams, and palustrine (those that are found in the high altitudes of the country), are found in Lesotho. The Khubelu wetland, which is the focus of this study, is a typical palustrine wetland.

2.3.2 Wetland characteristics

The characteristics of wetlands are useful for identifying them and for delineating and differentiating them from other ecosystems. These characteristics relate to wetland hydrology, soils and vegetation types. Wetlands experience a shift from dry/moist (oxic) conditions, to wet and extremely flooded conditions (anoxic conditions) due to seasonal precipitation variations. In their study, Gardiner and James (2012) observed that increase in organic matter (OM) content of wetland soil led to a decrease in redox potential of such soils. Anoxic conditions do not allow growth of most plants due to difficulty of the roots to respire (Mitsch & Gosselink, 2007) and hence an advantage to those plants that easily adapt to these conditions. A series of reactions occur in these anoxic conditions, beginning with oxygen depletion, reduction of NO_3^-, Mn^{4+}, Fe^{2+} and SO_4^{2-} (Sposito, 1989; Reddy & D'Angelo, 1994). Oxygen depletion is a condition that impedes root respiration of some wetland plants, enabling invasive species to thrive. Unavailability of nitrates is another limiting factor for vegetation growth when conditions are anoxic. As reduced conditions occur, there is an increase in availability of NH_4^+ and PO_4^{3-} ions (Mitsch & Gosselink, 2007), as depicted in Figure 2.4 below. Ammonia, on the other hand, creates toxic conditions for plant growth, resulting in wetland vegetation death, while excessive phosphates support the development of algal blooms.



(Source: Reddy & D'Angelo, 1994)

Figure 2.4: Transformations in soil nutrients after a flooding event

2.3.2.1 Wetland hydrology

Water is the basic component of wetlands and it regulates movement and exchange of nutrients and other substances between wetland soil, plants (Credit Valley Conservation, 2010) and water itself. Each type of wetland has a water level regime that is referred to as the hydroperiod. Hydroperiod refers to the seasonal pattern of water levels or the periodic or regular occurrence of flooding and/or saturated soil conditions including depth, frequency, duration, and seasonal pattern of inundation (Tour du Valat, 2018). Ewel (1990) and CVC (2010) describe hydroperiod as the length of time during the year when soil is saturated with water and as the seasonal water level patterns of a wetland, respectively. Hydroperiod determines the physicochemical characteristics of a wetland, and hence its functions. Hydrological processes within wetlands control wetland size, formation and functions (Carter, 1997; Jackson *et al*., 2014) thus determining their sustainability (Carter, 1997). Other factors that control wetland hydrology are soil permeability, land topography, plant cover and precipitation (Carter 1997). Wetland hydroperiod has been suggested by Coops *et al.* (2004) as a contributing factor towards plant establishment in a wetland ecosystem. It can be suggested therefore, that vegetation and hydrology of wetlands interact in order to maintain wetland health. On the basis of this, wetland degradation due to loss of vegetation cover and soil erosion is likely to have an impact on wetland water quality.

2.3.2.2 Wetland soil

Soil is one of the crucial components of wetland ecosystems that support plant growth, regulates water flow and nutrient loads, and transforms some harmful chemicals (Benitez *et al*., 2006). Soils that dominate wetland ecosystems are called hydric soils because of their saturated and waterlogged conditions. According to Natural Resources Conservation Service NRCS (1998), hydric soils are soils formed under conditions of saturation, flooding, or ponding for long periods during the growing season to develop anaerobic conditions in the upper horizons. These soils also have physical and chemical properties that together define wetland ecosystems (Jackson *et al.,* 2014). These properties are highly likely to influence processes that contribute towards the way wetlands carry out functions like water retention, movement of substances in/out of wetlands (Jackson *et al.,* 2014), and pollutant and nutrient retention. Wetland soils are the medium where chemicals and nutrients are stored as well as where biogeochemical reactions take place (Mitsch & Gosselink, 2007). They are characterised by high clay and organic matter content and consequently high Cation Exchange Capacity (CEC). Soils rich in OM and clay have a high capacity to attract cations (Ketterings *et al*., 2007; Ross & Ketterings 2011; Jaremko & Kalembasa, 2014; Sidi *et al.,* 2015; Efretuei, 2016). Cowardin *et al.* (1979) and Mitsch & Gosselink (2007) have pointed out that waterlogged soils are anaerobic, favouring slow rate of OM decomposition, a characteristic that ensures high OM content in wetland soils (Ballantine *et al.*, 2011). During dry periods, there could be pockets of air in the soil that could allow for the presence of bacteria and plant root respiration. During periods of high precipitation, the air is replaced with water, making the soils gleyed and encouraging the prevalence of redox conditions (Pezeshki & DeLaune, 2012) and associated processes. In the context of all these, wetlands are areas that are characterised by unique soils, being able to hold water for a longer period than adjacent areas. The activities, soil processes (biogeochemical and hydrologic) and reactions in wetlands are governed by the duration of the flooded condition in the wetland (Jackson *et al.,* 2014). Dry conditions lead to a shift of wetland vegetation from water-tolerant to those that adapt to dry conditions, (Mitsch & Gosselink, 2007).

2.3.2.3 Wetland biodiversity

The variety of micro-organisms, macro-organisms and overall biota in a wetland is usually an indication of how healthy a wetland is, and hence the ability of such wetlands to perform a variety of functions. Plants in inundated wetland environments are physiologically and morphologically adapted to flooded environments (Bobbink *et al.,* 2006), and are influenced by other factors like duration of flooded conditions, water depth, microbial activity, and nutrient and carbon dioxide/oxygen availability. Palustrine wetland vegetation includes sedges, *Geum capensi*, *Harplocarpha nervosa*, *Ranunculus meyeri*, Harplofora, *Limosella grandiflora*, and *Limosella capensis,* with *L. Grandiflora* being the less desiccation-tolerant species (Freiberg *et al.,* 2005). *Harplocarpha nervosa* is a moisture-loving groundcover plant and is also capable of resisting frost, hence named frost-hardy. It also grows horizontally to form a mat on wetlands. *Limosella capensis* is one of the floating wetland plants typical of bogs in altitudes above 3300 m (Davies & Walker, 1986). *Limosella grandiflora* is an aquatic taxa of *Limosella*, which are characterised by elongated stems, ability to tolerate dry conditions and are found in African regions, inclusive of southern Africa. *Ranunculus meyeri* is endemic to Lesotho (van Zinderren Bakker & Werger, 1974) and other countries like South Africa, Mozambique and Swaziland (Cholo & Foden, 2010). The plant is also a perennial hydrophyte that is mostly adapted to wet, swampy freshwater areas.

A study by Xiong *et al.* (2008) indicates that types of wetland vegetation are related to wetland soil pH and salinity, whereas OM, total nitrogen (TN) and total phosphorus (P) portrayed no significant link. On the contrary, Gilliam (2006) and Wang *et al.* (2016) maintain that plant communities depend on soil conditions, and these conditions include nutrients like P, N, and Organic Carbon (OC) due to their ability to absorb these nutrients from soil (Li *et al*., 2017). It is, however, worth noting that as wetland water saturation decreases, a shift of plant composition occurs, from typical to transitional. This is due to low DO in water-logged conditions that the “now” alien species would not tolerate (Tiner, 1999). Hydric soils and hydroperiod together normally infer to some extent the species variation of a wetland. Vegetation that is best adapted to hydric and anoxic soil environments is referred to as hydrophilic vegetation and these are the ones commonly found in wetlands. In a study by Kotze and O'Connor (2000), it was found that factors like altitude and degree of wetland wetness determine species richness and hence type of vegetation. They further showed that for wetlands in high altitudes, sedges dominated the wet zones, with grasses dominating the least wet ones. This variation in species distribution and abundance affects functions like nutrient recycling and storage, and flood attenuation.

Common micro-organisms including Eubacteria and Archaebacteria present in wetlands (Solomon *et al.,* 1993) are responsible for plant matter decomposition, mineralisation and transformation of organic pollutants, and nutrients respectively (Stottmeister *et al*., 2003). Other micro-organisms present in wetlands are nitrogen-fixing diazotrophs that help maintain nutrients especially in salt marshes (Lovell & Davis, 2012). *Nitrosomonas* and *Nitrosospira*-related bacteria are categorised as ammonia oxidisers, sulphate reducers (Pester *et al.,* 2012), nitrogen-fixing Alphaproteobacteria, denitrifiers, and methanotrophs (Kolb and Horn, 2012). Degradation of wetlands due to factors like global warming and fires could lead to a shift in species composition and loss of species richness. It can thus be said that there is an interrelationship between wetland hydrology, wetland soil type and vegetation, which forms a roadmap towards wetland water purification function - one of the hypotheses in this study. Water purification function is a success if wetlands maintain the type of vegetation that is tolerant to pollutants and nutrients that flow into them, even though too high levels of pollutants may degrade such wetlands (Albert & Minc, 2004; Mitsch & Gosselink, 2007).

2.3.3 Functions of wetlands

Wetland functions are dependent on the behaviour of soil and water (Acreman & Miller, 2007; Ballantine *et al.,* 2011) in such wetlands, and have to be considered in management and conservation practices of wetlands. Soil properties contribute towards wetland ability to perform functions like water retention, water purification or pollution control (Adhikari *et al.,* 2009), biogeochemical processes and nutrient assimilation (Hermandez & Mitsch, 2007; Faithful, 2015). Wetland vegetation also contributes towards some wetland functions. Macrophytes are able to absorb nutrients like PO_3^{4-}, thus allowing water with lower concentrations of nutrients to flow into nearby rivers (Fisher & Acreman, 2004). Koschorreck and Darwich (2003) also showed that nitrogen uptake occurs during growth of wetland vegetation. The ability of vegetation to reduce velocity of water enables the wetland to trap sediments, a function that is associated with removal of nutrients (Hruby *et al.,* 1999). Some wetland functions are discussed in the following sections.

2.3.3.1 Hydrological function

Wetland hydrology is one of the factors that determine the type of biota present in a wetland, as well as the condition of the wetland (Mitsch & Gosselink, 2007). Three wetland characteristics have been identified and are used to characterise the behaviour of wetlands in conducting their hydrological functions. These are wetland level (depth of a wetland in relation to its soil surface), hydro pattern - defined as variability of water levels in time (that is how long water will stay with the wetland and the extent of its distribution), and residence time of water within a wetland before it can leave the ecosystem (EPA, 2008). Wetland hydrological functions include flood attenuation, and surface and groundwater recharge. Flood attenuation by wetlands occurs as a result of the rich vegetation cover, which enhances high water infiltration. Biological activity by roots and invertebrates in topsoil contributes towards high organic carbon content, which assists in high water retention capacity of wetlands (Jackson *et al.,* 2014). Surface water resources discharge occurs when groundwater level is higher than wetland level (Acreman & Miller, 2007) and conversely groundwater recharge is a phenomenon showing that wetland level is higher than piezometric level. Wetlands in the study area are expected to discharge into surface water resources in dry season and recharge groundwater in rainy season. Organic and clayey soils can improve water-holding capacity of wetlands, facilitating absorption of nutrients and other pollutants.

2.3.3.2 Wetland water purification function

Wetland water purification function refers to the removal of pollutants from water entering them and is related to the quantity of water passing through the wetlands (Huang *et al*., 2012). Wetlands can remove incoming sediments, nutrients and pollutants so that receiving streams have water of good quality. Sediments are trapped by wetlands with high vegetation density, and low water velocity. Sediments under these conditions ultimately adsorb onto them any nutrients (Adamus, 1996; Olapade & Sheku 2014), and organic and toxic pollutants contained in the water. Under certain stream flow conditions, wetlands also remove nitrates that would otherwise enrich rivers (Hansen *et al.,* 2018). A study by Hammersmark *et al.* (2009) showed that nutrient retention is highly influenced by vegetation and wetland types (Fisher & Acreman, 2004). This is further explained by Reddy *et al.* (1999) who showed that assimilation and storage of P are highly dependent on the type of vegetation as well as their growth patterns. During flood pulse, aquatic macrophytes act as a sink for soil mineral nitrogen which they use for their growth, but when decomposing, the same plants are sources of inorganic nitrogen (Koschorreck & Darwich, 2003). The nutrient removal rate of wetlands is affected by wetland loading, wetland characteristics and environmental factors (Land *et al*., 2013). Environmental factors that are typically significant include temperature and precipitation, whereby Mitsch *et al.* (2005) in their study have attributed low N removal to cool wetland climate and higher removal in warmer climate. With regard to the type of wetland, Fisher and Acreman (2004) have shown that swamps and marshes are more efficient in nutrient removal than riparian zones. Long retention time of water in wetlands is associated with high absorption rates of pollutants and salts onto wetland soil. Conversely, high flows are allied with increased erodibility of soils, and increasing transport of pollutants and pathogens (Kovats *et al.,* 2005; Ebi *et al.,* 2006) into the receiving water bodies. In general, wetlands trap, precipitate, recycle and export constituents entering them, making water leaving them of better quality (Mitsch & Gosselink, 1993).

Wetland vegetation has three properties that enhance pollutant reduction; ability to reduce water speed, and pollutant absorption by plant roots; and nutrient uptake by roots (Stevenson *et al.,* 1988; Faithful, 2015). In a study by Barnes *et al.* (2002), it was revealed that high rate of transpiration by wetland vegetation contributes towards high rate of solute concentration in wetland soils, and due to selective extraction of the solutes, some of them end up precipitating in soils. According to Barnes *et al*. (2002), low water flows lead to high residence time within a wetland enabling interaction of roots and soil and hence gradual retention of pollutants. Because of the properties listed above, wetlands tend to be effective as water treatment systems (Rogers *et al.,* 1985; Barnes *et al.,* 2002; Meindl, 2005; Faithful, 2015). Water quality of streams thus depends on wetland hydrology and soil quality (Brady & Weil, 2016), rendering a degraded wetland less capable of removing pollutants and attenuating storm water peak flows (Bedford & Preston, 1988). If the wetland is degraded, it is likely to deliver increased amounts of sediment, nutrients and other pollutants to the water bodies in its surrounding, thereby acting as a conduit, transporting pollutants through it instead of a treatment system (Brinson, 1988).

2.3.3.3 Wetland role in biogeochemical processes

Biogeochemistry is defined as the exchange of materials between the living and non-living components that also involves interaction of processes governed by physical, chemical and biological factors within wetland ecosystems (Mitsch & Gosselink, 2007; Reddy *et al.,* 2010). Wetlands play a major role in the cycling of various elements. They store carbon through different processes including photosynthesis and conversion of carbon dioxide into biomass (Adhikari *et al.,* 2009). Wetlands are furthermore estimated to store about 548 gigatons of carbon, being nearly 1.5% of the total C storage globally (MEA, 2005). Transformation of carbon in wetlands takes place during both aerobic and anaerobic conditions (Mitsch & Gosselink, 2007). Aerobic transformations include photosynthesis and respiration as the dominant processes, followed by methane oxidation into carbon dioxide (Mitsch & Gosselink, 2007) in water and soil. Anaerobic horizons experience fermentation of Dissolved Organic Carbon (DOC) and Particulate Organic Carbon (POC) into lactic acid and ethanol, methanogenesis of DOC into methane, as well as anaerobic methane oxidation into carbon dioxide. However, in wetlands, waterlogged soils create anaerobic conditions that lead to fermentation of OM by facultative micro-organisms, with OM being electron acceptors. Net Primary Productivity (NPP) in wetlands, coupled with decomposition, determines the rate at which OM accumulates in wetland soils, as well as the nutrient uptake and retention in the wetland ecosystem (Harmon *et al.,* 1999).

Nitrogen cycling is another geochemical process which occurs in wetlands. Wetland vegetation absorbs ammonium-N and nitrates which could be lost easily through volatilisation and leaching/denitrification respectively. Nitrification in wetlands occurs in the oxidised wetland rhizosphere and within the oxidised wetland soil layer. In this region of wetland soil, organic nitrogen is converted into ammonia (NH_3) and then ammonium (NH_4^+), these being the forms that are oxidized by bacteria (nitrosomonas) into nitrites (NO_2^-). Ion exchange has been found to facilitate immobilisation of NH_4^+ ions onto charged wetland soil particles (Mitsch & Gosselink, 2007). Nitrites are then oxidised by nitrobacter into nitrates (NO_3^-). Nitrate loss has been associated with decreased redox potential in wetland soils (Mansfeldt, 2004). Nitrates are highly soluble and mobile and therefore easily washed out of the wetland soil, thus threatening water quality of the receiving water bodies. However, the nitrites can either be assimilated by plants or undergo reduction into nitrogen (N_2) or nitrous oxide (N_2O) during denitrification, a process that is favoured by anaerobic conditions brought about by water-logged wetland conditions (Reddy *et al., 1989*; Jordan *et al.,* 1993). Denitrification occurs under anaerobic conditions when the wetland soil is saturated with water (Hermandez & Mitsch, 2007) but it can be indirectly limited by availability of carbon in wetland vegetation (Broadbent & Clark, 1965), as well as reduced microbial activity during low soil temperatures and pH (Machefact *et al.,* 2002). Nitrogen is the first electron acceptor once anaerobic conditions are pronounced in waterlogged wetlands (Mitsch & Gosselink, 2007). Clay soils absorb NH_4^+ which can be later released from colloids by cation exchange. Nitrate nitrogen can also be reduced to NH_4^+ (Megonigal *et al.,* 2004) during the process called Dissimilatory Nitrate Reduction to Ammonia (DNRA), as shown in Equation 2.1 below:

$$\boldsymbol{4N0_3{}^- + 4H_2 + 2H^+ \rightarrow 3H_2O + NH_4{}^+} \qquad (2.1)$$

Sulphur compounds follow nitrates as electron acceptors in the redox scale (Mitsch & Gosselink, 2007). Sulphur cycle begins with conversion of sulphur into hydrogen sulphite (H_2S). In this reaction sulphates are reduced with the assistance of sulphur reducing obligates whereby during their anaerobic respiration sulphates are used as electron acceptors (Mitsch & Gosselink, 2007). Hydrogen sulphide can either be stored in wetland soil or released into the atmosphere or, when aerobic conditions prevail (as is the case with dry wetland conditions), be oxidised into sulphates (Pester *et al.,* 2012). Sulphates are then readily available for plant uptake and if not all utilised can be washed off into streams flowing from the wetland.

High phosphorus levels in water bodies indicate that a freshwater body is threatened and there is a possibility of excessive growth of plants in such a water body - a phenomenon known as eutrophication (Kalff, 2002; Johannesson *et al.,* 2015). Particulate Organic Phosphorus (POP) in the reduced wetland soil first decomposes into Soluble Organic Phosphorus (SOP), which can diffuse into oxidised soil or be transformed into soluble inorganic phosphates (PO_4^{3-}). During the period when water is retained in wetlands, sediments also settle, thus allowing wetland vegetation to absorb nutrients including phosphorus (Mitsch & Gosselink, 1993). This PO_4^{3-} may thus be available for wetland plants, and can also be adsorbed and retained onto clayey soil particles (Bridgham *et al.,* 2001), organic peat through precipitation (Mitsch & Gosselink, 2007), biological uptake (Mitsch *et al.,* 1995), and accretion by peat (Reddy *et al.,* 1999; Richardson, 1999). Types of phosphorus that easily binds to wetland soil are Al-P and Fe-P in acidic soils, while precipitating with Ca and Mg in alkaline soils. Redox potential does not alter phosphorus in the same manner it does other ions like sulphur and nitrogen (Mitsch & Gosselink, 2007).

Exposure of soil to prolonged saturated conditions has some consequences on biogeochemical processes. Tian *et al.* (2017) found that in waterlogged conditions, the rate of soil P release is higher than in aerobic conditions. However, Quintero *et al.* (2007) has associated P transformation with soil pH, and other soil characteristics like crystallinity, SOM, and redox cycling (Young & Ross, 2001). When wetlands are flooded, they are deprived of oxygen and these conditions augment sulphate and nitrate reduction (Reddy & Patrick, 1984; Mitsch & Gosselink, 2007; Marton *et al.,* 2015). Variations occurring in the amounts of carbon and nitrogen, and their solubility and forms in which they occur in soils are interrelated with precipitation and temperature dynamics (Sienkiewicz *et al.,* 2014).

2.4 Climate change and wetlands

2.4.1 Effects of climate change on wetland water quality

Climatic factors influence wetland resources and processes (Nan *et al.,* 2011). With the expected increase in ambient temperatures due to global warming and other factors like low relative humidity, the rate of evaporation from water bodies is likely to increase, leading to high concentrations of nutrients (phosphorus and nitrogen) and other pollutants in wetlands (Delpla *et al.,* 2009; Whitehead *et al.,* 2009). Oxygen dissolves at a slow rate in water and its solubility is even lower under high temperatures, making high temperatures inapt for freshwaters. Low DO due to high temperatures in a water body results in a high rate of photosynthesis or Net Primary Productivity (NPP). When plant productivity increases, there will be more plant residue and utilisation of DO for decomposition, leading to high Biological Oxygen Demand (BOD).

Expected low water flows within wetlands and streams caused by changes in precipitation patterns will result in increased nutrient concentration and hence decreased DO as plants die and consume available DO for decomposition (Whitehead *et al*., 2009).

Under these circumstances species adapted to low DO are more likely to be more numerous. Whitehead *et al.* (2009) further show that nitrification is more pronounced under reduced water flows, resulting in an increase in the concentration of nitrates in water bodies when wetland water levels are low. Exchangeable cations including Ca^{++}, K^{+}, Mg^{++} and Na^{+} are continually moving between wetland soil and water. Soil degradation due to high soil and water temperatures could lead to a decrease in Mg solubility, resulting in its subsequent replacement by K. Sodium may be displaced from soil by calcium and magnesium, polluting adjacent water bodies through leaching.

Human interventions and natural variability like drought lead to salinisation of wetland and stream waters, which ultimately impacts on biogeochemistry and micro-organism distribution in these freshwaters. Kileen (2008) reported that low flows due to decrease in precipitation could result in less chloride dilution and hence their high concentration in wetlands. Extremely high temperatures also lead to high concentration of dissolved chlorides according to Burkett and Kusler (2000). Gerla (2013) and Herbert *et al.* (2015) have reiterated that high rates of evaporation and evapotranspiration are likely to have an impact on the EC of wetland soil and water. Substances of plant and organic origin may decompose during drought and thus contribute towards high levels of sulphur in water bodies (William *et al.,* 2011), including wetlands. With the observed increase in atmospheric temperature, decomposition rates may increase leading to even higher sulphate levels in water (Khatri & Tyagi, 2015). With increase in temperature and declining rainfall, wetlands tend to be ineffective as water treatment systems (Meindl, 2005; Faithful, 2015). Water leaving these wetlands could therefore be contaminated by the sulphates and chlorides.

2.4.2 Effects of climate change on wetland soils

Climate change is one of the factors that influence both nutrient uptake and their release in wetlands, whereby cold temperate climates are characteristic of nutrient retention due to low microbial activity (Mitsch & Gosselink, 2007). Organic matter decomposition in wetland soil is regulated by DO and nutrient availability, and temperature (Katterer *et al.,* 1998; Davidson & Janssens, 2006; Vargas *et al*., 2010). Prolonged high temperatures and other climate-related events like storm-caused erosion may lead to degradation of wetland soils according to Kusler (2006). Degraded soil has poor ability to remove pollutants from water (Meyer & Sale, 1999; Johannesson *et al.,* 2015) and has limited infiltration capacity, especially during peak storms, which further result in erosion of nutrients and OM. Excessive exposure of soil to dry conditions interspersed by heavy rainfall events has detrimental effects on soil such as escalation of soil erosion. Soils may, as a result of floods be washed away carrying nutrients and OM with them (GoL, 2013). With the observed increase in atmospheric temperature, decomposition rates and soil organic carbon (SOC) content may also increase (Savage & Davidson, 2001) leading towards even higher sulphate levels in water bodies.

Flooding in wetlands would contribute towards changes in soil physical and chemical characteristics. A study by Pezeshki and DeLaune (2012) shows that the changes may include reduced soil redox potential (Eh) and hence a high demand for oxygen within the soil profile in question. While some studies associate flooded environments with low OM decomposition rate, others argue that extreme flooding that runs through wetlands would wash away the organic soils (Hooijer, 2003), especially if they had been exposed to dry conditions prior to the floods. In this context, inundated environments can be perceived as conditions that enhance long water residence time within wetlands, giving allowance to nutrient absorption by plant roots, and pollutant adsorption to soil. Extreme flooding, on the other hand entails rapid movement of water of high speed - washing away the topsoil.

2.4.3 Effects of climate change on wetland vegetation

Wetlands typically have sedges that assist in dissipation of water flow, enhancing water purification by adsorption of any pollutants by the roots. Escalating temperatures are directly linked with evapotranspiration and are responsible for a shift in vegetation cover (Meyer & Sale, 1999; Erwin, 2009). A study by Barros and Albernaz (2014) in Brazil shows that with loss of wetlands as a result of climate change, species composition, adaptation and distribution are highly likely to be affected. In their study, an increase in precipitation was anticipated to cause a shift in plant species towards those that could tolerate flooded conditions. The study went on to show that expected high water temperatures in the floodplains would cause extended duration of hypoxic conditions, leading to reduced growth rates of many species. In Lesotho, a study by Olaleye and Sekaleli (2011) showed that a decrease in rainfall during the period 1967-2006 contributed to loss of indigenous vegetation within riverine wetlands, leaving a gap regarding the effects on palustrine wetlands.

Water temperature is a major driver of several processes in water bodies and wetland ecosystems, affecting biogeochemical processes (USEPA, 2008). High rate of OM decomposition may occur as a result of extreme temperatures, hence leading to reduction of soil carbon (Mupenzi *et al*., 2011). Prolonged temperature and precipitation changes, as predicted, might have repercussions in biogeochemical processes (Burkett & Kusler, 2000; Erwin, 2009). The anticipated changes caused by changes in temperature are shown in Table 2.1.

Table 2.1: Effects of climate change on wetlands functions and processes

Variable	**Effect**
Increased temperature	Rapid growth of plants and accelerated rate of biogeochemical processes. High emissions of greenhouse gases (methane and nitrous oxide).
Changes in precipitation patterns.	Longer wet periods – high hydraulic and pollutant (sediments, nutrients, and other chemical constituents) loading rates. Increased primary productivity and C assimilation. Increased dry period – rapid rates of decomposition processes and nutrient cycling. Change in diversity of biotic communities.
Hydro period and hydraulic loading rates; pollutant loading rates.	Degraded water quality.

(Adapted from Reddy et al., 2010)

2.4.4 Economic and social implications of climate change impacts on wetlands

Globally, wetlands provide services to society as well as to the environment (DWA, 2005; Liu & Sun, 2010; Moor *et al.,* 2015). In America, wetlands gained recognition due to their ability to provide services like habitats for fish and production of food products like cranberries, blueberries and wild rice (Tiner, 1999). In Lesotho, palustrine wetlands are sources of medicinal plants (DWA, 2005) and are the headwaters of international rivers that bring some royalties, thus boosting Lesotho's economy (PEMconsult *et al.*, 2008; Les Energy Review, 2014). With wetlands already being under pressure to provide social and economic services to users, other external pressures like climate change are overlooked, worsening degradation of these wetlands (Turner *et al*., 1998). In the light of predicted droughts interchanging with extremely cold and prolonged winters, water shortages are highly likely to be experienced. This coupled with over abstraction of water by industries, agricultural sector and transboundary transfers as emphasised by Gibbs & Gibbs (2002), will see the country experiencing job cuts, and hence risking economic growth. Animals solely utilise wetlands for their watering (even though they do so in an unregulated manner) and drying up of wetlands could compromise the livelihoods of communities that rely on water from the Khubelu stream for subsistence farming, since the major sources of income and livelihoods for the rural communities are animal rearing and subsistence farming. Conservation of these wetlands would thus sustain supply of clean water for these activities.

2.5 Monitoring climate change impacts on wetlands

There needs to be a balance between climatic conditions (temperature, precipitation) and wetland biodiversity/ community structure, as well as wetland functions and nutrient cycling within wetlands (Oechel *et al.,* 2000; Reddy *et al.,* 2010) for this ecosystem to function at its optimum. On the basis of this, wetland systems need to be monitored in order to get an insight of their community structure, functions and other environmental properties (USEPA, 2008)**.** Previous, current and future climatic scenarios have to be known to provide guidance on any significant changes in the manner in which wetlands respond to such climatic variations. Particularly, the intensity of precipitation directly impacts physical, chemical and biological processes, vegetation cover, soil structure and hydrology or wetland health, the same way temperature would do.

Suitable and relevant wetland indicators must be chosen, so as to monitor impacts of climate variations on wetlands' functions and/ or values (Sienkiewicz *et al.,* 2014). In a study by Sienkiewicz *et al.* (2014) it has been determined that SOM is the most sensitive indicator towards climate warming through its mineralisation and since the process of mineralisation results in release of nitrogen into soil, soil nitrogen content could be another climate change indicator. Other useful soil parameters that indicate degradation and require monitoring over time are soil texture and physico-chemical properties. These can be used to calculate the Chemical Degradation Index (CDI) of the soil.

Ecosystem health has been monitored through measurement of species diversity (Skidmore *et al.,* 2015) and has been done using techniques based on Satellite through the use of Satellite Remote Sensing - SRS (Rocchini *et al.,* 2016) such as Cyanolakes. This technique, in addition to saving time, helps cover the entire study area while identifying changes in species composition. Water purification function of the wetlands is monitored by both direct and indirect methods. Direct methods entail soil and water sampling for analysis of parameters that are directly linked to removal of water pollutants and nutrients, whereas Rapid Assessment is an indirect method that monitors the potential to remove sediments, nutrients and organic compounds. The direct method is more precise and requires sampling and laboratory analyses to be done over an extended period, in order to observe changes during different climatic scenarios.

2.6 Chapter summary

This chapter gave an overview of literature that demonstrates that water quality, soil properties and vegetation cover are all interlinked in determining wetland health. Reviewed literature has further showed how predicted temperatures and precipitation are likely to influence wetlands' water purification function. If temperatures keep increasing, there may be high rates of evapotranspiration and the possibility of a shift in vegetable species. Drought may lead to high rate of evapotranspiration, ultimately enabling vegetation that is more tolerant to drought to invade the wetland. There would also be a change in vegetation distribution. Eventually there would be reduced flood reduction, low pollutant and nutrient retention by the wetland. Erosion would ultimately lead towards degradation of soil, with changed texture and components, making it impossible for wetlands to provide certain functions. All these would contribute towards polluted streams. Floods would, on the other hand, lead to direct degradation of wetlands through erosion, and hence inability of the soils and wetlands to sustain nutrient and pollutant retention, putting streams fed by wetlands at risk of high pollutant and nutrient loads.

CHAPTER 3

RESEARCH METHODS

3.1 Introduction

This chapter presents the methods used to collect data in this study. The study area is described, followed by the research design utilised. Data collection progressed in four phases namely: reconnaissance survey that led to study area selection and delineation, field data collection that entailed soil and water sampling from the wetland, laboratory analysis of soil and water samples collected, and finally analyses of laboratory and field data generated. Utilisation of Water Evaluation and Planning (WEAP) model for simulations of water quality is also presented. These data collection activities and processes are described in detail in the following sections.

3.2 Description of the study area

This study was confined to Khubelu wetland, within Phapong sub-catchment. The sub-catchment has an area of 69,700 m^2 within the Khubelu catchment in Mokhotlong district, north of Lesotho, with a population of 20,000 people (PEMconsult *et al.,* 2008) from which about 8,700 benefit directly from the catchment. The catchment is located in the northern highlands of the country at 29º1'19.10" S 28º52'26.01" E (Figure 3.1), with minimum and maximum elevation of 2984 m and 3019 m respectively. The catchment is upstream of the Lesotho Highlands Water Project (LHWP) Phase II from which the Polihali Dam supplied by Khubelu River will be constructed. The dam wall will be constructed across Khubelu River. Palustrine wetlands in this catchment are expected to sustain the Khubelu stream flow, and hence also called discharge wetlands. These wetlands are fed through surface water inputs and hence wetter in summer due to rainfall, than in winter.

3.2.1 Lesotho Climate and Hydrology

The climate of Lesotho is largely influenced by the country’s location on the Southern African Plateau. It is described as sub-humid to temperate cool, with warm and rainy summers and cool to cold dry winters. The mean minimum temperature of 0ºC occurs in June: being the coldest month in winter (LMS, 2013). The monthly mean temperatures in the lowlands range from -3 to -1ºC whereas the highlands record -6 to 8.5ºC in winter, with extreme monthly mean winter minimums of -10ºC and daily minimum of -21ºC in winter (LMS, 2013). January is the hottest month at 32ºC in the lowlands and 20ºC in the highlands, with a maximum of 34ºC in the lowlands and 24ºC in the highlands (LMS, 2018).

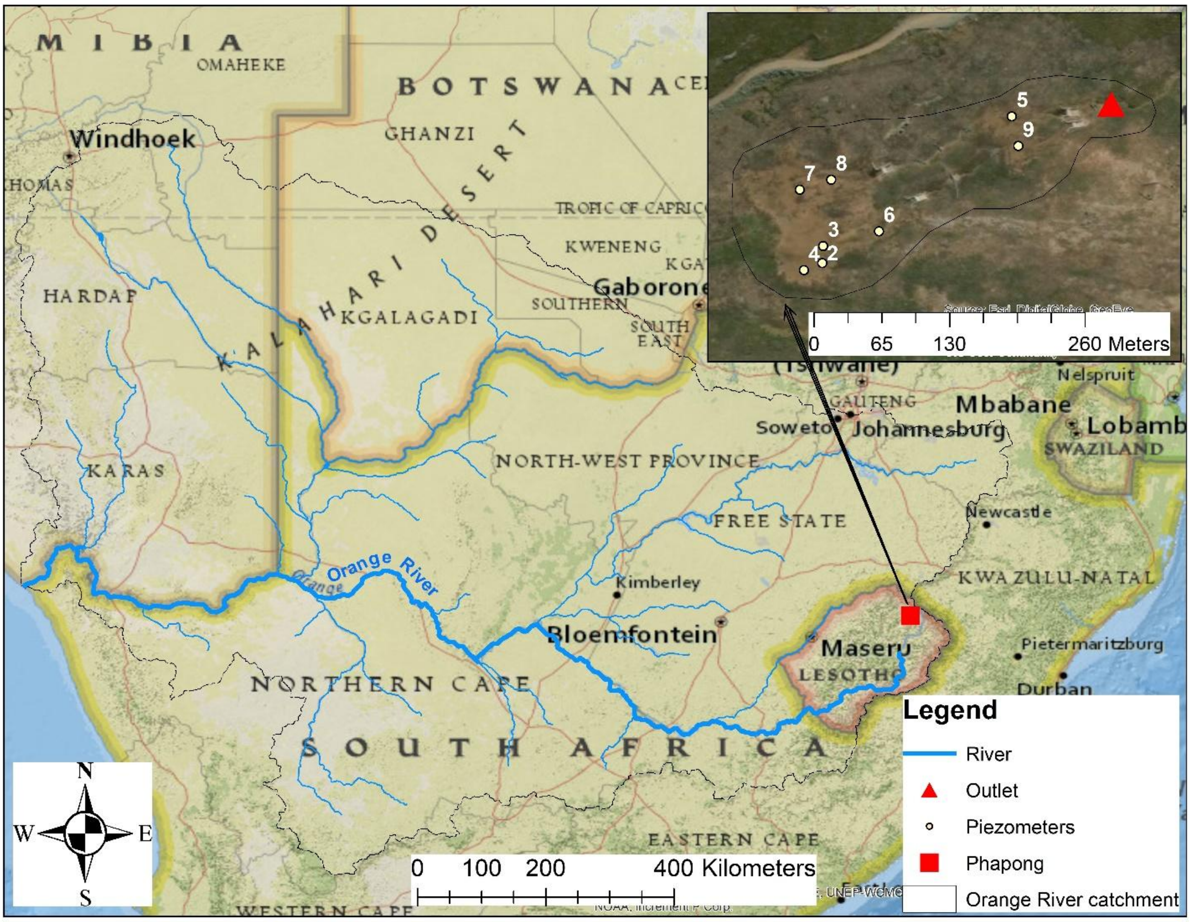
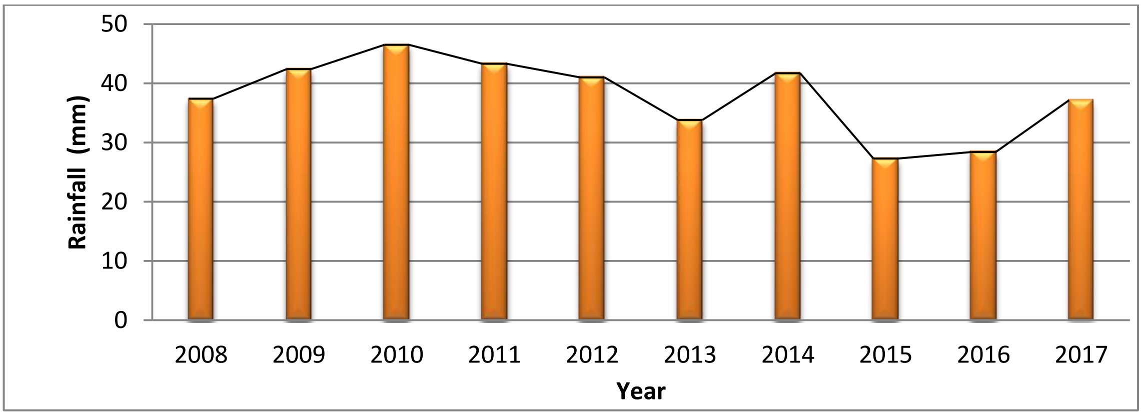


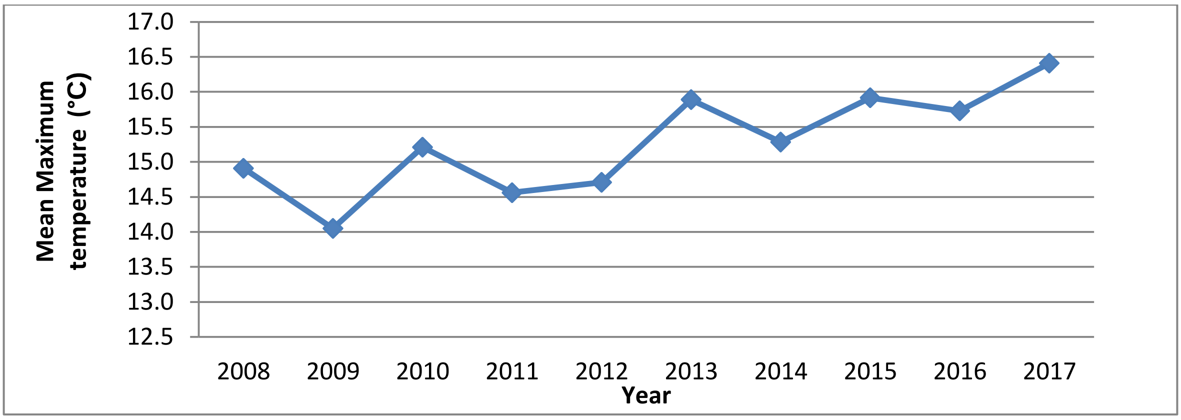
Figure 3.1: Lesotho rivers and Khubelu River contribution into the Orange-Senqu catchment

The mean annual precipitation in the study area ranges from 500 mm in the Senqu Valley to 1200 mm in the north and eastern parts of the country (LMS, 2013). The study area had annual rainfall in the range of 327 mm to 558 mm from 2008 to 2018. Eighty-five percent (85%) of rainfall in the study area is received between October and April with frost and snow being common in winter. The mountains are regularly covered with snow during winter. Rainfall and temperature projections up to the year 2100 show that the El Nino Southern Oscillation (ENSO) may be controlled by increasing global temperatures (Chapman, 2012). Projections for the year 2030 to 2050 from assembly of General Circulation Model (GCM) show that Lesotho temperatures will increase in the range of 0.8ºC to 2.9ºC (World Bank, 2016), whereas Daron (2014) shows that projections to 2050 in southern Africa are 0 - 4ºC in summer and 0 - 3.5ºC in winter. Rainfall and temperature distribution from 2008 to 2017 in the area are shown in Figure 3.2, 3.3 and 3.4.



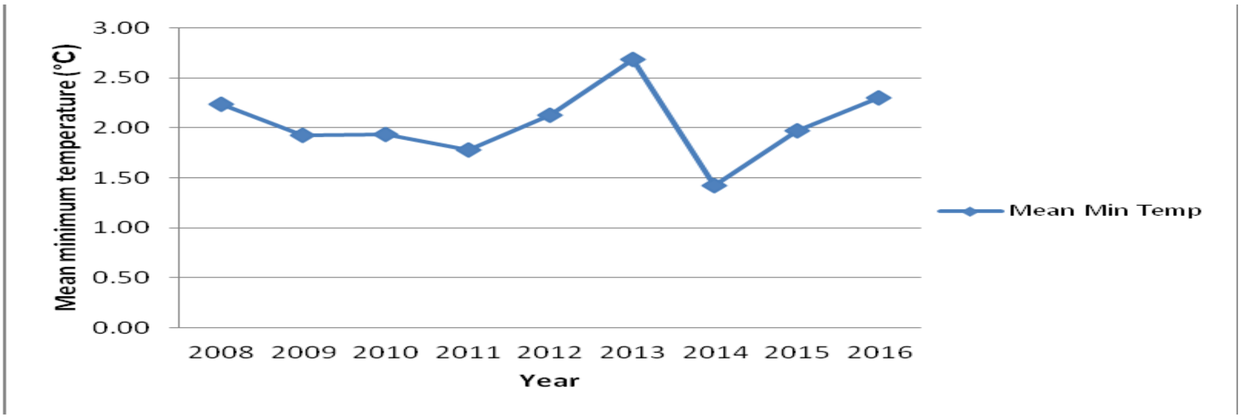
(Source: Lesotho Meteorological Services, 2017)

Figure 3.2: Mean monthly Oxbow Rainfall distribution chart for the years 2008 to 2017



(Source: Lesotho Meteorological Services, 2017)

Figure 3.3: Oxbow Maximum temperature distribution for the years 2008 to 2017



(Source: Lesotho Meteorological Services, 2017)

Figure 3.4: Oxbow Mean Minimum temperature for the years 2008 to 2016

Results from previous studies indicate that water entering the Khubelu wetlands from groundwater discharge is stored within the organic and clayey soils before being slowly released over time (DWA, 2005). The Orange-Senqu catchment receives 45% of its runoff from Lesotho (PEMconsult *et al*., 2008). According to preliminary analysis of the Khubelu wetland, water storage and release between dry and wet periods is approximately 120 mm (PEMconsult *et al.,* 2008).

3.2.2 Geology and soils of the study area

Khubelu wetlands are characterised by basaltic parent material of alluvial formation (DWA, 2005; PEMconsult *et al.,* 2008). These basaltic formations cover at least two thirds of the country, posing steep ridges and valleys, and hence poor soil development. Mature soil profiles are found in flat areas where colluvial soil material accumulates. Development of soils is also inhibited by surface runoff that leads to intense erosion due to the topography.

3.2.3 Description of the Khubelu wetland

The Khubelu wetland covers an area of 0.52 km^2, and it is currently utilised by herders for animal grazing and watering. The wetland has sustained the LHWP through the Orange-Senqu River Basin. Botswana, Lesotho, Namibia and South Africa contribute water into the River Basin that is managed by Orange Senqu River Commission (ORASECOM). The wetland is not in the proximity of communities who would directly utilise its water for domestic use but the wetland water is used for activities like crop irrigation and other agricultural activities. However, herders use it during the animal grazing period, and, with the Khubelu stream being the Orange-Senqu tributary, its water has to be protected. Herders over-utilise the wetland resources despite the observed degradation that threatens water purification and sustenance of water supply to the nearby stream. Rehabilitation works have been done within the area to eliminate factors like animal grazing, ice rat invasion and other degradation sources. The wetland is faced with invasion of alien vegetation, being initial signs of wetland degradation and escalating as a result of climate change (DRRM, 2014). This could be due to intolerant behaviour of native vegetation to gradual change in suitable soil conditions.

3.3 Study design

This study adopted both quantitative and qualitative designs with the greater volume of data generated through quantitative techniques. Quantitative data are described by Babbie (2010) as those that focus on numerical analysis of data collected. Creswell (2009) describes this method of study as having features like usage of instruments and/or surveys for data collection. Environmental variables that may have led to deteriorating water quantity and quality were quantified through rigorous experiments. Qualitative approaches in this study entailed delineating the wetland so that data collection boundaries would be clear. The wetland area was also surveyed for different biological, physical, vegetation, soils, stream and depth/slope properties.

3.4 Wetland site delineation

The wetland was first mapped, its area determined, and the different sub-areas used to assess wetland functionality. Wetland mapping was done during the wet season, which made it easy to identify obligate vegetation species that are characteristic of wetlands. Kusler (2006) and Lichvar *et al.* (2012) define obligate plant species as those that grow in wetlands only, being strong indicators of wetland boundaries. Other attributes used to determine wetland boundaries were: Terrain Unit Indicator (TUI) also called position of landscape channels within the wetland which are areas where water is highly likely to accumulate and hence provide moisture for wetland vegetation, and Soil Form Indicator (SFI), which are areas showing signs that soils are frequently saturated. Signs utilised to determine frequent saturation conditions included the presence of reddish and brown colours, which are indicative of reduced iron due to anaerobic conditions otherwise described as gleyed conditions. Soil Wetness Indicator (SWI) was also used in the identification of the wetland. Signatures of SWI were identified by determining the presence of hydromorphic conditions (prolonged and/or frequent saturation properties) such as mottling in soils sampled using an auger.

Another wetland delineator used was Vegetation Indicator (VI) (DWAF, 2005; Ross & Ross, 2010) whereby plant species that are common in Lesotho palustrine wetlands were identified and used for wetland boundary determination. According to EPA (1988), vegetation assessment is used as the basic indicator in wetland identification, with the rest of the indicators used to support and confirm that an area is a wetland. The area mapped was referred to as the Assessment Unit (AU). An AU is “the wetland area in which the level of performance for various functions is being assessed” (Hruby *et al.,* 1999). The AU in this study was chosen by selecting the area that discharges water into the stream. These tasks were completed with the use of a handheld Global Positioning System (GPS) unit (Garmin Etrex Vista H model 1.01). The coordinates were then integrated into GIS database ArcGIS 10.1 for mapping.

3.5 Data collection

Data collected included water quality parameters, soil properties, and wetland characteristics needed for the study. Vegetation cover in the wetland was classified, followed by water and soil sampling. Both primary and secondary sources of data were utilised. Primary data were generated through analyses of soil and water samples collected and measurements taken during the field work. Secondary sources of data collection included the Lesotho Meteorological Services (LMS). Geographical Information System (GIS) Arc map Version 10.1 was used to map the wetland area, inundated area, piezometers location, soil and water sampling points, as well as to determine other aspects of the study area like slope. The following sections present details of how data were collected in this study.

3.5.1 Meteorological data collection

Meteorological data on Oxbow climate for the previous ten years due to data availability were obtained from the LMS. These data were necessary to determine the climatic variations that have taken place and how they may impact on Khubelu wetland water quality. Climatic data collected were rainfall and temperature data for the years 2007 to 2018. The data were initially collected on a daily basis by LMS, then monthly mean temperature and rainfall determined from the data set. The year 2017 had gaps, in which case such months were not utilised for monthly mean temperatures and rainfall resulting in some missing values in the data set.

3.5.2 Piezometer installation

In order to have an insight of water retention and release into the Khubelu stream from the Khubelu wetland, seven piezometers were used in the study. Three of the seven piezometers (GW3, GW4 and GW5) had been installed by German Technical Cooperation (GTZ), and so only four additional ones (GW6, GW7, GW8 and GW9) were installed in this study. Additional piezometers needed to be installed to ensure a representative sample of the whole AU. Piezometer GW2 installed by GTZ was not used for water quality assessment because it was too close to GW3 and GW4. The piezometer depths were: GW3 -1.64 m, GW4 -1.6 m, GW5 - 1.1 m, GW6 - 1.1 m; GW7-1.8 m; GW8 -1.25 m; and GW9 -1.1 m. Figure 3.5 shows the sites in the wetland where piezometers were installed as well as the soil sample collection points. In the wetland, sampling sites GW2, GW3, GW4 and GW7 were grouped upstream, GW6 and GW8 midstream, and GW5 and GW9 downstream of the wetland.

3.5.3 Sample collection

3.5.3.1 Water samples collection

Two sampling points with GPS coordinates: S1- S29º01'18.40" E028º52'24.88" and S2-S29º01'18.62" E028º52'25.64" were identified at the Assessment Unit (AU) outlet of the wetland as representative sites of the Khubelu stream. The stream is approximately 15 metres away from the wetland (Figure 3.5). Surface water samples were collected from these two points (Figure 3.5) as well as from the seven piezometers on a monthly basis, over a one-year period, being an acceptable period suitable for WQI (CCME, 2001), and the minimum acceptable period for wetland data collection (Land *et al.,* 2013). The water level in the piezometers was determined using Solinst Miniwater level meter model 102M, which produces an audio signal once it gets in contact with water, enabling readings to be instantly taken. Water sampling was done using an Eijkelbailer sampler 33 mm 250cc. Water pH, EC and DO were measured *in situ* using pH meter model HI 8424, conductivity meter HI 8033, and a DO meter model HI 9142, respectively. For water sampling, 2L polyethylene bottles were washed using soap without any metals and then rinsed with distilled water. The bottles were then soaked overnight in 10% nitric acid and again rinsed with distilled water. At the sampling site, the bottles were rinsed with wetland water before sampling. Water samples were collected from the piezometers and the two sites at the mouth of the wetland monthly. Sampling depended on water availability within the piezometers and the streams; no water from piezometers could be sampled between June and August because these are dry months in the study area. Water samples collected were stored at 4ºC until time of analysis.

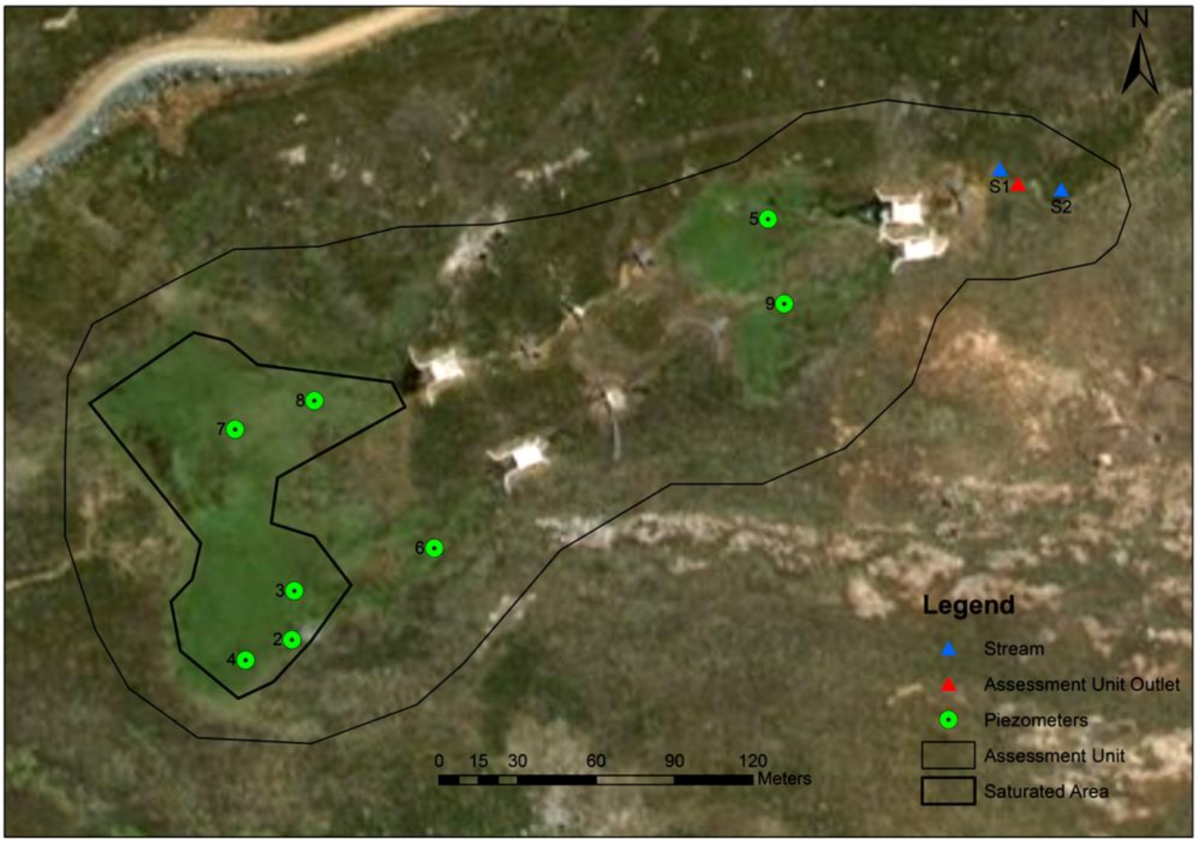


Figure 3.5: Location of water sampling points in the Khubelu wetland

3.5.3.2 Soil sample collection

Soil samples were taken across the wetland at varying depths (Amusan *et al.,* 2006), at the beginning of the study. Pits were dug at depths of 0 - 15 cm, 15 - 30 cm and 30 - 45 cm in order to make descriptions of the profiles. An auger was used to collect soil samples at these different depths (0 - 15 cm; 15 - 30 cm and 30 - 45 cm). The 15 cm intervals between depths were preferred in order to characterise variations that could have been hidden (Pe´rie´ & Ouimet, 2007) within depths and for samples to be representative. Vadas *et al.* (2005) have shown that for agronomic purposes, soil samples have to be taken at 0 - 15 or 0 – 20 cm depths; this being the most crucial for plant root development, but with the study going beyond availability of phosphorus for plants, sampling may go deeper to 45 cm. Soil was sampled from three points that were 2 m away from each of the eight (in the case of soil) piezometers in order to get three replicates from each sampling point. Three samples were also collected at each of the three depths. The choice of a distance of 2 m from each piezometer to the soil sampling point at each site was to avoid disturbance and possible contamination of water in the piezometers especially during saturated conditions that existed in the wetlands at the time of sampling. Sampling points were located at the SE, SW/NW and NE of the piezometers. Using a 10 cm wide auger, approximately 500g of soil was collected at each site and depth and carried in sealed vacuum bags to the National University of Lesotho (NUL) Soil Science and Environmental Health laboratories for further analysis. Soil sample preparation entailed air-drying, removal of roots and stones and crushing the soil so that it could be sieved through a 2 mm mesh.

3.5.4 Laboratory analysis of samples

3.5.4.1 Analyses of water samples

Water properties including BOD_5, COD, DO, Cl, $NO_{3,}$ $PO_{4,}$ Ca, Na, Mg, K, and TDS of the water samples were determined. Though properties like temperature, pH, DO and EC were analysed *in situ*, pH and DO were also analysed in the laboratory. All water analyses were done in the National University of Lesotho (NUL) Environmental Health laboratory. A standard method - 5210 B 5-day BOD test - was done according to APHA *et al.(*1998) to determine the BOD_5 of the water samples. Total Dissolved Solids analysis was done gravimetrically, where mass of a crucible was obtained, followed by mass of crucible plus 20 ml of filtered water sample. The crucible containing water sample was oven-dried, and the new mass of crucible found and used to determine the amount of TDS in the water samples. Phosphate concentrations in the water samples were determined using molybdenum blue method according to STN EN ISO 6878- 75 7465 (Soldan *et al.,* 2012). This method relies on the fact that phosphomolybdate complex is formed with molybdenum and added to the sample which is reduced with hydrazine hydrate (Pradhan & Pokhrel, 2013). Nitrates were determined through colorimetric Brucine method prescribed in USEPA Method 352.1 (US EPA, 1971 and Bain *et al.,* 2009) due to its accuracy and simplicity. However, there is some interference with this method, for example salinity, which is controlled by addition of sodium chloride to the blanks. Chlorides in water were determined by titration of the water against silver nitrate solution (APHA *et al.,* 1998). The principle behind this method is the reaction of silver nitrate with chloride, to form silver chloride. Determination of Ca, K, Mg and Na content in the water samples was done by use of an AAnalyst 200 Perkin Elmer model flame Atomic Absorption Spectrometer (AAS). In the determination of Ca, K, Mg and Na concentrations, the water samples were filtered and acidified to a pH less than 2 using HNO_3 prior to analyses with the AAS.

For the determination of COD in water samples, potassium dichromate ($K_2Cr_2O_7$) was added to heated sulphuric acid (H_2SO_4) medium for 2 hrs using a HACH COD reactor. The mixture was then cooled and added to the water samples. The full procedure is described in detail in APHA (2005). Readings were taken using a HACH (model DR-2000) spectrophotometer. This method is preferable because excess $K_2Cr_2O_7$ may be added to ensure that all OM in the sample is completely oxidised. This is accomplished through titration of the $K_2Cr_2O_7$ with ferrous ammonium sulphate (Sawyer *et al.,* 2003). On occasions where analysis could not be done within 24 hrs of refrigeration, samples were acidified with H_2SO_4 to a pH less than 2 (APHA, 2005).

3.5.4.2 Soil analysis

Soil EC, CEC, pH, Ca, K, Mg, Na, texture, particle size distribution, and available P, were determined at the NUL Soil Science laboratory, whereas Total Carbon (TC) and Total Nitrogen (TN) were analysed at the Ministry of Agriculture Research laboratory. Standard methods were employed in the analyses of soil samples. 1M KCl suspension was used for determination of soil pH, with solution to soil ratio of 2:1 (Hendershot *et al.,* 1993). For soil texture determination, the Bouyoucos Hydrometer method was preferred due to its degree of separation accuracy and adaptation to determination of general categories of sizes analysed (Gee & Or, 2002; Elfaki *et al.,* 2016). The weight percent (wt %) sand, silt and clay of each sample obtained from the Bouyoucos Hydrometer method were used with the aid of a soil textural triangle to determine the texture of the soil. Soil available P was analysed according to Bray and Kurtz No.1 using 0.03M NH4.F and 0.025 M HCl. In this method, phosphorus is extracted from soil by the Bray and Kurtz No. 1 solution, and reacted with ammonium molybdate, leading to the blue molybdate colour development which enables colorimetric determination of phosphorus (Bray & Kurtz, 1945; Frank *et al*., 1998; Kovar & Pierzynski, 2009). Exchangeable Ca, Mg, K and Na were determined using 1M ammonium acetate (Reeuwijk, 2002; Walworth, 2007). Walworth (2007) has shown that even though Na is not one of the essential elements for plant development, it has to be included in the method especially if the sum of exchangeable bases is to be used for calculation of CEC, as was done in this study. Water extract of the soil solution was used to measure soil EC. A CN analyser was used to determine TC and TN using dry combustion method (Purakayastha *et al.,* 2008). In this method, a LECO CN 628 analyser with its furnace temperature set at 950ºC was used to determine the amount of TC and TN in 100 mg of each sample. Loss-On-Ignition (LOI) method was used for OM determination. This method is preferred over other methods because it requires minimal preparation of soil sample prior to combustion (Schumacher, 2002) and does not use any chemicals. It is environment-friendly. The mass of each soil sample was determined before and after ignition, and the difference used to calculate percentage of OM in each soil sample as in equation 3.1 below.

$$OM\ (\%) = \frac{initial\ mass - final\ mass}{[initial\ mass]} \times 100 \qquad (3.1)$$

3.5.5 Wetland characterisation

The water purification functions of the wetland were evaluated by determining its ability to remove sediments, nutrients and organic compounds from the wetland water. Several wetland characteristics are suitable to be used to determine the wetland's ability to perform these various functions that eventually result in water purification by the wetland. The methods used for characterising these wetland characteristics are presented in the following sections.

3.5.5.1 Wetland ability to remove sediment

The potential of a wetland to remove sediment from water is determined by its ability to prevent them from moving into water bodies downstream of the wetland. Wetlands achieve this through various processes like velocity reduction and filtration. When the speed of water is lowered either by vegetation (Adamus *et al.,* 1991) or with the aid of undulation, more sediment is held back or settles (Mitsch & Gosselink, 1993). Retention time is one other aspect that enhances sedimentation and, since it cannot be measured directly within a wetland, the volume of water stored and the amount of constriction at the wetland outlet were used to qualitatively determine retention time (Adamus *et al.,* 1991). To determine the wetland's ability to retain sediments, several wetland properties were needed in addition to the soil and water properties. These wetland properties and the methods used in determining them are described below.

3.5.5.1.1 Wetland outlet constriction (V_{out})

Velocity reduction occurs within a wetland when its outlet is constricted, thus holding back a considerable volume of water during a wet season while increasing water residence time within the wetland (Adamus, 1996). This characteristic was measured by marking flooding or inundation marks at least one metre above the wetland outlet. When there is no hindrance at least one metre above the wetland outlet, then a wetland is considered to have unconstricted or slightly constricted outlet according to Hruby *et al.* (1999). Unconstricted or slightly constricted outlets are given a score of 0, moderately constricted outlets a score of 0.5 and severely constricted outlets a score of 1 (Hruby *et al*., 1999).

3.5.5.1.2 Wetland vegetation class ($V_{vegclass}$)

The percentage of vegetation that covers the wetland was determined and assessment done using the Cowardin classes of emergent, scrub/shrub, forest and aquatic bed vegetation (Cowardin *et al.,* 1979). These classes are allocated based on the efficiency of different types of vegetation to trap sediment, with emergent vegetation being the most efficient in trapping sediment when compared to the other listed types, and hence scored as 1. Scoring of vegetation was based on which class of vegetation covered a larger area, with emergent vegetation scoring 1 since it is nearer the ground level and performs better in velocity reduction and hence trapping sediments; scrub/shrub vegetation scoring 0.8; forest vegetation scoring 0.3 (but not found in the wetland assessed), and aquatic bed scoring 0 since no sediment is trapped in the absence of vegetation (Hruby *et al*., 1999).

3.5.5.1.3 Area of wetland with herbaceous vegetation ($V_{understory}$)

This category was not used since the wetland under study did not have any forest. Though a scoring for herbaceous vegetation was a requirement for calculation of sediment removal index, it was given a 0 % because it was absent in the wetland.

3.5.5.1.4 Water storage ($V_{storage}$)

Livestorage and deadstorage were used to measure water storage within the wetland where livestorage measures the volume of water that is available during major rain events and deadstorage refers to water below a wetland outlet. These were determined by marking the difference in depth between flood marks on vegetation and the wetland outlet (Hruby *et al.,* 1999). The GPS coordinates for the region where flood marks began and the wetland outlets were taken. The coordinates were subjected to ArcGIS 10.1 for calculation of the difference in elevation between the two regions. The extent of permanent exposed water was used to determine deadstorage. Assuming that these areas in the Khubelu wetland were 2 m deep on average, percentage cover of the area was multiplied by 2. When depth of livestorage together with deadstorage is above or equal to 1 m, a 1 score was allocated; and absence of either live or deadstorage scored a 0 (Hruby *et al.,* 1999).

3.5.5.1.5 Area of wetland permanently inundated in water ($V_{effectarea1}$)

The inundated area of a wetland assists in the reduction of water velocity and hence sediment removal from water running through the wetland (Barnes *et al*., 2002; Huang *et al.,* 2012). The area of the wetland considered was the portion that is inundated on annual basis (Adamus, 1996). GPS coordinates of water marks and deposition lines were taken and subjected to ArcGIS10.1 in order to determine the area of the permanently inundated section of the AU, and scaled as a % of the total AU (area/100). Areas that were entirely covered with water scored 1, and other areas scored according to % area inundated, for example, areas with 10% of AU that were inundated were given a score of 0.1 (Hruby *et al*., 1999).

3.5.5.2 Wetland ability to remove nutrients

The potential for removing nutrients by a wetland is described by Mitsch and Gosselink (1993) as the wetland's ability to retain phosphorus and nitrogen contained in water entering it, thus preventing them from going downstream or being discharged into any stream fed by the wetland. Wetlands are able to perform this function if their sediments are able to trap the nutrients (Khalid *et al.,* 1977; Stevenson *et al.,* 1988; Adamus, 1996; Olapade & Sheku, 2014). This could occur if:

- Wetlands soils have a high clay and/or organic matter content and hence have high sorption property.
- Nitrification and denitrification occur during oxic and anoxic wetland conditions (Lowrance *et al.,* 1984; Jordan *et al.,* 1993) reducing the amount of nitrogen in the water.

Wetland properties used to determine its ability to remove nutrients include its ability to sorp phosphorus. This is related to the clay and organic matter content of the wetland soils, percentage of total wetland that is annually inundated and suitable for denitrification. This also includes amount of constriction at the outflow of the wetland which indicates duration of residence time of water in the wetland. The longer the water resides in the wetland, the longer the time taken for denitrification in pursuit for nitrogen removal from the wetland waters (Mitsch and Gosselink 1993). The determination of these wetland characteristics is presented below.

3.5.5.2.1 Sediment removal (S_{sed})

This is the same as the Index for sediment removal, which indicates ability of a wetland to remove phosphorus bound to soils with high percentage of clay or organic matter (Mitsch & Gosselink, 1993) or being trapped along with sediments (Olapade & Sheku, 2014). This variable is the same as that of sediment removal since phosphorus coming into wetlands is bound to sediments (Adamus *et al.,* 1991).

3.5.5.2.2 Percentage of wetland with clay and organic soil (V_{sorp})

As elaborated by Hruby *et al.* (1999), this property was measured by determining the amount of clay in soils sampled across the AU. A score of 1 was given to soils with less than 50% mineral soils, with soils having 50 to 95% composition of mineral soils scoring 0.5 and those with non-clay minerals above 95% scoring 0.

3.5.5.2.3 Percentage of AU where conditions change from oxic and anoxic ($V_{effectarea2}$)

$V_{effectarea2}$ was used to assess the level of nitrogen transformation as the AU experiences changes between anoxic and oxic conditions. Seasonally inundated areas have enough time for exchange between anoxic and oxic conditions that enable denitrification and nitrification, respectively (Wang *et al.,* 2015). On the other hand, annually inundated areas do not have sufficient period during which nitrification would occur due to shortage of oxygen (Hermandez & Mitsch, 2007). The percentage of the AU where conditions change from oxic and anoxic was determined by subtracting % area that is permanently inundated from the annually inundated area. Areas that were inundated for more than one month, areas that had permanent open water, and areas that had open water which was covered with plants were identified and allocated individual scores. Areas that were completely annually inundated were scored 1, and the rest scored according to % that has water on seasonal basis as per Hruby *et al.* (1999).

3.5.5.2.4 The amount of constriction in outflow from the AU (V_{out})

This was also necessary to determine nitrogen transformation. This is the same index as for outlet constriction (V_{out}) described in section 3.5.5.1.1.

3.5.5.3 Wetland's ability to remove organic compounds

Sedimentation, adsorption, precipitation and plant uptake are processes that enhance removal of organic compounds from wetlands (Adhikari *et al.,* 2009; Johannesson *et al*., 2015). These processes are all affected by the retention time of sediments in the wetland, the sorption properties of the wetland soils, the interstitial water pH of the wetland, and the percentage of wetland area with emergent vegetation species. Soils with higher clay and/or organic matter content have high cation exchange capacity, and hence high sorptive properties (Mengel & Kirkby, 1982). The interstitial water pH of the wetland affects the precipitation of organic compounds and heavy metals. The percentage of wetland area with emergent species was regarded the best for removal of organic compounds when compared to other forms of vegetation like forest and shrubs (Horner, 1992). To determine the wetland's ability to remove organic pollutants, the following wetland characteristics were determined.

3.5.5.3.1 Sedimentation (S_{sed})

This is the same index calculated for the ability to remove sediments on which organic compounds get bound, as determined in section 3.5.5.1.

3.5.5.3.2 Adsorption ($_{Vsorp}$)

This is related to the percentage of clay and organic soil in the AU since they determine the soil cation exchange capacity. This is the same value as percentage of wetland with clay and organic soil (V_{sorp}) determined in section 3.5.5.2.2.

3.5.5.3.3 Chemical precipitation (V_{pH})

Hruby *et al.* (1999) scoring method was used, such that after assessing pH of interstitial water, AU with water pH less than or equal to 4.5 was given a score of 1, whereas those with pH between 4.5 and 5.5 were given a score of 0.5, and those greater than 5.5 a score of 0.

3.5.5.3.4 Percentage of AU with emergent vegetation ($V_{totemergent}$)

The presence of emergent vegetation indicates that there are plant uptake processes of toxic and organic compounds going on. The area covered by this vegetation type was determined in a 1 m^2 quadrat (Brummer *et al.,* 1994). Different plant species within the quadrat were counted repeatedly and the average count from several counts used to estimate species abundance (Mahajan & Fatima, 2017) represented in the AU. Assessment units with 100% cover of emergent vegetation were scored 1, and the rest scored according to % cover in the AU.

3.5.5.3.5 Percentage of AU that is annually inundated with water ($V_{effectarea1}$)

Water marks were used to determine the level of inundation in the wetland as indicated in section 3.5.5.1.5. Similarly, areas that were entirely covered with water were given a score of 1, and other areas scored according to % area inundated (Hruby *et al*., 1999).

3.6 Quality control and quality assurance measures

Potential sources of errors during water and soil sampling were minimised by taking several precautions. Water and soil samples were stored in labelled containers and kept in cooler boxes while awaiting laboratory analysis to prevent the deterioration of the chemical and biological state of the samples. For parameters that could not be analysed within 24 hrs, the window period for their preservation was observed as per standard methods (APHA, 2005). Samples were analysed in triplicate and results obtained by finding an average for each parameter in the three samples. Cross contamination was minimised by using clean work areas, sampling equipment and wearing clean gloves throughout the sample analysis. Prevention of cross contamination of samples entailed sealing them in between their analyses to avoid, amongst others, temperature changes from the analysis environment; picking up contaminant during storage (from refrigerator). Reagents used for soil and water analyses were all Analar grade reagents. Approved standards were used for calibration of all instruments used for measurements and equipment setup followed guidelines from the manufacturer.

3.7 Data analysis

Data generated were subjected to various statistical analyses and environmental indices to achieve the specific objectives of the study. Principal Component Analysis (PCA) and Chemical index of soil degradation (CDI) were used for soil data analysis, whereas the Water Quality Index (WQI) was used for water data analysis. Details of data analyses carried out in this study are presented below.

3.7.1 Statistical analyses

To determine whether the differences observed in soil and water quality parameters between the different sampling sites in the wetland and the stream, and between the upstream, midstream, downstream sections of the wetland as well as the stream, One-Way Analysis of Variance (ANOVA) with Tukey's Honest Significance Difference (HSD) Post Hoc test was carried out. All analyses were carried out at a confidence limit of 95% using Statistical Package for Social Sciences (SPSS) version 25.0.

3.7.2 Determination of the quality of water in Khubelu wetlands and stream

Four well-known water quality indices commonly used are National Sanitation Foundation Index, Canadian Council of Ministers of the Environment Index, Oregon Index and Weighted Arithmetic Index. Weighted Arithmetic Index can determine water quality for a particular use and can describe the suitability of both surface and groundwater sources for human consumption, incorporating data from multiple water quality parameters (Akoteyon *et al.,* 2011). For these reasons Weighted Arithmetic Index method was chosen for determination of WQI in this study. Thirteen water parameters were determined and used for calculation of WQI of the wetland, using WHO water quality standards. WHO standards were preferred since Lesotho has no standards for drinking water quality and is currently utilising WHO Guidelines. The wetland water properties were also compared to the South Africa agricultural water quality standards. WQI was calculated using equation 3.2 as described by Curtis (2001) and Pathak *et al.* (2015).

$$\boldsymbol{WQI = \frac{\sum Wi\, qi}{\sum Wi}} \tag{3.2}$$

Where:

WQI = Water Quality Index,

i = number of water quality parameters

qi = quality rating, for the 13 water quality parameters

Wi = relative weight, for the 13 water quality parameters

Quality rating Qi was determined according to equation 3.3

$$\boldsymbol{Qi = \left\lfloor \frac{V_{actual-}V_{ideal}}{V_{standard-}V_{ideal}} \right\rfloor \times 100} \tag{3.3}$$

Where:

Qi = Quality rating of the 13 water quality parameters.

Vactual = Actual value of the water quality parameter obtained from laboratory analysis.

Videal = Ideal value of that water quality parameter that is assumed to be zero for drinking water, except pH with 7.0 and DO with 14.6 mg/l.

Vstandard = Recommended WHO standard of the water quality parameter. The WHO standards used in this study are presented in Table 3.1.

Table 3.1 WHO drinking water standards

Parameter	**WHO standard**	**Parameter**	**WHO standard**
EC (mS/cm)	1.5	K (mg/L)	12
pH (pH units)	6.5- 8.5	Mg (mg/L)	150
DO (mg/L)	5	Na (mg/L)	200
BOD (mg/l)	5	TDS (mg/L)	500
COD (mg/L)	10	Cl (mg/L)	250
Ca (mg/L)	200	NO_3 (mg/L)	50
PO_4 (mg/L)	0.01– 0.1		

(Adapted from WHO, 2011)

Relative weight (Wi) calculation for each parameter was as shown in equation 3.4 below:

$$\boldsymbol{Wi = 1/Si} \tag{3.4}$$

Where:

Wi= Relative (unit) weight for the 13 parameters

Si = Standard permissible value for the 13 parameters

1 = Proportionality constant

The Relative (unit) weight (Wi) for the various water quality parameters are inversely proportional to the recommended standards for the corresponding parameters, e.g.

for BOD_5, permissible level = 5 therefore Wi= 1/5= 0.2;

for NO_3, Wi= 1/50= 0.02; etc.

The classification of water quality based on values of water quality index and classification presented in Table 3.2 was used for the classification of Khubelu wetland and stream WQ. Bi-plots were used to determine variations of water quality parameters in both the stream and piezometers. Correlation coefficient was used to determine any existing relationship amongst water quality parameters in the stream and in piezometers, and between the piezometers and the stream.

Table 3.2 Suitability of WQI values for human consumption

Water Quality Index level	Description
0 – 25	Excellent
26-50	Good
51- 75	Poor
76-100	Very poor
100 and above	Unsuitable for drinking

(Adapted from Mishra & Patel, 2001)

3.7.3 Characterisation of soil quality of Khubelu wetland

The extent of soil degradation in the wetland was assessed using the soil Chemical Degradation Index (CDI). Chemical Degradation Index is a simplified index that is used to evaluate the level of soil degradation (Huang *et al.,* 2012). This index was used in order to evaluate the wetland soil quality, and has been widely used to monitor and assess soil condition (Fu *et al.,* 2004; Huang *et al.,* 2012) for ease of management and restoration of those soils that are degraded. The determination of CDI of the soil was carried out as described by Andrews *et al.* (2002); Gvozdic´ *et al.* (2012) and Ghaemi *et al.* (2014). Principal Component Analysis (PCA) was used as directed by Huang *et al.* (2012) and Ghaemi *et al.* (2014) in the determination of soil chemical degradation index. Through PCA, factor loadings for the different soil properties determined were obtained. These factor loadings were used as weight factors for the determination of CDI (Fu *et al.,* 2004). Of the eleven soil parameters (EC, pH, TC, OM, TN, CEC, Cations (Ca, Na, K, and Mg), and available P) determined in this study, only those with factor loadings above 0.5 in components with Eigen values above 1.0 were used (Andrews *et al.,* 2002). Chemical Degradation Index of the soil was calculated according to Fu *et al.* (2004) as in equation 3.5.

$$CDI = \sum WiQ(Xi) \qquad (3.5)$$

Where Wi = weight vector for the soil quality determined from PCA results.

Q (x_i) = membership value for each soil quality factor determined according to equation 3.6 and 3.7 (Fu *et al.,* 2004; Huang *et al.,* 2012)

$$Q(Xi) = \frac{Xij - Xi\,min}{Xi\,max - Xi\,min} \qquad (3.6)$$

$$Q(Xi) = \frac{Xi\,max - xij}{Xi\,max - Xi\,min} \qquad (3.7)$$

Where:

x_{ij} = Mean value for each soil property

x_{imin} and x_{imax} are minimum and maximum values for each of the soil properties in the study respectively.

Equation 3.6 was used to determine membership value for those soil properties that would have high value in undegraded land, whereas equation 3.7 was used for the determination of membership values for soil properties that would have high value if the soil is degraded. Soils with CDI values above 2.0 indicate a degraded wetland, whereas soils with CDI values below 2.0 indicate an undegraded wetland (Huang *et al*., 2012).

3.7.4 Assessing water purification function of Khubelu wetlands

The following functions were used to determine the wetland's water purification ability:

- Potential for removing sediment;
- Potential for removing nutrients; and
- Potential for removing organic compounds.

To determine the wetland's ability to remove sediment the following model by Hruby *et al*. (1999) presented in equation 3.8 was used:

$$Index\ for\ removing\ sediment\ (S_{sed}) = (V_{storage} + V_{out} + V_{effectarea1} + V_{vegclass} + V_{understory}\ ) x\ 2.56 \qquad (3.8)$$

Where:

$V_{storage}$ = average depth of both livestorage and deadstorage

V_{out} = quantitative descriptors of outlet constriction

$V_{effectarea1}$ = % of AU that is inundated

$V_{vegclass}$ = % of AU in different Cowardian vegetation classes

$V_{understory}$ = % AU area of herbaceous vegetation found under forest & shrub/scrub

2.56 = Factor utilised to normalise the scores (Daniels *et al.,* 2010) since for each evaluated function, the best performing wetlands of similar geomorphic settings (Hruby *et al.,* 1999; Daniels *et al.,* 2010) scores 10.

A wetland's ability to remove nutrients is assessed through processes that remove nitrogen and phosphorus, and this is measured as a decrease in concentration of the nutrients as water moves down and across the wetland, until it enters the stream. The model by Hruby *et al.* (1999), as presented in equation 3.9, shows how the wetland's ability to remove nutrients was determined in this study.

$$Index\ to\ remove\ nutrients = (S_{sed} + V_{sorp} + V_{effectarea2} + V_{out})x\ 2.56 \qquad (3.9)$$

Where:
S_{sed} = the index for removing sediment
V_{sorp} = % of the wetland with clay soil and organic soil
$V_{effectarea2}$ = the area of annual inundation – area of permanent exposed water
V_{out} = qualitative description of outlet characteristics
2.56 = Factor utilised in order to normalise the score (Daniels *et al.,* 2010).

The removal of metals and toxic organic compounds from water by the wetland is determined by its ability to retain these potential contaminants and keep them from migrating out of the wetland. The following model (equation 3.10) as developed by Hruby *et al*. (1999) was used to determine the ability of Khubelu wetland to remove toxic metals and organic compounds from water:

$$Index\ for\ removing\ pollutants =$$
$$(S_{sed} + V_{sorp} + V_{pH} + V_{totemergent} + V_{effectarea1})x\ 2.38 \qquad (3.10)$$

Where:
S_{sed} = wetland's index for removing sediments
V_{sorp} = percentage of wetland with clay and organic soil
V_{pH} = pH of interstitial water,
$V_{totemergent}$ = percentage area of emergent vegetation in the wetland
$V_{effectarea1}$ = percentage of wetland that is annually inundated
2.38 = Factor utilised in order to normalise the score (Daniels *et al.,* 2010)

The values obtained from the various models were used to determine whether the wetland is able to perform its water purification function or not.

3.7.5 Determining the effect of climate change on water quality of Khubelu wetland and stream

The Water Evaluation and Planning (WEAP) model was used to predict water quality of the wetland and stream in the light of varying global climatic conditions. This model was chosen due to its ease of application, and ability to simulate pollution generation and in-stream water quality. Furthermore, it uses simple mixing and assumes conservative behaviour of pollutants. It has built-in BOD, DO and temperature models, enabling the user to model these and other water quality components (Kumar *et al.,* 2019). The model was developed by Stockholm Environment Institute and is useful for data-poor countries (Slaughter & Mantel, 2018); Lesotho being one of such.

The two climatic variables used in the study were precipitation and temperature, whereas water quality parameters modelled were BOD and DO. BOD and DO have been used as regulatory water quality parameters because they assess the levels of oxygen-depleting activities and reactions, such as decomposition of organic matter and other anaerobic processes associated with nutrient enrichment of water bodies. These processes are sensitive to changes in temperatures and precipitation levels and any changes in these climatic variables are likely to affect them. In setting up the model, Phapong area was created using ArcGIS and the layer added onto the Phapong area map. A Digital Elevation Model (DEM) for the Phapong area where the wetland is found was developed using ArcMap. Figure 3.6 shows the protocol followed to input data into the WEAP Model. The WEAP model was run using Daily Time-Series Wizard built with the 2006 data as a baseline account for which there were available input data for the model (Esteve *et al.,* 2015), 2017 as current account and 2018 to 2025 as reference years. The Global Climate Model dataset called Representative Concentration Pathways (RCP- 8.5) was downloaded from NOAA (NOAA) and used to calculate the impact of climate change on Khubelu stream water quality. RCP 4.5 and RCP 8.5 describe a concentration of CO_2 that causes global warming beyond 2100 at an average of 4.5 W/m^2 (~ 650 ppm CO_2) (Clarke *et al*., 2007) across the planet, and the rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2), respectively (Riahi *et al.,* 2007; Riahi *et al*., 2011). RCP 8.5 is further assumed to cause a temperature increase of 4.3°C by the year 2100 (Nazarenko *et al*., 2015).

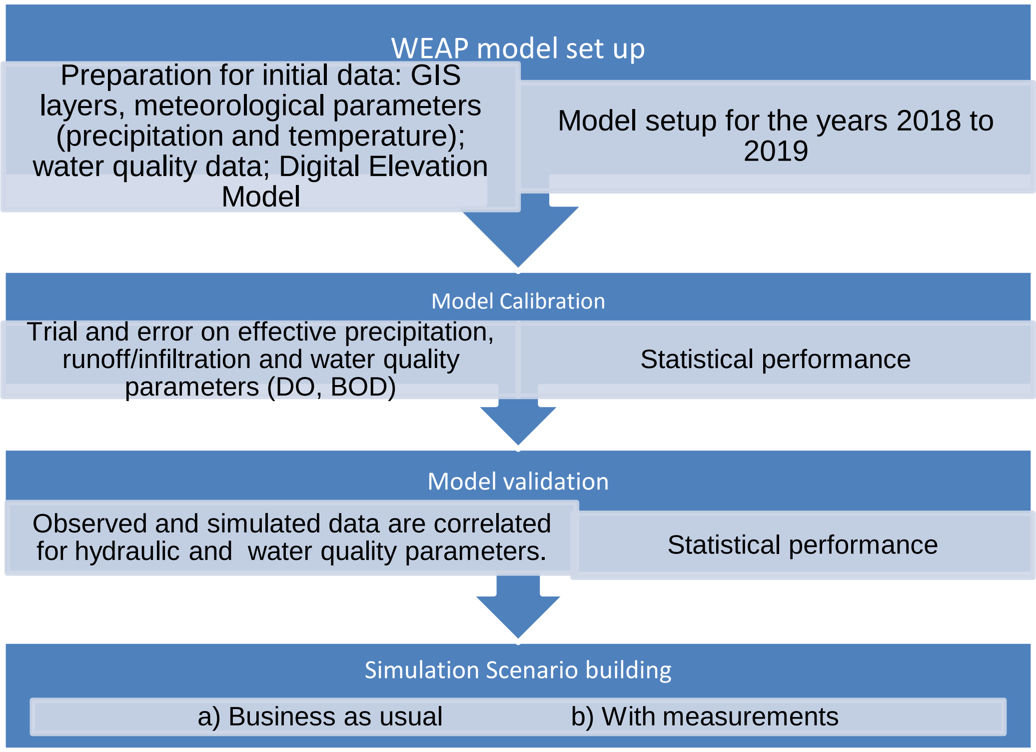


Figure 3.6: Schematic diagram showing data input for the WEAP Model

RCP 8.5 was therefore used since it assumes that Green House Gases (GHGs) that are measured as CO_2 concentration equivalents will be continually emmitted through the year 2100 (IPCC, 2014). The WEAP method used for simulation of the catchment processes was Rainfall Runoff (Simplified Coefficient Method), which is also called hydrologic response in other literature. This method was preferred because it determines evapotranspiration for rain-fed crops, with non-agricultural land uses included. This method has been used widely to describe catchment response (Blume *et al.,* 2007) on both annual and event basis.

The altitude and centroid of the catchment were utilised, and meteorological data (precipitation and temperature) obtained from Lesotho Meteorological Services (LMS) used to calculate evapotranspiration rate (Eto) of the Khubelu wetland (Allen *et al.,* 1998). Khubelu stream and wetland water BOD and DO data generated during this study were entered into the model. Temperature and precipitation data from 2007 to 2018 obtained from LMS were used for modelling. Model calibration was done using DO and BOD_5 data from April 2018 to June, 2018 against simulated data for the same months of the following year (2019). Validation was done using data obtained between February, 2019 and March 2019 against simulated data for the same months of the following year (2020). Model calibration was done in order to adjust the input parameters so that there was a closer agreement between observed data in the study and the simulated one (Ambrose, 1992; Azadani, 2012). Calibration also ensures that the model represents water quality of the study area. Simulation was done from 2018 to 2025. The Nash-Sutcliffe Efficiency (NSE) value, which is used to assess the predictive power of hydrological models (AgrimetSoft, 2019), was calculated in order to check the accuracy of the predictions of BOD and DO under different climatic scenarios in the study area (Khaba, 2018). Equation 3.11 was used for the calculation of NSE values.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(OBS_i - SIM_{\mathrm{i}})^2}{\sum_{i=1}^{n}(OBS_i - \overline{OBS})^2} \qquad (3.11)$$

Where:

SIM_i = Simulated water quality value

OBS_i = observation value, (being observed water quality at time t (2018 to 2019) 1 year)

$\overline{\mathrm{OBS}}$ = average of observed water quality values

The efficiency value lies between negative infinity (∞) and 1.0 and the closer the NSE value is to 1, the more accurate the model is (Krause *et al.,* 2005).

3.8 Ethics statement

Prior to the commencement of field work, approval to access the wetland for sample collection was requested from the Seate Community Council under which the wetland site belongs, as well as from the Department of Water Affairs (DWA). The LMS approved utilisation of meteorological data (rainfall and temperature) from the years 2007 to 2018, used for this study. Letters of approval from the different departments can be found in Appendix I, Appendix II, and Appendix III at the end of this report. Consideration for possibilities of disturbed flora and fauna during sampling came to being, and sampling was done with utmost care to ensure minimal disturbance of the ecosystem. In this regard, soil was returned to pits after profiling and ensuring that no foreign material was added to the wetland. Analyses of both water and soil samples took into consideration the laboratory rules and regulations and the disposal of used reagents and waste samples done in accordance with laboratory guidelines. Ethics clearance certificate (2018/CEAS/42) was obtained from the University of South Africa Ethics Review Committee, (see ethics certificate in appendix IV) prior to the commencement of the research.

3.9 Study limitations

It was expected that water quality data would be available for the 2008 to 2018 period, but it was only known in the middle of the study that such data were not available. This was a challenge because data collected during the study period could not give a broader picture of how variations in temperature and precipitation could have affected the Khubelu water quality prior to the study. However, predictions were still versatile so that in the future, it can be suggested how water quality is likely to be impacted by predicted climate variations. Piezometers were not as deep as would be desired due to shallow parent material, making them susceptible to side flows as soil expanded or froze, the latter happening during winter. The wetlands are unprotected and threatened by uncontrolled grazing. As a result, animals are likely to contribute to Total Suspended Sediments (TSS) and nutrients, especially nitrates from urine and dung. Soil compaction by animals as they move around is another threat, creating gullies and ultimately making the wetland prone to erosion. Infiltration capacity of wetlands is thus decreased.

CHAPTER 4

RESULTS AND DISCUSSION: KHUBELU WETLANDS WATER QUALITY

4.1 Introduction

This chapter presents the findings of the analyses of physico-chemical properties of water from the Khubelu stream and wetland. The stream and wetland water properties are discussed and the water quality index of the wetland presented. The variations in water quality of the two sites are also included in this chapter. Results from modelling Khubelu stream and wetland BOD and DO levels under different temperature and rainfall scenarios are included at the end of the chapter.

4.2 Stream and wetland water physico-chemical properties

In the wetland, sampling sites GW3, GW4 and GW7 were grouped as upstream, GW6 and GW8 as midstream of the wetland, and GW5 and GW9 as downstream of the wetland. The characteristics of the different sampling sites are discussed below including how these properties vary from upstream to downstream of the wetland, and then the stream is presented.

4.2.1 Temperature

Mean water temperatures ranged from 9.8 to 13.3°C in the wetland and from 14°C to 19.3°C in the stream (Table 4.1). For surface water, the WHO limit of 27-30°C was not reached. There was a temperature range difference of 3.5°C and 5.3°C in the wetland and stream respectively. The temperature changes in the stream and wetland are influenced by several factors including diurnal air temperature, wind, relative humidity and shading. According to a study by Morrill *et al.* (2001), with every 1°C rise in air temperature, water temperature is increased by 0.6 to 0.8°C. This is indicative of surface water gains and losses of heat, which occur faster than with soil (Wilby *et al.,* 2010). The high heat capacity of the soil could have contributed to the lower temperature of the wetland water since the piezometers used for sampling wetland water were at least 1.8 m below ground level. Changes in air temperature are not likely to have had a direct impact on water in the piezometers.

4.2.2 pH

Mean water pH varied from 6.32 to 7.11 in the wetland and from 6.67 to 7.69 in the stream (Table 4.1). Across the wetland, pH decreased towards midstream but increased thereafter as the mean pH of stream (7.69) was the highest recorded in the study (Figure 4.1). The differences observed in the mean pH values were however insignificant between sampling sites (*p* = 0.25) and from upstream through downstream to the Khubelu stream (*p* = 0.06).

Table 4.1 Means of stream and wetland water quality parameters

Water quality parameter	**Wetland**			**Stream**			**WHO limit**	**FAO Stds**	**Irrigational limits**
	Min	Max	Mean	Min	Max	Mean	-	-	-
Temperature (°C)	9.8	13.3	13.03	14	19.3	17.2	27-35	-	-
pH	6.32	7.11	6.59	6.67	7.69	6.9	6.5-8.5	-	6.5- 8.4
EC (mS/cm)	0.41	1.12	0.75	0.67	2.11	1.21	1.5	1.5-5.0	0.4
DO (mg/l)	0.75	1.79	1.43	2.33	4.97	4.06	5	-	-
Ca (mg/l)	5.42	7.55	6.24	8.2	16.8	12.44	200	-	-
Na (mg/l)	5.01	13.25	10.69	3.17	6.23	4.74	200	-	70
Mg (mg/l)	8.36	10.75	9.41	7.29	11.39	8.13	150	250-500	115
K (mg/l)	0.08	4.8	2.96	0.19	1.81	0.74	12	-	-
TDS (mg/l)	189	463.5	277.79	45	314	151.6	500	-	-
NO_3 (mg/l)	8.16	9.96	8.76	5.01	13.03	8.73	50	-	-
PO_4 (mg/l)	0.17	0.61	0.33	0.06	1.26	0.53	0.01-0.1	-	-
BOD (mg/l)	1.47	3.92	2.51	1.02	6.92	3.33	5	-	-
COD (mg/l)	48	140.8	108.44	10.0	55.0	36.7	10	-	-
Cl (mg/l)	35.3	68.9	52.38	28.86	58	46.6	250	-	-

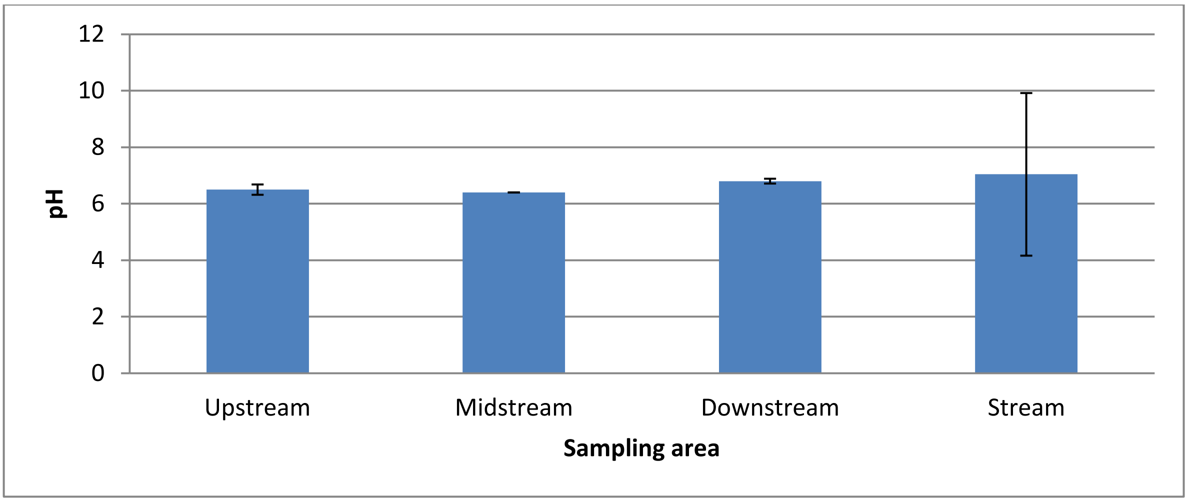


Figure 4.1: Variation of pH in stream and wetland water

This observed increase in pH from upstream to downstream of the wetland can be explained by the deposition of salts of basic cations further downstream the wetland. Another possibility could be due to pattern of tannic acids concentrations that also decreased in concentration from upstream to downstream of the wetland due to dilution caused by infiltration of water from other sources into the wetland. The stream pH was within the WHO drinking water standard of 6.5 to 8.5, whereas the wetland pH was slightly lower than permissible WHO minimum of 6.5, indicating a potential for the water to be corrosive. However, 6.32 is not far off the 6.5 minimum observed for global drainage basins (UNEP/GEMS, 2007), and it is also within the “no-effect range” of 6 – 8.5 for groundwater (WRC, 2003) and 3.33 to 7.0 according to Zhou *et al. (*2015). Causes of low wetland water pH could be dissociation of hydronium ion (H_3O^+) released from clay during weathering (Zhou *et al*., 2015). Similar observations were made by Abdul-Razak *et al*. (2009) and Adiyiah *et al.* (2013). It could also be related to the decomposition processes going on in the wetland. The pH levels obtained in this study could have several implications on the wetland and stream. A study by Le *et al.* (2017) revealed that in Tay Nihn River, a pH below 6.0 prevented the growth of nitrifying bacteria. Should Khubelu stream pH be below 6.0 there would be limited growth of nitrifying bacteria and inhibition of ammonia oxidation. This would threaten the stream with nutrient pollution. The current pH levels (6.67 to 7.69), however, are not likely to affect natural chemical and biological processes in the wetland and stream.

4.2.3 Electrical conductivity

Mean values of EC of the water samples ranged from 0.41 mS/cm to 1.12 mS/cm in the wetland, and 0.67 mS/cm to 2.11 mS/cm in the stream (Table 4.1) indicating higher values for the stream compared to the wetland. Similar to pH, results from ANOVA indicated that the differences observed in EC between sites (p = 0.78) and from upstream to the stream (p = 0.42) were insignificant. However, the EC values for the wetland were below the recommended 1.5 mS/cm recommended by the WHO for drinking water quality, and FAO drinking water standards for animals, but the stream EC was above the WHO standard. These levels were higher than the 0.4 mS/cm standard recommended by the SA water quality guidelines for irrigation (DWAF, 1996). The water would therefore pose some threat to vegetation if used for irrigation downstream of the wetland. No identifiable trend was observed in EC values from upstream to downstream along the wetland (Figure 4.2). The values for wetland water EC obtained in this study were similar to those reported by Oyem *et al.* (2014) for wetlands in Nigeria. Electrical conductivity generally increases with temperature as a result of increased rate of evaporation from water bodies which leaves behind concentrated salts in the water body, resulting in elevated concentrations of dissolved salts (Kadlec & Wallace, 2009) and consequently a high EC. There was a positive correlation between EC and exchangeable K (r = 0.804); Na (r = 0.648) and Ca (r = 0.531) as shown in Appendix VIII, further highlighting the role of these cations in the EC of the water.

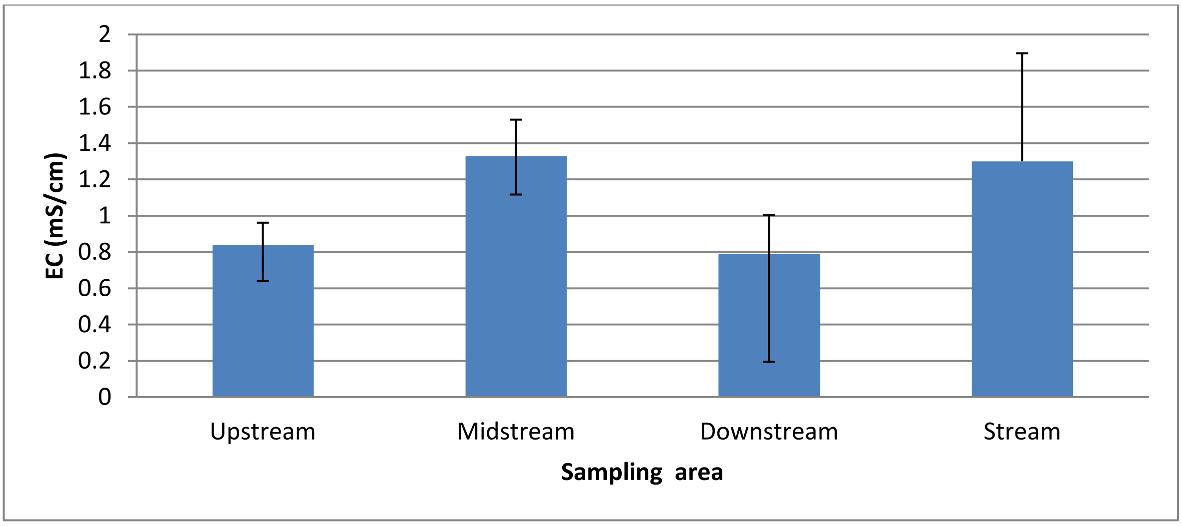


Figure 4.2: Variations in EC along the wetland and in stream

At these EC levels, the salinity of the water is not likely to affect microbial activities and plant growth in the wetland and stream. With expected increase in temperatures as predicted in literature however, there could be further evaporation from the Khubelu wetland and stream, increasing the concentrations of dissolved salts and, consequently, EC. Predicted changes in climate with regards to rainfall and temperature would therefore have an impact on the EC of the stream and wetland.

4.2.4 Dissolved oxygen

In the wetland water samples, DO concentration ranged from 0.75 mg/l to 1.79 mg/l whereas in the stream, a DO concentration range of 2.33 mg/l to 4.97 mg/l was observed (Table 4.1). Similar observations have been reported by Mason *et al.* (2007) where increase in the concentrations of DO from 2.0 to 6.1 mg/l were observed in Louisiana streams, and by Troyer *et al.* (2016) who reported mean DO concentration of 4.2 mg/l in rivers. These values are also below the WHO requirement of 5 mg/l for drinking water, which could point to some level of organic and nutrient pollution in these water resources (Troyer *et al.,* 2016). Little mixing of water in the wetland could be responsible for build-up of organic material from autochthonous sources, further causing low DO. An increase in temperature due to climate change could place even more demand on DO. There were no differences in DO concentrations between sites around the wetland (p = 0.37) but the DO concentrations at all sites in the wetland with the exception of sites GW4 and GW5 were significantly lower than that of the stream (p = 0.0003). There was an irregular trend in the content of DO from upstream the wetland towards the stream (Figure 4.3) but ANOVA results indicated that the DO contents upstream, midstream and downstream were significantly lower than what was obtained at the stream ($p < 0.01$).

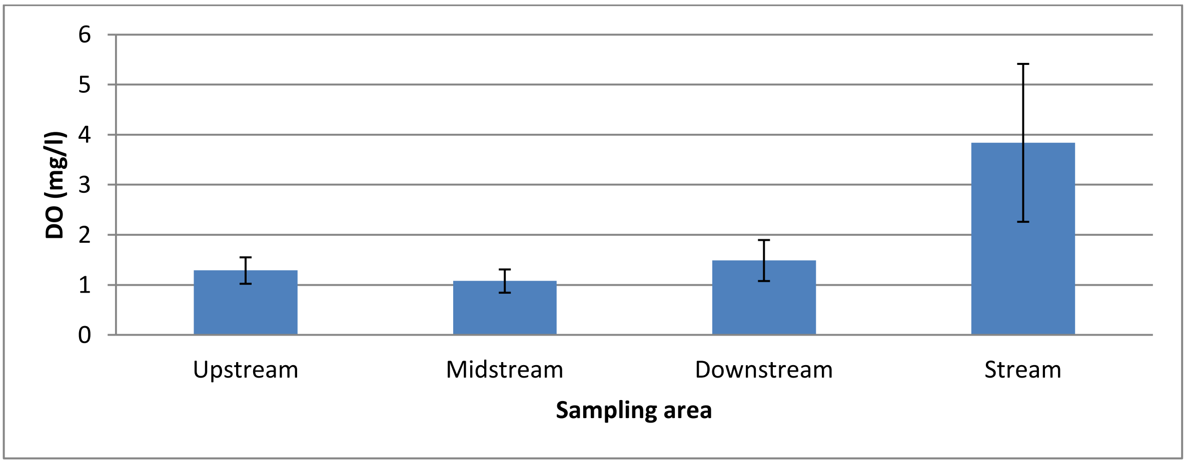


Figure 4.3: Mean dissolved oxygen concentrations at the Khubelu wetland (upstream, midstream and downstream) and the Khubelu stream

Low concentrations of DO in the wetland water could be due to the nature of the piezometers used where aeration and turbulence were impossible. These processes aerate water bodies, introducing oxygen into them that usually contributes to the amount of DO in surface water bodies. A low DO concentration ranging between 2.33 mg/l and 4.97 mg/l in stream water could possibly also be related to the higher temperatures in this water body. The solubility of oxygen is low when temperatures are high, which may result in less DO in the water. It could also be owing to high decomposition rates of organic materials in the wetland which tend to consume dissolved oxygen in the water body. Mason *et al.* (2007) and Troyer *et al.* (2016) both attributed low DO in stream and river water to increasing temperature and organic carbon pollution. Plant litter would deplete DO as they decompose; a situation that is common in wetlands because of the density of vegetation in these ecosystems compared to the stream. Organic matter decomposition and microbial activities both of which place a high demand on available oxygen are more prevalent in wetlands than in stream ecosystems because of the presence of vegetation. Another mechanism of DO depletion is utilisation of oxygen by micro-organisms as they try to get energy from organic substances (Le *et al*., 2017). The lower DO values obtained from the wetland compared to the stream is therefore not unexpected. Low DO concentrations would cause a shift in numbers and/or type of aquatic organisms that favour aerobic environment in both the stream and wetland, which would be a sign of changing ecological conditions of these water resources (Troyer *et al.,* 2016). The stream would experience nutrient pollution, anoxic conditions and eutrophication. The projected increase in temperatures and precipitation for the region might exacerbate oxygen solubility problems, causing DO depletion in the Khubelu wetland and stream.

4.2.5 Biological oxygen demand

Values for BOD_5 ranged from 1.47 to 3.92 mg/l in the wetland and from 1.02 to 6.92 mg/l in the stream waters (Table 4.1). The differences in BOD levels in the stream and wetland were insignificant ($p = 0.15$). A study by Usharani *et al.* (2010) reported stream BOD mean value of 9.5 mg/l, which is not very far off from stream water BOD results in this study. BOD in the stream was slightly above the acceptable limit of 5 mg/l according to WHO guidelines for drinking water (WHO, 2004). In the wetland, BOD decreased from upstream to midstream then increased until the water reached the stream. ANOVA with Post Hoc Tukey's HSD indicated that the BOD levels midstream of the wetland were significantly lower than what was obtained in the stream (*p* = 0.007). The observed BOD at the outlet of the wetland and stream might indicate the presence of biodegradable materials like decaying plant litter and animal waste which might have been washed downstream of the wetland (Figure 4.4). These organic materials require oxygen for them to be biodegraded, hence the high BOD values observed downstream and in the stream.

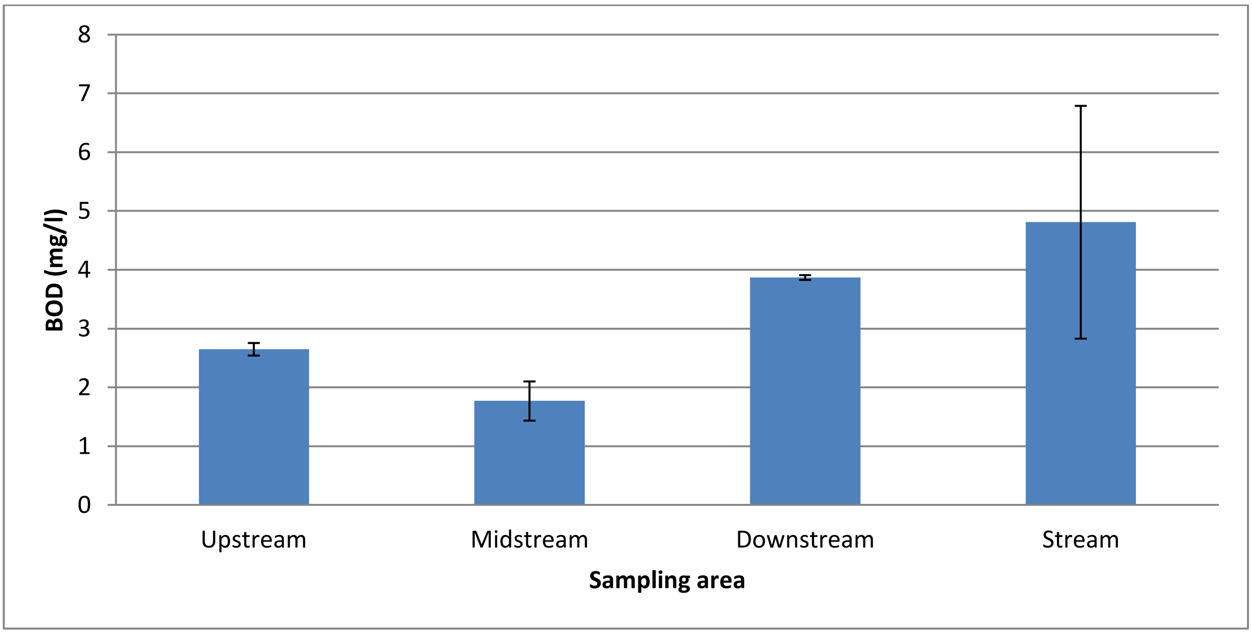


Figure 4.4: BOD variation from upstream Khubelu wetland down to Khubelu stream

The observed high BOD might also be an indication that the Khubelu stream is not able to self-cleanse due to high organic load. A similar explanation has been given by de Matos *et al.* (2014). In the light of the predicted warmer temperatures where minimum temperatures are expected to get higher than the current maximum temperatures in southern Africa (Kusangaya *et al.,* 2014), there will be less dissolved oxygen in these waters and an increased BOD in the Khubelu stream.

4.2.6 Chemical oxygen demand

Values for chemical oxygen demand in the wetland ranged from 48 to 140 mg/l and from 10 to 55 mg/l in the stream (Table 4.1), with the wetland minimum being four times the WHO limit of 10 mg/l (*p* = 0.00). Chemical oxygen demand showed an increasing trend from a mean of 84.39 to 215.5 mg/l from upstream to downstream of the wetland (Figure 4.5), then decreased to 35.38 mg/l in the stream. These differences were all significant (*p* <0.01). The COD values were higher than the BOD values. High COD values could be attributed to other forms of oxidizable pollutants in the wetland that cannot be oxidised biologically. Chemical oxygen demand accounts for all types of non-biodegradable but oxidizable pollutants (carbonaceous and nitrogenous), which constitute part of organic material (Zheng *et al.,* 2013; Oyem *et al.,* 2014). The chemical breakdown of these pollutants would have contributed to the high COD observed in this study. This is supported by findings of a study by Kadlec (2012) where removal of nitrates from marshes involved an increase in demand for oxygen by micro-organisms. In this study, COD had a moderate correlation with NO_3 (r = 0.572) (Appendix VIII), which further substantiates the chemical oxidation of the nitrates and its contribution towards COD in water bodies.

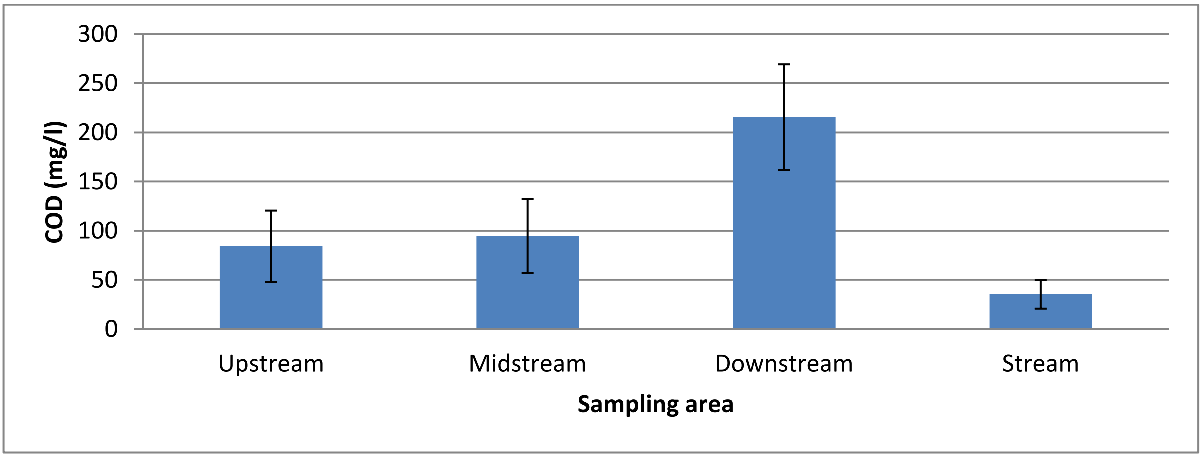


Figure 4.5: COD variation from upstream Khubelu wetland down to Khubelu stream

Projected changes that point to extreme rise in temperature and declining precipitation could lead to higher demand for oxygen for various decomposition processes as most chemical reactions progress faster with higher temperatures. Similar observations have been made by Tahershamsi *et al. (*2009) where they reported higher COD values in dry seasons than in other seasons. Should this occur, the Khubelu stream would face high DO depletion, associated with anoxic conditions. In the absence of oxygen, aerobic processes like nitrification would be compromised, adding to nitrate pollution of the water.

4.2.7 Major cations

Sodium concentrations varied from 5.01 mg/l to 13.25 mg/l in the wetland and from 3.17 mg/l to 6.23 mg/l in the stream (Table 4.1), these being below the WHO limit of 200 mg/l. The findings of this study were supported by observations by Kamal *et al.* (2007) where sodium ranged between 16 and 34.7 mg/l in the Mouri River, Khulna Bangladesh. However, as seen in Figure 4.6, Na showed an increasing trend in concentration from upstream to the wetland outlet, decreasing again to a mean of 5.14 mg/l in the stream. This pattern shows a possibility of Na^+ being retained in the wetland. However, the observed levels would not cause any water pollution problems in terms of salinisation.

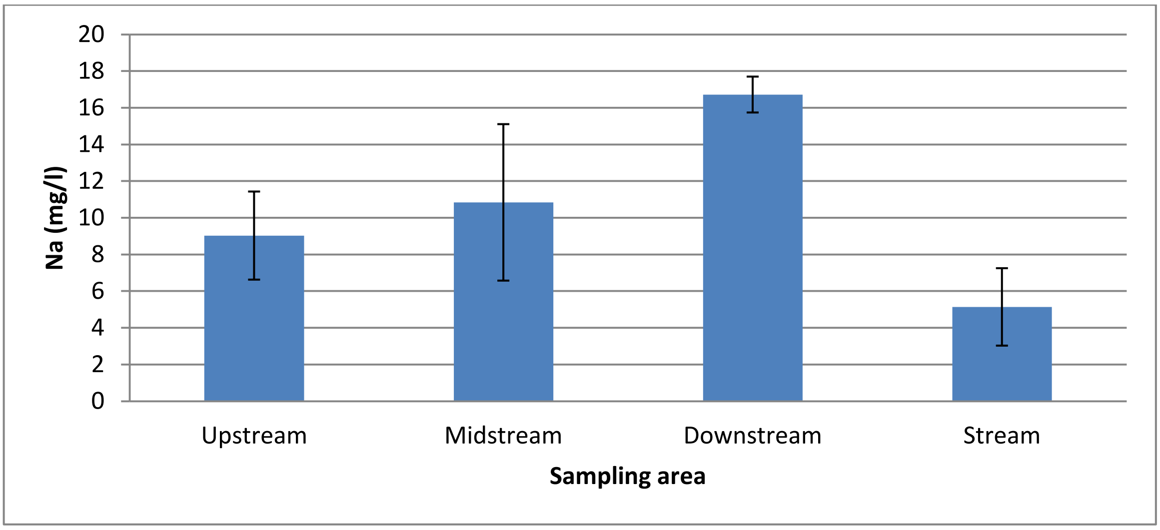


Figure 4.6: Variation of Na from upstream Khubelu wetland down to Khubelu stream

The observed Ca^{2+} concentration ranged from 5.42 mg/l to 7.55 mg/l in the wetland and ranged from 8.20 mg/l to 16.80 mg/l in the stream water (Table 4.1). Calcium concentration was higher in the stream than in the wetland (Figure 4.7). These levels were also below the 200 mg/l limit that is recommended by the WHO. Though Ca is naturally present in water bodies (Potasznik & Szymczyk, 2015), land use, plant cover (Grochowska & Tandyrak, 2009) and climatic variations could affect its concentration. Studies by Schot and Wassen (1993) determined that Ca is usually higher in groundwater that is recharged by water infiltrated from wetlands as compared to those recharged by surface water. The geology of the wetland area could also influence concentration of calcium. This may explain the higher Ca values in the Khubelu stream compared to the wetland.

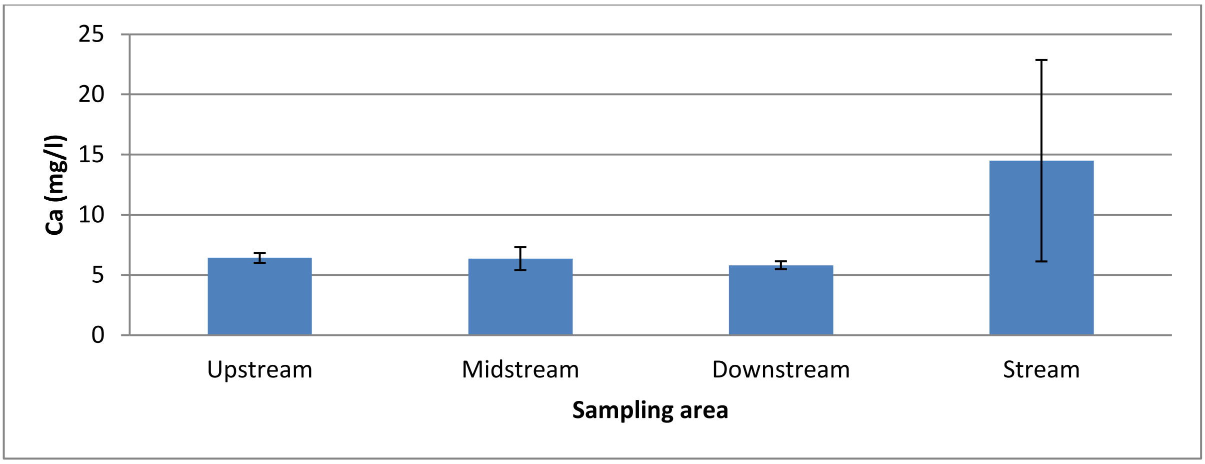


Figure 4.7: Ca variations from upstream Khubelu wetland down to Khubelu stream

Calcium showed a strong positive correlation with temperature (r = 0.759) and TDS (r = 0.753). A strong correlation with temperature might imply that the predicted high temperatures might increase Ca concentration in water bodies further, due to evaporation. This could be the case since temperature perhaps increases the dissolution rate of Ca in water. Jyoti and Akhtar (2007) have also associated low solubility of Ca with an increase in temperature. Its correlation with TDS might also highlight its role in EC values observed.

In the wetland, Mg content varied from 8.36 to 10.75 mg/l whereas the stream recorded a range of 7.29 mg/l to 11.39 mg/l, with a mean of 9.41 and 8.13 mg/l for the wetland and stream respectively (Table 4.1). No discernible trend was followed by Mg concentration down the wetland (Figure 4.8). However, the concentration increased noticeably from 8.77 mg/l in the wetland outlet to 12.43 mg/l in the stream. Magnesium levels were below the WHO limit of 150 mg/l and 250 mg/l for livestock drinking water standards posing no threat to the animals, wetland life and water quality. With the predicted increase in temperatures, however, high evaporation rates are anticipated which may leave Mg highly concentrated in the Khubelu stream and wetland. Low precipitation would also not dilute the concentrated cation. With time, if the predicted climatic changes are unremitting, the seemingly low Mg concentration might contribute towards the Khubelu stream salinisation.

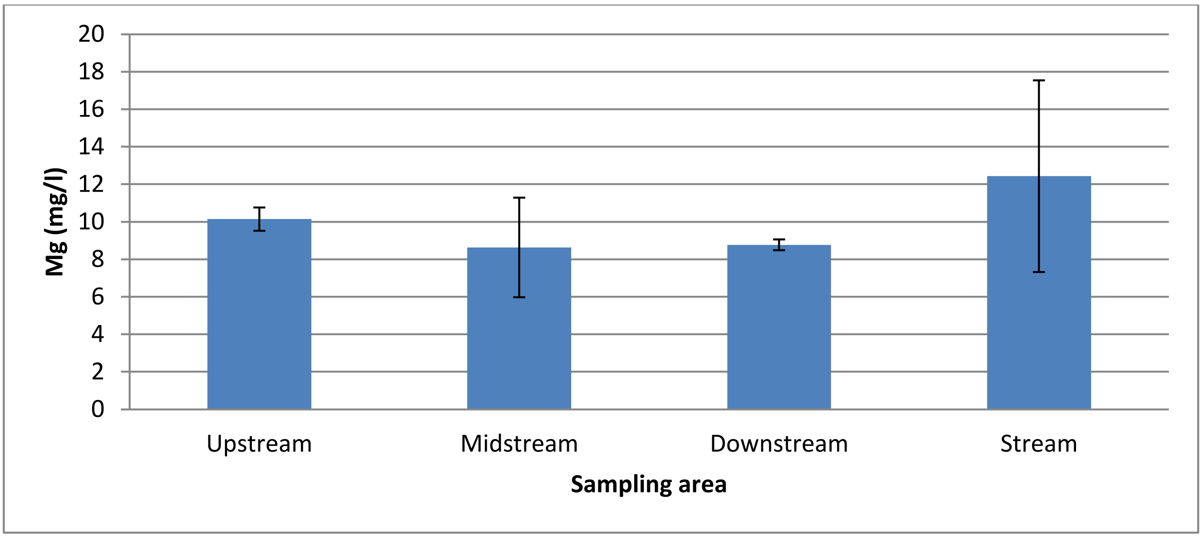


Figure 4.8: Variation of Mg from upstream Khubelu wetland down to Khubelu stream

Potassium concentrations ranged from 0.08 mg/l to the maximum of 4.80 mg/l in the wetland, with the stream showing a minimum of 0.19 and maximum of 1.81 mg/l (Table 4.1). Within the wetland, an increase in K from upstream to downstream was observed with a drastic decline to 0.86 mg/l in the stream (Figure 4.9). In all the sections of the stream and wetland, the 12 mg/l threshold stipulated by the WHO was not reached, which could signify that K pollution might not be a threat in the study area.

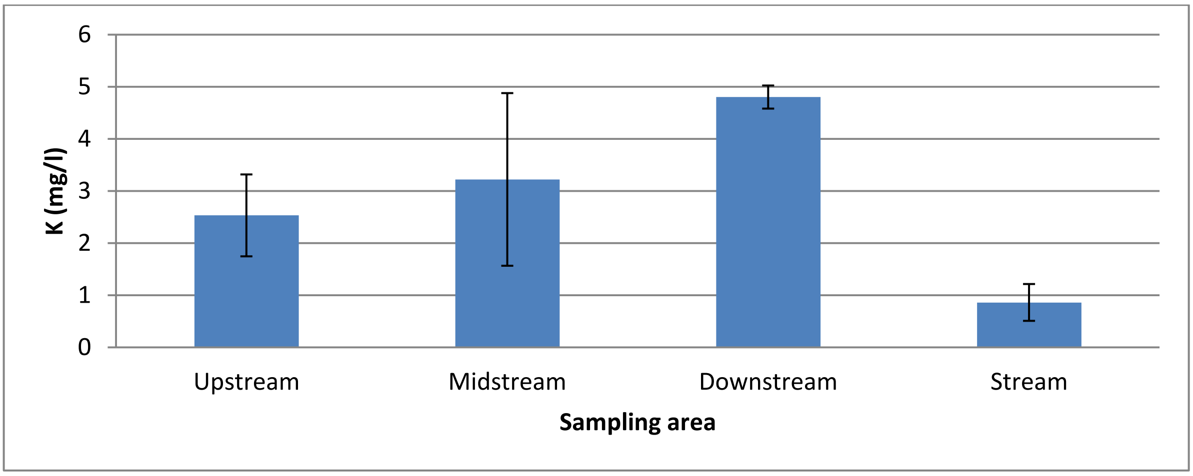


Figure 4.9: Variation of K from upstream Khubelu wetland down to Khubelu stream

Across the wetland, Mg dominated the other cations in terms of concentration, followed by Na and Ca, with K being the least. Ca was the dominant cation in the stream (Figure 4.10), followed by Mg and Na, with K showing the lowest concentration. Magnesium is often lower than Ca (about half in concentration) in other water bodies (Grochowska &

Tandyrak, 2009; Ndungu *et al.,* 2014). The pattern observed in the Khubelu wetland is therefore in tandem with what has been reported in other studies.

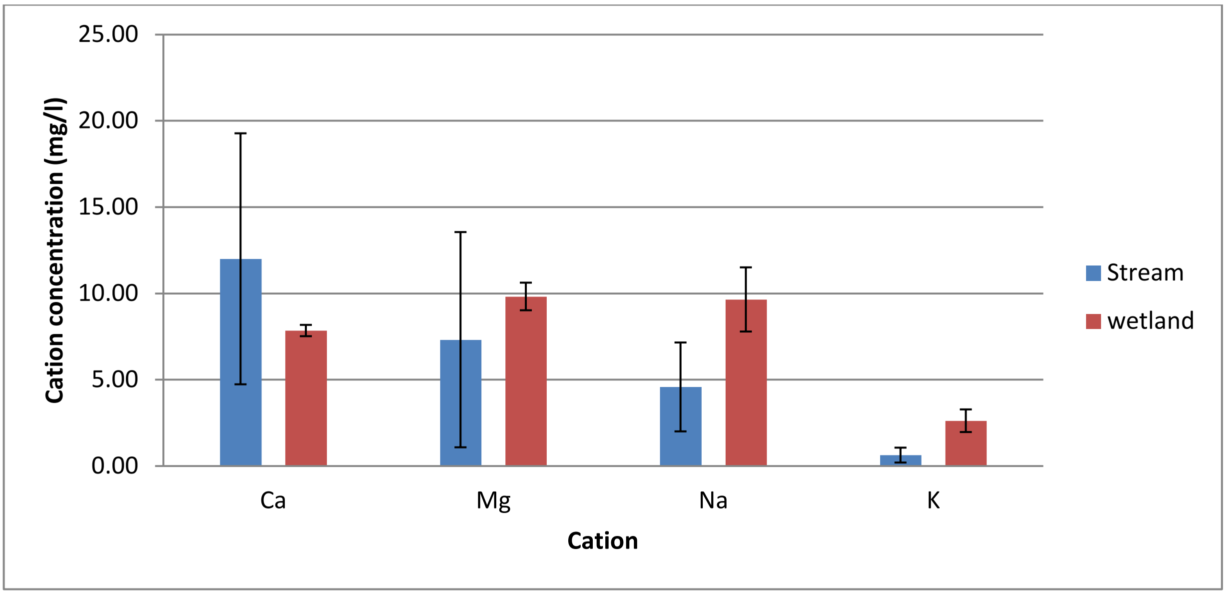


Figure 4.10: Variations in Ca, Mg, Na and K between the wetland and stream

4.2.8 Total dissolved solids

The study revealed a TDS range of 189 mg/l to 463 mg/l in the wetland and 45 mg/l to 314 mg/l in the stream (Table 4.1). Across the wetland, from upstream to downstream, there was no regular pattern in TDS concentration (Figure 4.11) but the highest mean TDS value recorded was 352.13 mg/l at the centre of the wetland. All the recorded TDS values were below the WHO limit of 500 mg/l. The high TDS observed in the study reflects the high EC as well as the low concentrations of cations in the study. The dissolved salts in the water bodies could have originated from dissolution of minerals and desorption of ions from the soils (Butler & Ford, 2018). Another possible source of TDS in the study area might be various activities like saline water ingression from groundwater (Shammi *et al.,* 2019) or soil erosion.

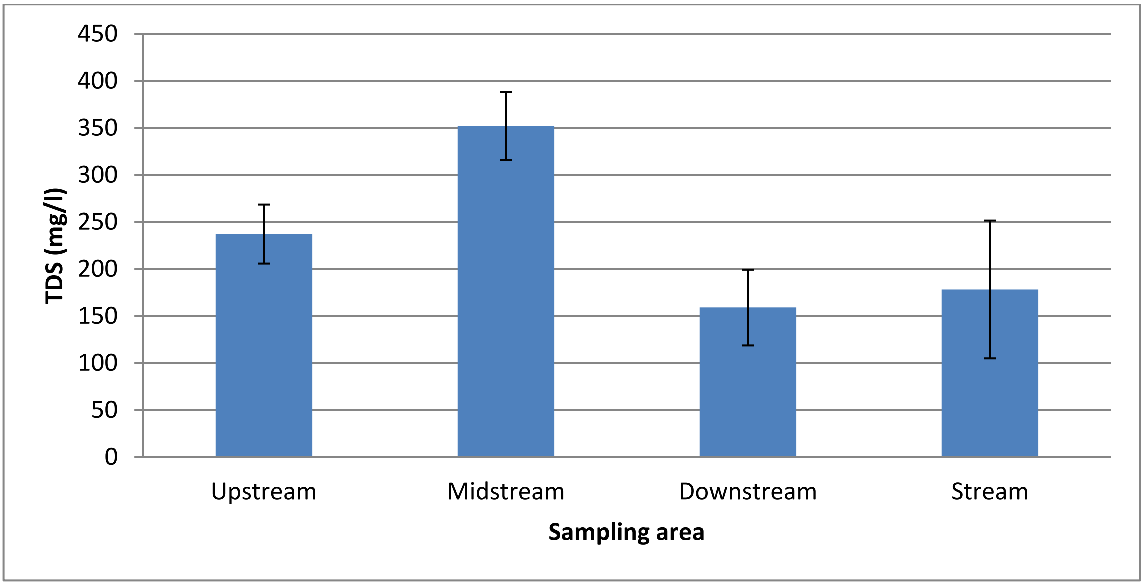


Figure 4.11: Mean concentrations of TDS from upstream Khubelu wetland down to Khubelu stream

4.2.9 Nitrates

The wetland NO_3 concentration varied between 8.16 and 9.96 mg/l, with stream mean ranging from 5.01 mg/l to 13.03 mg/l (Table 4.1). Mean nitrate concentrations in the stream were significantly higher than that in the wetland (p = 0.01). Figure 4.12 shows variation of nitrates across the wetland, where the levels increased from upstream to downstream, decreasing slightly in the stream. The differences in nitrate concentrations across the wetland were however insignificant (p = 0.21). Observed nitrate concentrations were all within WHO limit of 50 mg/l. These values are similar to observations by Alam *et al.* (2013) where a minimum NO_3 concentration of 0.03 mg/l was reported and by Van Metre *et al.* (2016) who reported a NO_3 concentration range of <0.04 to 41.8 mg/l. A decline in nitrates from the wetland into the stream could be associated with utilisation of NO_3 by wetland vegetation, leaving lower amounts in the wetland water to be leached into the stream. Research has shown that N removal from wetlands is governed by the ability of wetland soil to mineralise it, and its assimilation into biomass and nitrification-denitrification processes (Kadlec, 1987; Dent & Cocking, 2017; Thorslund *et al.,* 2017). With the temperature increase that has been predicted, there might be insignificant nitrogen loss through denitrification, threatening the stream with nitrogen loading and eutrophication. Reddy and Patrick (1984); Palta *et al*. (2016) and Palacin-Lizarbe *et al.* (2018) have observed that a decrease in nitrogen removal through denitrification is associated with temperatures below 15ºC and above 30ºC. In the study area, the lowest temperature was 14°C. Prolonged variations in precipitation and temperature might threaten the Khubelu stream with nutrient enrichment which might cause DO depletion and organism stress for those that require aerobic conditions for survival.

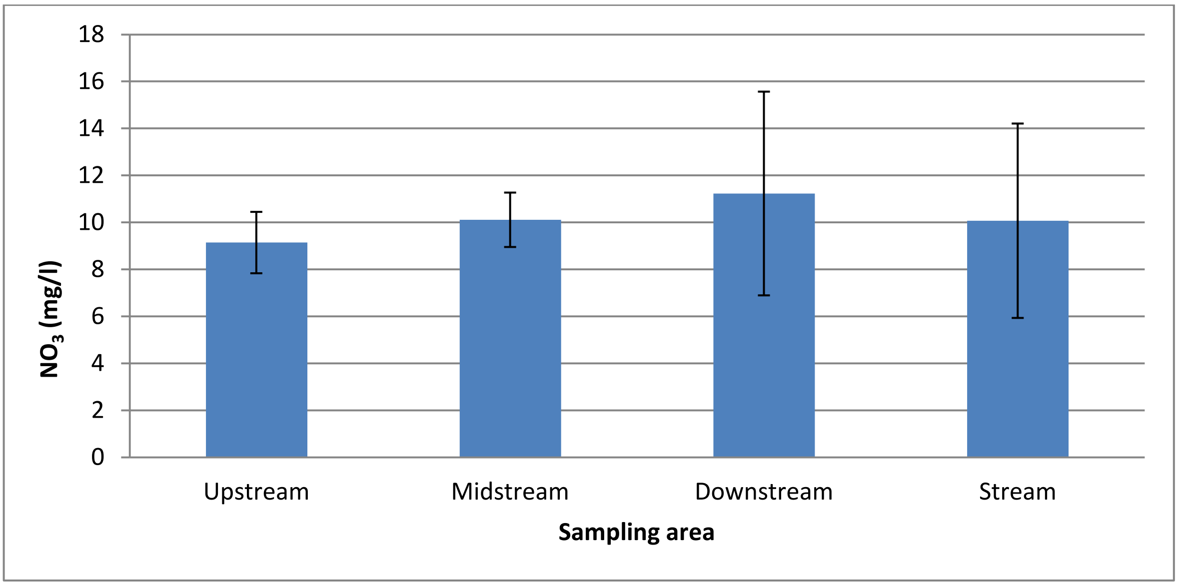


Figure 4.12: Variation of NO_3 from upstream Khubelu wetland down to Khubelu stream

4.2.10 Phosphates

Phosphate levels ranged from 0.17 to 0.61 mg/l in the wetland and from 0.06 mg/l to 1.26 mg/l in the stream (Table 4.1) with significant differences between the wetland and the stream (p = 0.00). There was no regular pattern followed by phosphates concentration in the wetland (Figure 4.13) but the midstream section of the wetland had lower phosphate concentrations compared to the upstream, downstream and the Khubelu stream (Figure 4.13) with ANOVA indicating that these differences were insignificant (p = 0.07). The phosphate levels in both the wetland and stream are above the WHO permissible level of 0.01-0.1 mg/l. There seems to be no phosphate load reduction at the wetland outlet, which may present a threat to the stream water quality through nutrient pollution. These findings conform to those of Li *et al.* (2013) who attributed P release to anoxic conditions. The observed phosphate levels could be associated with direct input by animal waste, and decomposition of plant material (Riddle & Bergstrőm, 2013) into the stream. Animal waste which is usually rich in phosphates might have been washed into the stream from the catchment as a result of animals grazing within the wetland. The other possibility is inability of emergent vegetation to assimilate P (Richardson & Marshall, 1986), thus resulting in its accumulation in the stream. Studies by Jin *et al.* (2006) and Li *et al.* (2013) have associated P release into water with high pH (8 to 10) and anoxic conditions. A high phosphate level in streams is a threat to water bodies as it could cause eutrophication, a phenomenon that results from excessive growth of algae. The stream environment is also threatened due to death of plants that are not able to photosynthesise once an algal mat is formed on the water surface, further causing DO depletion due to decomposition of dead plants. Predicted increase in temperatures could contribute towards algal growth in the stream, further threatening the stream with eutrophication, whereas water shortages caused by projected decrease in precipitation could result in poor development of wetland vegetation.

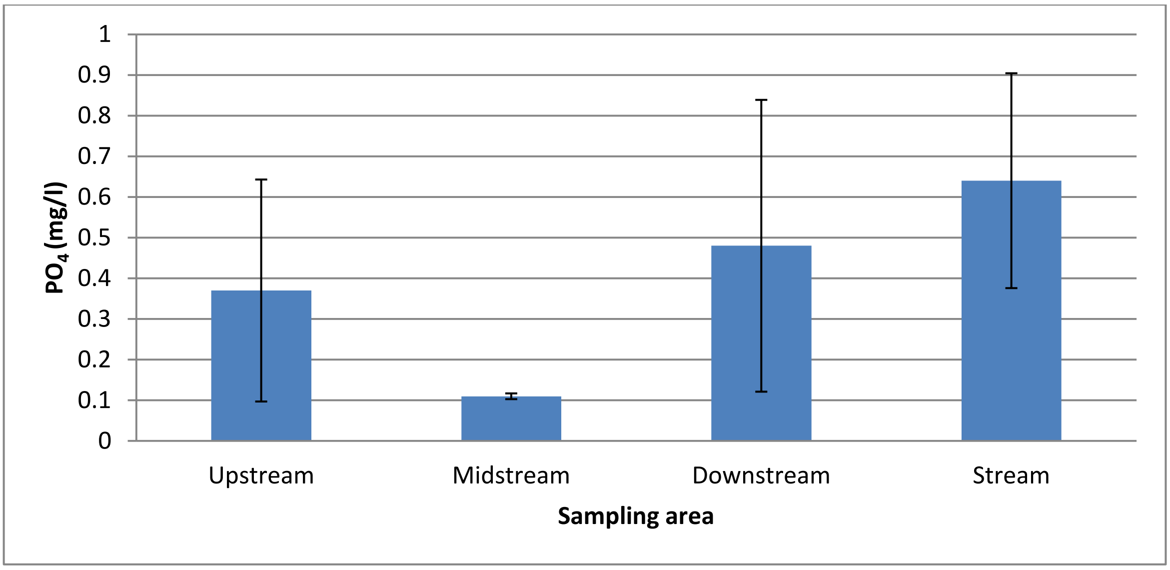


Figure 4.13: Variation of PO_4^{3-} concentrations from upstream Khubelu wetland down to Khubelu stream

4.2.11 Chlorides

Chloride concentration ranged from 35.33 to 68.93 mg/l in the wetland and from 28.86 to 58.00 mg/l in the stream with differences between the means being insignificant (p = 0.8). The chloride concentrations for both the wetland and the stream were way below the WHO limit of 250 mg/l. The mean levels fluctuated from upstream towards the downstream as shown in Figure 4.14 but the differences according to results from ANOVA with Tukey's HSD Post Hoc test applied indicated that the differences observed were insignificant (p = 0.5). Low chlorides, in the range of 3.0 – 4.4 mg/l and 3.7 mg/l were also found in surface water bodies by Meride and Ayenew (2016) and Soylak *et al.* (2002). High concentration of chlorides in natural waters is considered to be an indication of pollution due to soil weathering (Singh *et al.,* 2005). Predicted rising temperatures and declining precipitation would lead to high concentrations of the anion due to evaporation and chemical weathering processes. This would alter plant species composition since some do not survive in saline environments. The EC of the Khubelu water bodies would also increase.

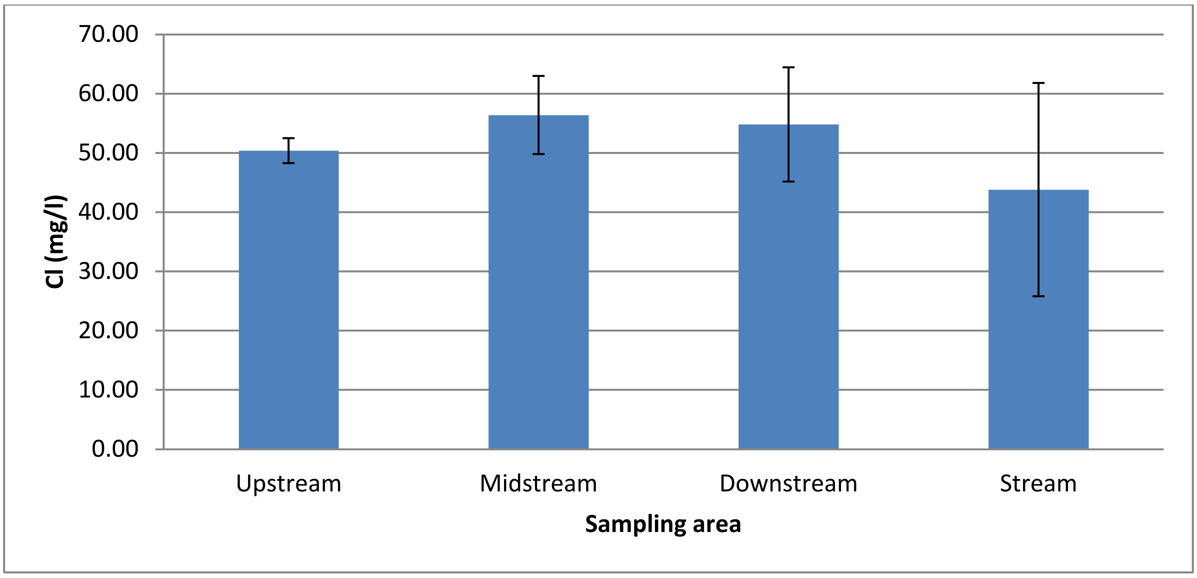


Figure 4.14: Variation of Cl from upstream Khubelu wetland down to Khubelu stream

Analyses of the water quality from the wetland and the stream have shown that these properties vary from one section of the wetland to the other (Figure 4.15) with temperature, Ca, PO_4^{3-} and Mg being higher in the stream than in the wetland. The results also indicate that upstream of the wetland; the mean values of most of the water properties were lower than downstream which may indicate a decline in water quality from upstream to downstream. In this study, the water quality index of the different sections of the wetland and the stream was also determined, and is shared below.

4.3 Water Quality Index of the Khubelu wetland and the stream

Water Quality Index (WQI) is a tool that communicates information regarding water quality to all water users, policy and decision makers using simple terms like excellent, good, poor or very poor. The weighted Arithmetic Mean index was used for determination of the stream and wetland WQI. The classification used to determine whether the water in the stream and wetland was of good quality is that of Mishra and Patel (2001) presented in Table 4.2. Details of the calculation of water quality in the samples are presented in Tables 4.3 to 4.7. For water quality standards with a range, the highest value was used in the calculation, for example, pH ranges between 6.5 and 8.5 and 8.5 was utilised for calculation of quality rating ($V_{standard}$) of pH.

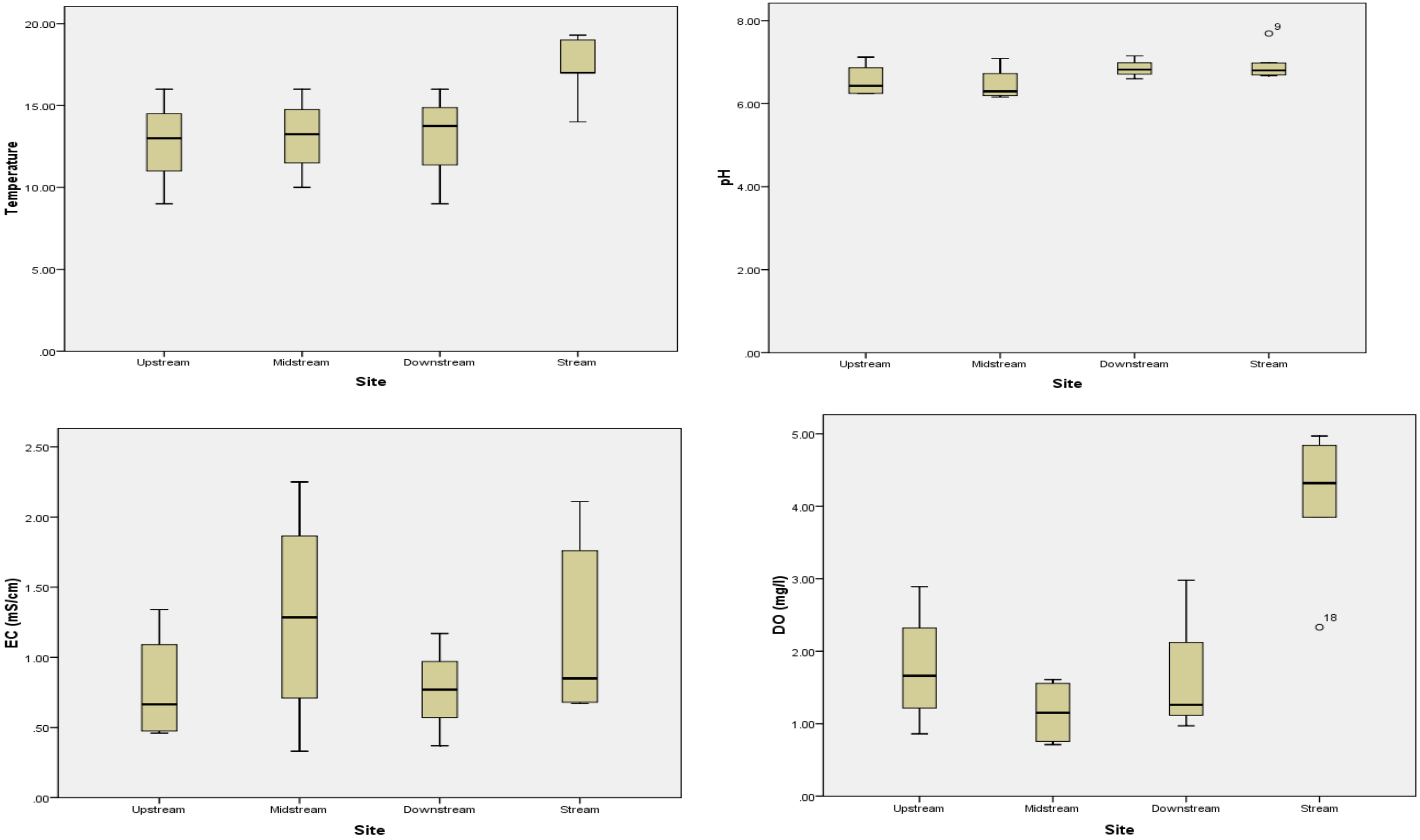


Figure 4.15: Box plots showing spatial variations, and descriptive statistics of water properties upstream, midstream and downstream of the Khubelu wetland as well as the Khubelu stream.

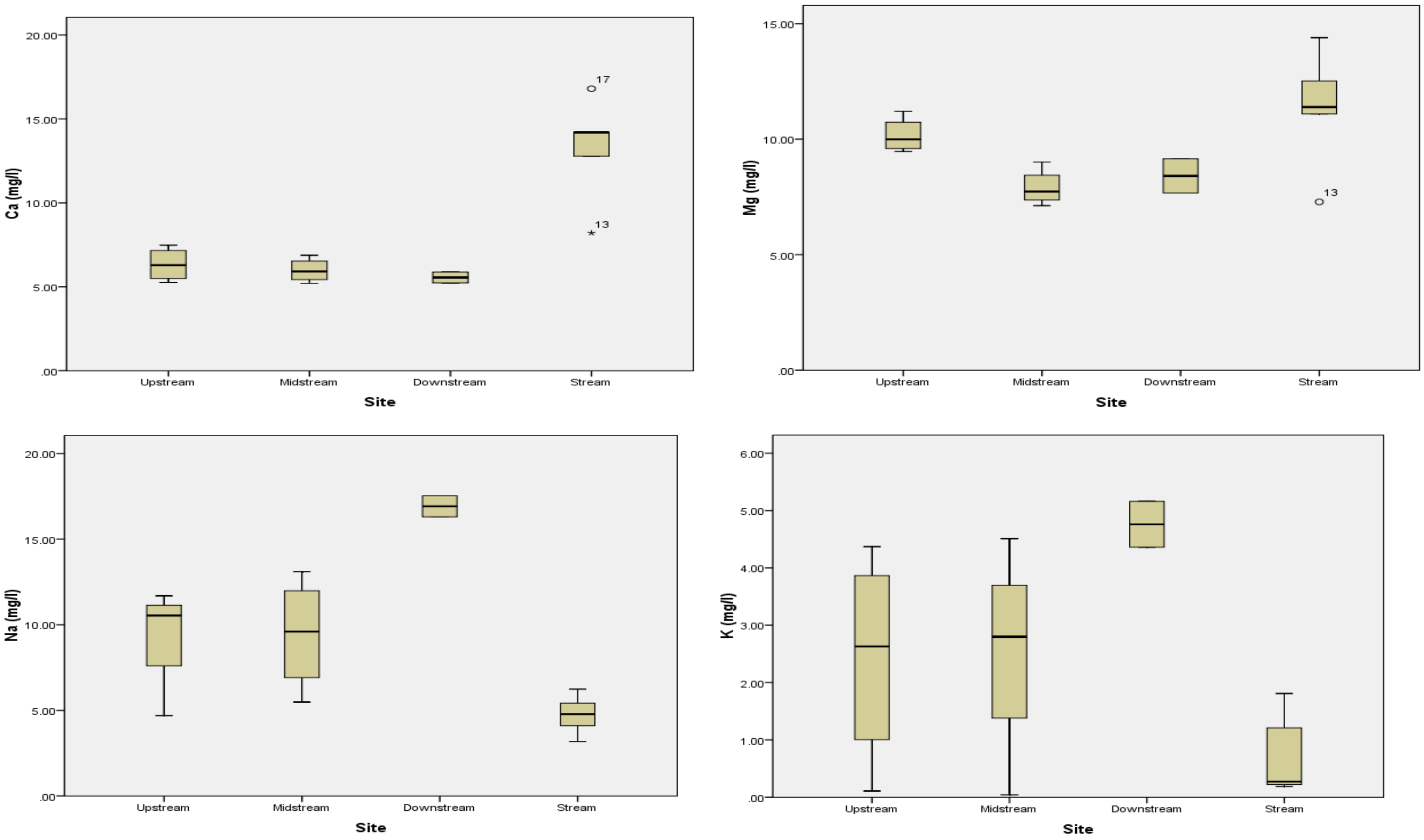


Figure 4.15: Box plots showing spatial variations, and descriptive statistics of water properties upstream, midstream and downstream of the Khubelu wetland as well as the Khubelu stream (cont'd).

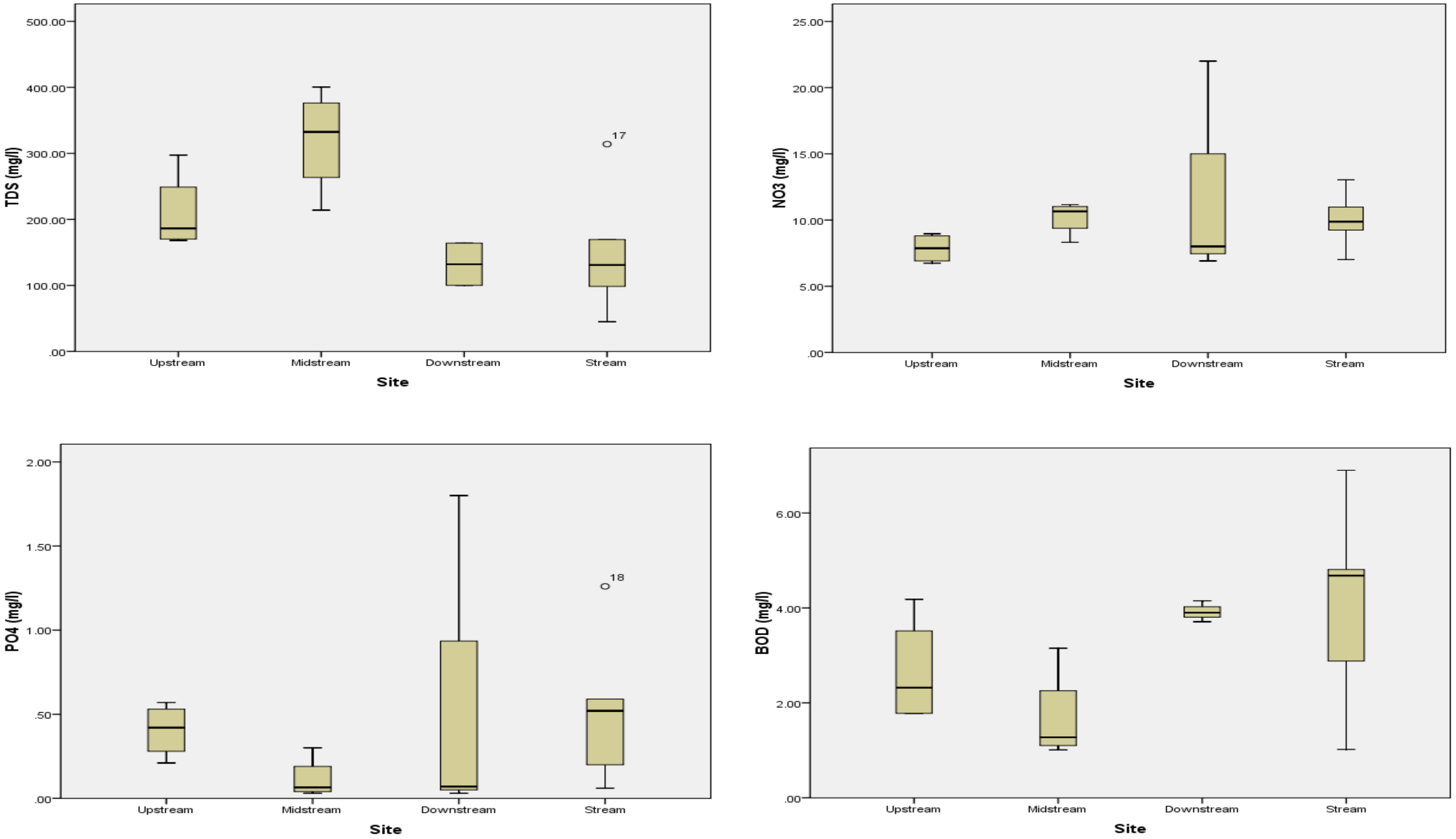


Figure 4.15: Box plots showing spatial variations, and descriptive statistics of water properties upstream, midstream and downstream of the Khubelu wetland as well as the Khubelu stream (cont'd).

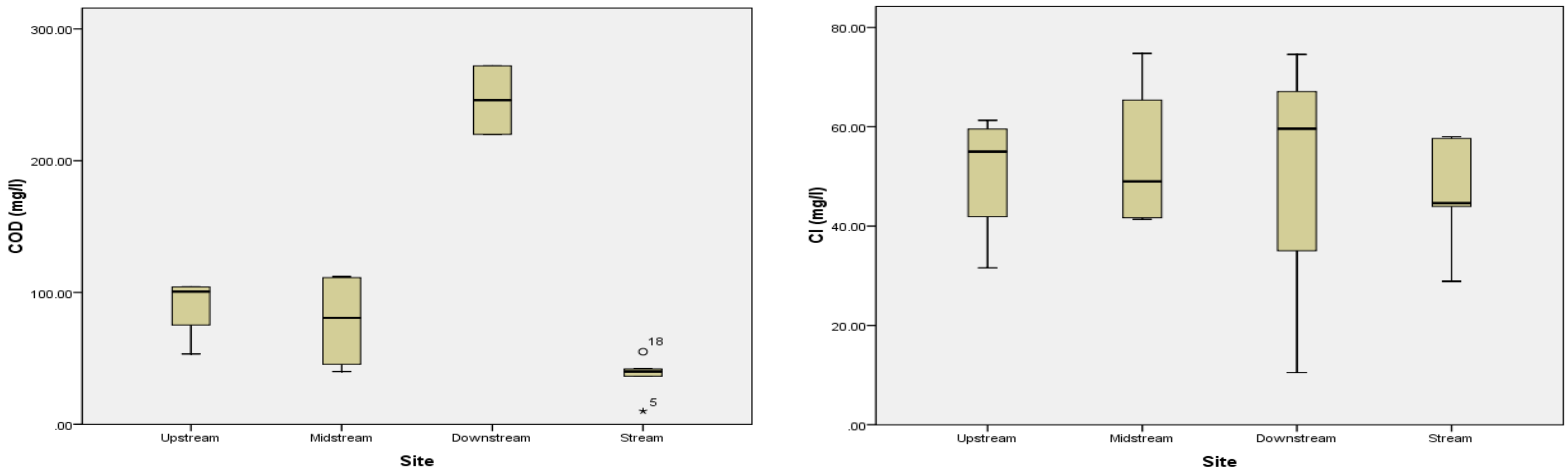


Figure 4.15: Box plots showing spatial variations, and descriptive statistics of water properties upstream, midstream and downstream of the Khubelu wetland as well as the Khubelu stream.

Table 4.2: Classification of WQI values for human consumption

Water Quality Index level	**Description**	**Grading**
0-25	Excellent	A
26-50	Good	B
51-75	Poor	C
76-100	Very poor	D
> 100	Unsuitable for drinking	E

(Adapted from Mishra & Patel, 2001)

Values for WQI within the wetland showed a fluctuating trend in water quality from upstream to downstream of the wetland where WQI values changed from 93 (very poor) upstream to 61 (poor) midstream, and then drops to 90 (very poor) downstream and finally 107.58 (unsuitable for drinking) in the stream (Tables 4.3 – 4.7). The overall WQI for the wetland was 93 and classified as very poor with a D grading. However, the quality in the wetland was better than that in the stream which was classified as unsuitable for drinking (Grade E according to Mishra and Patel (2001); see Table 4.2). Variation of water quality along the wetland may signify some external sources of pollutants from midstream of the Khubelu wetland right through to the stream where the WQI drops to 107.6 (Unsuitable for drinking graded as E). The water quality parameters that might have contributed to the poor water quality in the stream compared to the wetland were EC, Na, K, TDS, and COD as the means of these were significantly higher in the stream compared to the wetland. The amount of DO in the stream was also lower than what was in the wetland and could also have contributed towards the observed poorer water quality in the stream. The receiving rivers downstream may be at risk of pollution from the Khubelu stream because of the poor water quality. Downstream users may also be unable to utilise water from this stream if protective and management programmes are not put in place on time.

Table 4.3: Water Quality Index upstream of the wetland

Parameter	**Observed**	**WHO standards**	**Unit weight (Wi)**	**Quality rating (qi)**	**Wi× qi**
Temp (°C)	12.78	27-30	0.1	42.60	4.26
pH	6.55	6.5-8.5	0.118	-30.00	-3.54
EC (mS/cm)	0.87	1.5	0.004	58.00	0.23
DO (mg/l)	1.74	5	0.2	133.96	26.79
Ca (mg/l)	6.08	200	0.005	3.04	0.02
Na (mg/l)	9.5	200	0.005	4.75	0.02
Mg(mg/l)	9.27	150	0.007	6.18	0.04
K(mg/l)	2.37	12	0.083	19.75	1.64
TDS(mg/l)	264.1	500	0.002	52.82	0.11
NO_3(mg/l)	8.19	50	0.02	16.38	0.33
PO_4 (mg/l)	0.35	0.01-0.1	0.1	350.00	35.00
BOD (mg/l)	2.58	5	0.2	51.60	10.32
COD (mg/l)	92.25	10	0.009	922.50	8.30
Cl(mg/l)	51.43	250	0.004	20.57	0.08
			0.857	1609.55	79.34
$\boldsymbol{WQI = \frac{\sum qiWi}{\sum Wi}}$ **= 92.58**					

Table 4.4: Water Quality Index midstream of Khubelu wetland

Parameter	**Observed**	**WHO standards**	**Unit weight (Wi)**	**Quality rating (qi)**	**Wi× qi**
Temp (°C)	13.08	27-30	0.1	43.60	4.36
pH	6.43	6.5-8.5	0.118	-38.00	-4.48
EC (mS/cm)	1.26	1.5	0.004	84.00	0.34
DO (mg/l)	1.05	5	0.2	141.15	28.23
Ca (mg/l)	6.38	200	0.005	3.19	0.02
Na (mg/l)	9.8	200	0.005	4.90	0.02
Mg(mg/l)	8.68	150	0.007	5.79	0.04
K(mg/l)	3.17	12	0.083	26.42	2.19
TDS(mg/l)	332.33	500	0.002	66.47	0.13
NO_3(mg/l)	9.63	50	0.02	19.26	0.39
PO_4 (mg/l)	0.1	0.01-0.1	0.1	100.00	10.00
BOD (mg/l)	2.01	5	0.2	40.20	8.04
COD (mg/l)	82.25	10	0.009	822.50	7.40
Cl(mg/l)	55.25	250	0.004	22.10	0.09
			0.857	1297.97	52.40
$\boldsymbol{WQI} = \frac{\sum qiWi}{\sum Wi}$ = **61.15**					

Table 4.5: Water Quality Index downstream of Khubelu wetland

Parameter	**Observed values**	**WHO standards**	**Unit weight (Wi)**	**Quality rating (qi)**	**Wi× qi**
Temp (°C)	13.25	27-30	0.1	44.17	4.42
pH	6.59	6.5-8.5	0.118	-27.33	-3.23
EC (mS/cm)	1.3	1.5	0.004	86.67	0.35
DO (mg/l)	1.11	5	0.2	140.52	28.10
Ca (mg/l)	6.53	200	0.005	3.27	0.02
Na (mg/l)	12.8	200	0.005	6.40	0.03
Mg(mg/l)	8.77	150	0.007	5.85	0.04
K(mg/l)	4.51	12	0.083	37.58	3.12
TDS(mg/l)	330.98	500	0.002	66.20	0.13
NO_3(mg/l)	9.45	50	0.02	18.90	0.38
PO_4 (mg/l)	0.24	0.01-0.1	0.1	240.00	24.00
BOD (mg/l)	2.93	5	0.2	58.60	11.72
COD (mg/l)	132.78	10	0.009	1327.80	11.95
Cl(mg/l)	56.1	250	0.004	22.44	0.09
			0.857	1986.89	76.70
$\boldsymbol{WQI = \frac{\sum qiWi}{\sum Wi}}$ **= 89.50**					

Table 4.6: Water Quality Index for the wetland

Parameter	**Observed values (Mean)**	**WHO standards**	**Unit weight (Wi)**	**Quality rating (qi)**	**Wi× qi**
Temp (°C)	13.03	27-30	0.10	43.43	4.83
pH	6.59	6.5-8.5	**0.118**	-27.33	-3.23
EC (mS/cm)	0.75	1.5	0.004	50.00	0.20
DO (mg/l)	1.43	5	0.200	137.19	27.44
Ca (mg/l)	6.24	200	0.005	3.12	0.02
Na (mg/l)	10.69	200	0.005	5.35	0.03
Mg(mg/l)	9.41	150	0.007	6.27	0.04
K(mg/l)	2.96	12	0.083	24.67	2.05
TDS(mg/l)	277.8	500	0.002	55.56	0.11
NO_3(mg/l)	8.76	50	0.020	17.52	0.35
PO_4 (mg/l)	0.33	0.01-0.1	0.100	330.00	33.00
BOD (mg/l)	2.51	5.00	0.200	50.20	10.04
COD (mg/l)	108.4	10.00	0.009	1084.00	9.76
Cl(mg/l)	52.38	250.00	0.004	20.95	0.08
			0.86	1757.49	**79.89**
$\boldsymbol{WQI = \frac{\sum qiWi}{\sum Wi} = 93.22}$					

Table 4.7: Water Quality Index for Khubelu stream

Parameter	**Mean observed values (C_i)**	**WHO standards (S_i)**	**Unit weight (W_i)**	**Quality rating (q_i)**	**$W_i \times q_i$**
Temp (°C)	17.2	27- 30	0.100	57.11	5.71
pH	6.9	6.5-8.5	**0.118**	-6.67	-0.79
EC (mS/cm)	1.21	1.50	0.004	80.67	0.32
DO (mg/l)	4.06	5.00	**0.200**	109.79	21.96
Ca (mg/l)	12.44	200.00	0.005	6.22	0.03
Na (mg/l)	4.74	200.00	0.005	2.37	0.01
Mg(mg/l)	8.13	150.00	0.007	5.42	0.04
K(mg/l)	0.74	12.00	0.083	6.17	0.51
TDS(mg/l)	151.6	500.00	0.002	30.32	0.06
NO_3(mg/l)	8.73	50.00	0.020	17.46	0.35
PO_4 (mg/l)	0.53	0.01-0.1	**0.100**	530.00	53.00
BOD (mg/l)	3.33	5.00	**0.200**	66.60	13.32
COD (mg/l)	36.7	10.00	0.009	367.00	3.30
Cl(mg/l)	46.6	250.00	0.004	18.64	0.07
			0.86	1233.99	**92.19**
$WQI = \frac{\sum qiWi}{\sum Wi} =$ **107.58**					

4.4 Possible impacts of changes in climatic conditions on WQI in the study area

With predicted rising temperatures, more evaporation from surface water could be experienced, leaving high concentrations of pollutants and salts in the water. WQI would thus be even poorer, rendering the water unsuitable for consumption, animal drinking and irrigation. Low precipitation, or hydrological drought, would lower stream flows, leading to failure of contaminant dilution. Djabri *et al.* (2014) also observed that groundwater salinity decreased during the rainy season, whereas the dry season experienced evapotranspiration and subsequent high salinity. Precipitation dilutes pollutants, lowering their concentrations. However, excess precipitation would wash away sediments along with storm water, carrying with them nutrients that are attached onto particles. While in the stream, nutrients like nitrogen would be used up by emergent and submerged vegetation, causing excessive growth. Not only will excessive growth of undesirable algae occur but when they die they would create BOD as bacteria utilise DO for decomposition. A study by Weyhenmeyer *et al.* (2004) revealed that other variables that were exceptionally high following floods were Total Organic Carbon and humic substances causing a brown colour in the water body. However, in the same study, conductivity was the only parameter that was exceptionally low after the floods. The difference between impacts during drought and excessive precipitation is that the latter has temporary effects (Rui *et al*., 2018). In general, type and concentration of contaminants in flood water are the determinants of whether there will be dilution or degradation of the receiving water body (Nabelkova *et al.,* 2012).

4.5 Predicted effect of climate change on water quality of Khubelu stream

This section presents results of the modelling of water quality under different climate scenarios. The two climatic variables used in the prediction were precipitation and temperature, whereas water quality parameters assessed and likely to be affected by climate were dissolved oxygen and Biological oxygen demand. WEAP model uses its built-in BOD model for simulation of BOD in the river, and is able to do this using temperature as one of the water quality constituents (Sieber & Huber-Lee, 2005).

Temperature was therefore one of the data inputs. Furthermore, for simulation of DO, BOD has to be one of the inputs. Since the Temperature (data) option was used, temperature for Phapong reach was left blank, while WEAP assigned temperature for the upstream reach. Data availability restricted calibration and validation to one year (using wet season data due to dry Lesotho season) when using NSE calculator and projections to five years. However, the model is less data-sensitive (Ingol-Blanco & McKinney, 2013). Table 4.8 shows the input data into the WEAP Model while the schematic view of the model is presented in Figure 4.16. A Digital Elevation Model (DEM) for the Phapong area where the wetland is found was developed using ArcMap. The DEM model is presented in Figure 4.17

Table 4.8: Data input into the WEAP model

Parameter	**Variables**	**Values used**
	Humidity	(80%)
	Wind speed	(2 m/s)
	Cloudness fraction	(0.7 to 1)
Land use	Kc (Crop coefficient)	1
	Effective precipitation	100%
	Area	0.52 km^2
	BOD intensity	40×10^9 mg/km^2
	DO intensity	(40×10^8 mg/km^2)
Distance marker	Phapong runoff	0.3 km
	Tailflow point	0.5 km
	Stage-flow-width (headflow) (Catchment Runoff)	(0.59,0.63,0.65,2.87) (0.4,0.52,0.55,2.85)

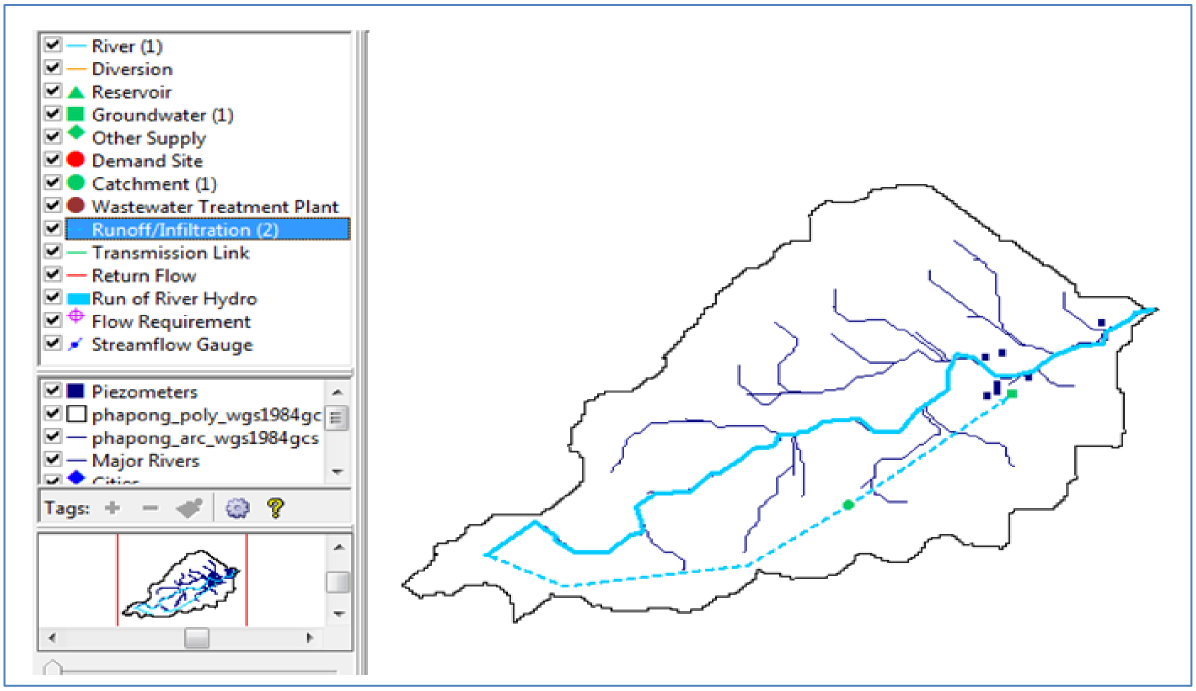


Figure 4.16: Schematic view of the WEAP model

Figure 4.17: Phapong Digital Elevation Model

4.5.1 Modelled climatic variations and implication on Khubelu water quality

The base year, current and future years for predictions were 2006, 2017 and 2018 to 2025 respectively. Lesotho Meteorological Services (LMS) rainfall and temperature data for the year 2007 to 2018 from the study area were used, while water quality for the period April 2018 to March 2019 was used for calibration and validation of the WEAP model respectively. Rainfall Runoff method was chosen, further using Intensity method for the water quality parameters (BOD and DO). The model addressed the "what if" question related to possible change in water quality due to climatic variations, that would alter the catchment and river hydrology (Sieber & Huber-Lee, 2005). Other meteorological variables like humidity, wind speed and cloudiness fraction were from desk top studies and literature. Input data were flow-stage-width (Head flow) relationships of the stream, catchment runoff, and stream length and tail flow. As a means of attaining a proper simulation, trial and errors were run on Flow-Stage-Width wizard below and at head flow of the Phapong catchment. Pollution loads entering the catchment are calculated from head flows and surface water inflows, while complete mixing is assumed by the WEAP model (Equation 4.1). As water quality constituents (non-conservative) move downstream, their decay is calculated, and their amount is linked to the volume of flow.

$$\mathrm{c} = \frac{\mathrm{Qw\ cw} \pm \mathrm{Qr\ cr}}{\mathrm{Qw} + \mathrm{Qr}} \qquad (4.1)$$

Where:

c = new concentration

Q_w = flow of wastewater discharged (m^3/time)

c_w = concentration of pollutant in the wastewater (mg/l)

Qr = flow of receiving water (m^3/time)

cr = concentration of pollutant in the receiving water (mg/l

4.5.1.1 Variations in precipitation

Observed and projected monthly precipitation values (Table 4.9) were used in order to determine how BOD levels would vary in the face of changing precipitation conditions.

Projected values of precipitation have shown that precipitation (monthly mean) will decrease from December 2019 to November 2020 (declining from 13.6 to 9.72 mm and from 9.65 to 8.57 mm and further to 7.11 mm in April 2020). A decrease was also observed for May of 2019 and May of 2020 from 9.72 to 3.45 mm. However, June, July, August, September, October and November of 2021 are predicted to have higher precipitation increasing from 3.45 to 3.50 mm; 0.61 to 3.06 mm; 1.26 to 6.93 mm; 3.66 to 7.01 mm; 7.15 to 7.53 mm and 14.78 to 18.93 mm respectively (Table 4.11). The projected precipitation is shown in Figure 4.18 below.

Table 4.9: Observed and projected values for precipitation

Month	**Observed**	**Projected**
April	7.34	7.39
May	10.55	8.43
June	4.91	10.96
July	3.93	4.29
August	3.28	3.60
September	2.68	11.26
October	7.23	13.59
November	17.00	17.06
December	13.59	11.69
January	12.60	9.69
February	13.94	9.50
March	12.55	8.87

The observed BOD increased from February to March (Figure 4.19), and this may imply that low precipitation had impacted negatively on the stream, causing low dilution of pollutants and subsequent increase in BOD. Wetland vegetation tends to die off in winter, creating a build-up of organic matter, which, as temperature increases in spring would likely decompose and increase BOD. This agrees with a study by Wen *et al.* (2017) where climatic variations caused a decline in dilution of pollutants. Mimikou *et al*. (2000); Wilby *et al*. (2006) and Whitehead *et al*. (2009) also observed that low flows in river regimes led to high concentration of nutrients, which ultimately caused high BOD. Projections have also shown an increase in BOD in the same period. Biological oxygen demand NSE value from the model calibration was 0.718, whereas for validation it was calculated as 0.76. The BOD calibration and validation results and curve (Figure 4.19 and Figure 4.20) show that the model is accurate since it is close to 1 (AgrimetSoft, 2019). Due to limitation of observed data to one year, data that was used for calibration and validation was also limited to one year (Table 4.10). Figure 4.18 shows projected precipitation for the period 2018 to 2025.

Table 4.10: The evaluation of calibration and validation for DO and BOD

Indicator	Period	Year	NSE value
BOD	Calibration	April to June 2018	0.718
	Validation	February to March 2019	0.76
DO	Calibration	April to June 2018	0.699
	Validation	February to March 2019	0.57

Table 4.11: Projected monthly precipitation (mm) for the period 2018 to 2025

Year	Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec
2018	14.1	13.5	11.6	7.34	10.55	4.19	3.93	3.28	2.69	7.23	17.00	13.59
2019	12.60	13.94	12.55	7.48	9.72	10.91	4.47	3.48	10.83	13.39	17.04	11.36
2020	9.72	9.65	8.57	7.11	3.45	0.12	0.61	1.26	3.66	7.15	14.78	14.28
2021	16.49	15.81	20.08	7.23	3.50	2.00	3.06	6.93	7.01	7.53	18.93	18.38
2022	13.92	14.08	9.58	6.52	0.76	3.88	7.81	0.00	3.16	12.00	16.58	24.44
2023	29.25	15.69	12.94	2.03	0.56	0.03	3.69	2.97	4.90	14.55	10.12	13.47
2024	20.00	15.38	12.48	9.78	6.39	1.47	0.75	8.80	13.36	25.56	14.58	13.86
2025	23.14	14.46	5.51	6.29	1.19	1.41	2.74	0.12	10.54	17.60	25.61	16.71

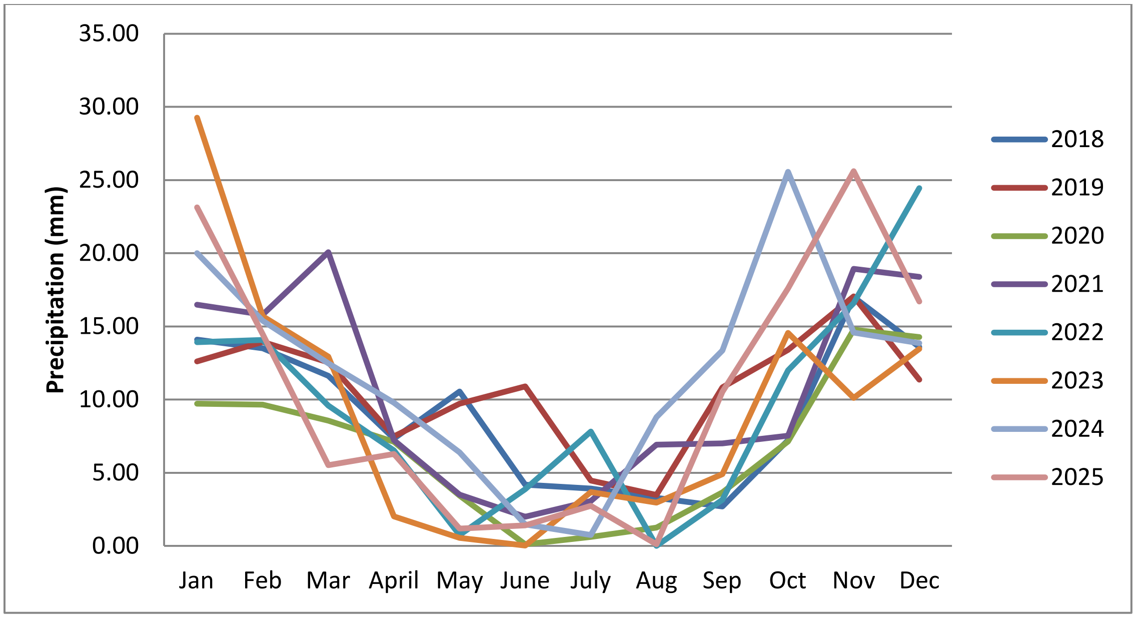
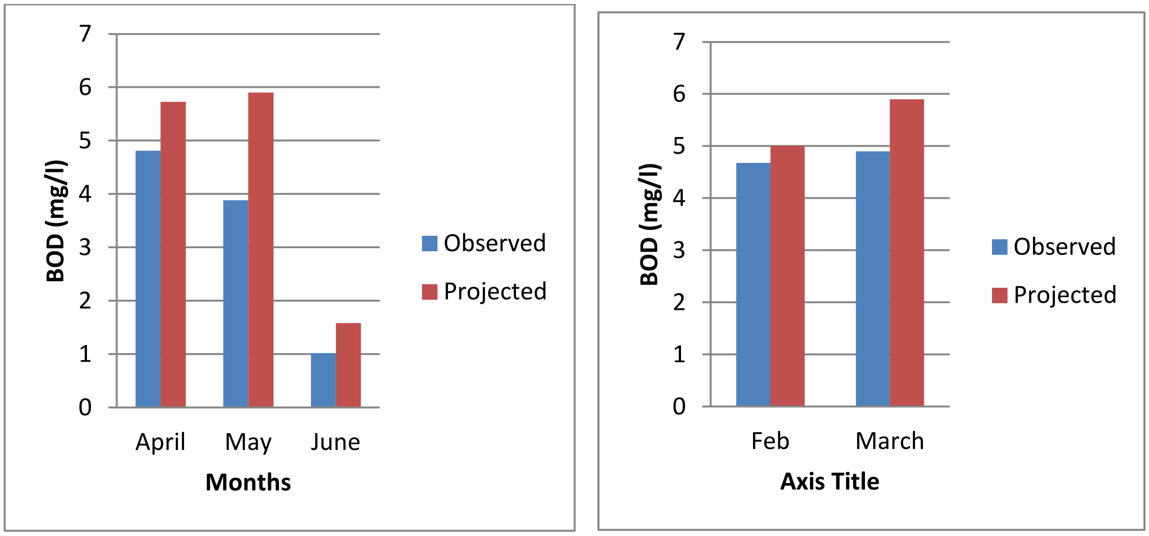


Figure 4.18: Projected precipitation for the years 2018 to 2025



a) 2018 b) 2019

Figure 4.19: Results of BOD (a) calibration and (b) validation

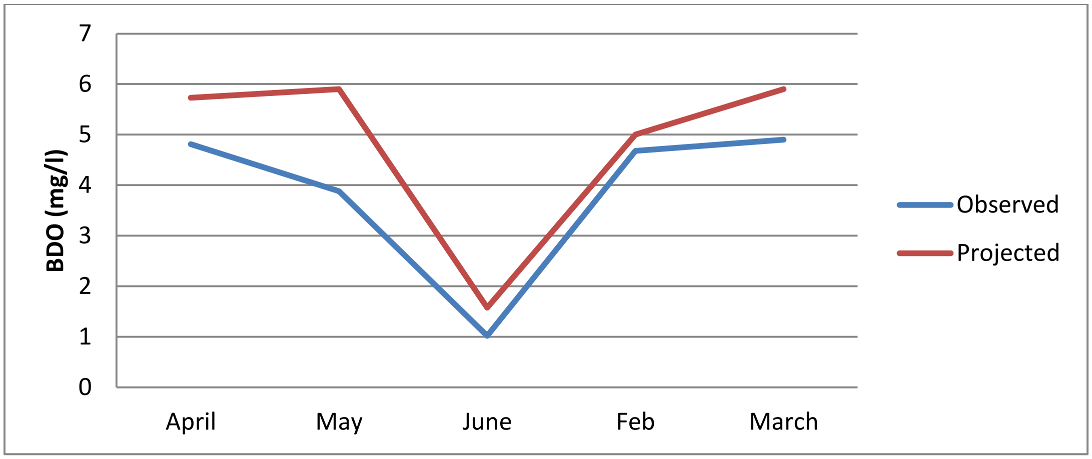
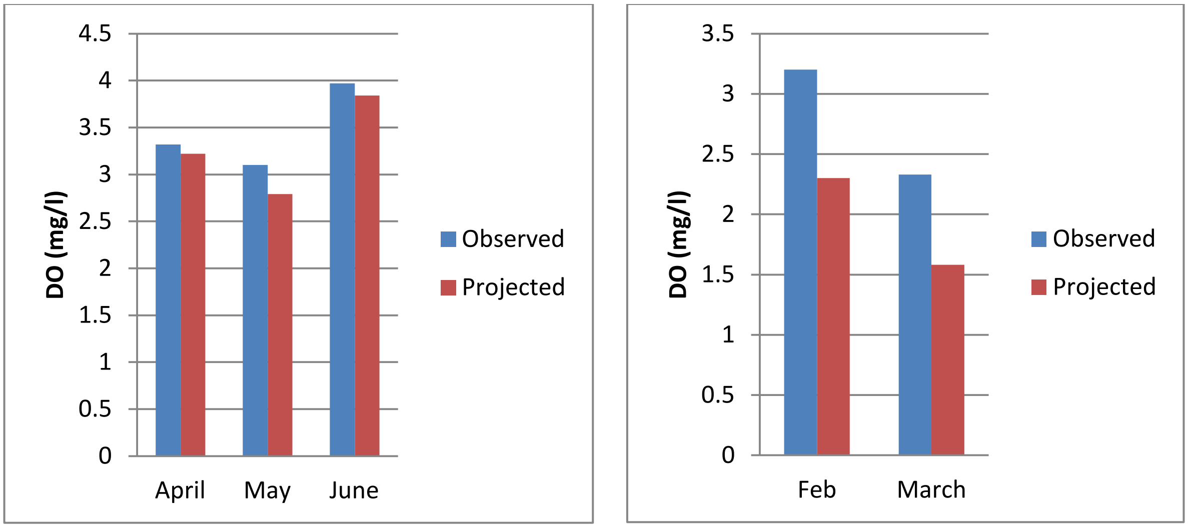


Figure 4.20: Calibration and validation curves for BOD

There was a sharp increase in BOD from February to March of the observation period (Figure 4.19). At this time, there was low precipitation of 13.5 mm and 11.6 mm recorded respectively (Table 4.11). Transportation of organic material along with surface runoff into the stream could have contributed towards high BOD (Susilowati *et al*., 2018). This conforms to studies by Susilowati *et al*. (2018) and Zhao *et al.* (2018) where pollutant dilution was positively and highly correlated with precipitation.

The amount of dissolved oxygen increased from May to June of the study period (Figure 4.21) which coincided with periods of decreasing temperatures. When temperatures are low, bacterial activity is low as well and minimal DO is utilised for organic matter decomposition. DO calibration of the model resulted in NSE value of 0.699 (Table 4.10) and also reflect the accuracy of the predictions.



a) 2018 b) 2019

Figure 4.21: Results of DO (a) calibration and (b) validation

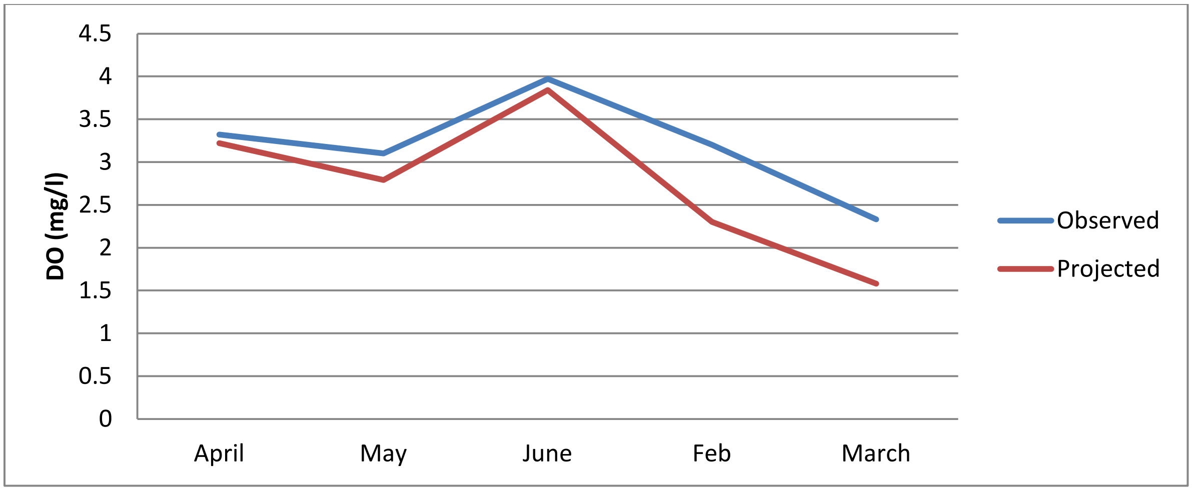


Figure 4.22: Calibration and validation curves for DO

A decline in precipitation was predicted during the rainy months (January to March) of the years 2023 to 2025. The decline ranges from 29.25 mm in January, 2023 to 20.00 mm in January, 2024; from 15.69 in February, 2023 to 15.38 mm in February 2024 then to 14.46 mm in February, 2025; and from 12.94 mm in March, 2023 to 5.51 mm in March, 2025 (Table 4.11).This decline may cause further deterioration in water quality due to poor dilution that causes increases in concentration of pollutants. The predicted DO and BOD are shown in Figure 4.23 below.

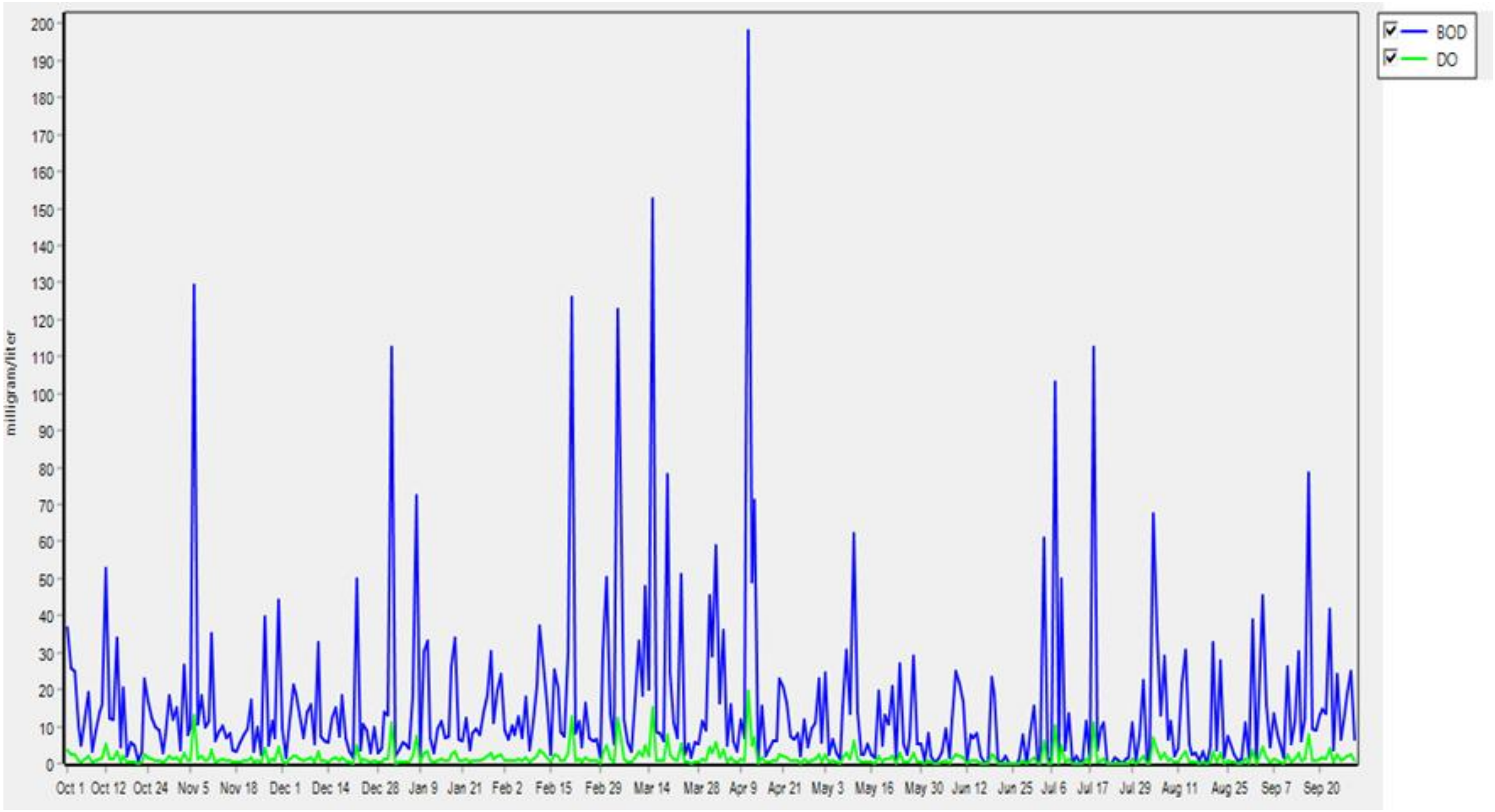


Figure 4.23: Modelled DO and BOD in the Khubelu stream

4.5.1.2 Variations in temperature

Temperature plays the biggest role in decomposition of organic substances, which tend to pollute water bodies. Equation 4.2 shows that oxygen saturation (OS) for each catchment segment is a function of water temperature (T).

$$\mathrm{OS} = 14.54 - (0.39\mathrm{T}) + (0.01T^{2}) \qquad (4.2)$$

It was also pointed out that BOD loads are used for calculation of oxygen concentration, and equation 4.3 shows application of Streeter-Phelps model by WEAP model.

$$\mathrm{O} = \mathrm{OS} - (\mathrm{k_a}/\mathrm{k_a} - \mathrm{k_r})\,(\exp^{-\mathrm{kr}\,(\mathrm{L/U}}))\, - \exp^{-\mathrm{ka}\,(\mathrm{L/U}})\mathrm{BOD}_{\mathrm{IN}} - ((\mathrm{OS} - \mathrm{O_{IN}})\exp^{-\mathrm{kr}\,(\mathrm{L/U}}) \qquad (4.3)$$

Where:

K_d = 0.4 (decomposition rate)

K_a = 0.95 (reaction rate)

K_r = 0.4 (re-aeration rate)

L= reach length (m)

U = velocity of water in the reach

O_{IN} = Oxygen concentration (mg/l) at the top of the reach

BOD_{IN} = concentration of pollutant loading (mg/l) at the top of the reach

BOD removal is given by Equation 4.4 as:

$$BOD = BOD_{IN}(exp^{-kr\mathrm{BOD}\,(\mathrm{L/U}}) \qquad (4.4)$$

Factors like temperature, settling velocity of particles and water depth influence the removal rate (k_{rBOD}) (Chapra, 1997); therefore the removal rate is expressed in equation 4.5 as:

$$krBOD = k_{d20}\,^{(1.047\,(T-20))}V_s/H \qquad (4.5)$$

Where:

T = water temperature (°C)

H = water depth

V_S = settling velocity

K_{d20} is a reference temperature of 20°C

$k_{d20} = 0.3\ (H/8)^{-0.434}$ when H is between 0 and 2.4m ($0 \le H \le 2.4$m)

and:

$K_{d20} = 0.3$ when H is greater than 2.4m ($H > 2.4$ m)

The modelled years have shown an increase in temperature in August (Table 4.12). There was also a remarkable increase in temperature from November 2018 to February 2019 (Table 4.12), which coincided with an increase in BOD during the study period (Figure 4.19). In a study by Bi *et al.* (2018), it was also found that temperature increase leads to an increase in biodegradation. Most microbes involved in this process are mainly aerobic microbes which require oxygen for their activities and consequently for the breakdown of these compounds. Should temperatures keep increasing, OM decomposition rates will increase, and this will cause an increase in BOD. This is the case since high temperatures favour degradation and decomposition activities of the micro-organisms (Mason *et al*., 2007; Conant *et al.,* 2011; Dutta & Dutta, 2016) which may result in the high BOD. With the predicted rise in water temperature due to increase in air temperature between 1.5°C and 4.8°C (Harris & Roach, 2017), phytoplankton growth will further deplete dissolved oxygen, causing high BOD in the stream. Death of these plants will cause further oxygen depletion. The impact of low flows and high temperatures on water quality, especially DO was also observed in studies by Mason *et al.* (2007). Long term increase in temperature due to global warming has been found to cause high decomposition rate of organic material in wetlands (Worrall & Adamson, 2004), leading to the leaching of decomposition products into the nearby streams. In a study by Crawford (2013), there was a positive and high response of BOD to increase in temperature as concentrations of phosphates and nitrate increased in a river. Table 4.12 and Figure 4.24 show how temperature varied from the year 2018 to 2025.

Table 4.12: Temperature differences for the period 2018 to 2025 in the study area

Year	Jan	Feb	March	April	May	June	July	August	Sep	October	Nov	Dec
2018	13.66	13.08	12.49	11.1	8.85	6.00	5.68	6.00	9.73	11.48	10.73	11.90
2019	12.41	12.56	10.55	9.94	6.39	4.26	3.98	4.97	8.12	11.50	11.06	12.54
2020	13.78	13.11	10.70	10.04	6.52	4.12	3.76	5.28	8.5	11.84	12.36	13.46
2021	14.91	14.44	13.06	12.11	7.73	5.09	5.69	7.11	9.35	11.07	12.14	12.92
2022	13.89	13.95	13.07	10.72	7.69	3.59	5.54	7.68	8.99	11.69	12.43	11.69
2023	12.99	12.54	11.99	10.49	7.04	5.43	5.52	5.50	8.69	10.96	10.66	12.03
2024	13.42	13.54	11.82	9.94	7.07	5.06	3.55	7.35	9.51	11.35	11.43	11.23
2025	12.88	12.09	12.36	11.96	8.87	5.54	4.73	5.73	8.66	10.95	13.64	13.37

Figure 4.24 shows temperature differences for the years 2018 to 2025

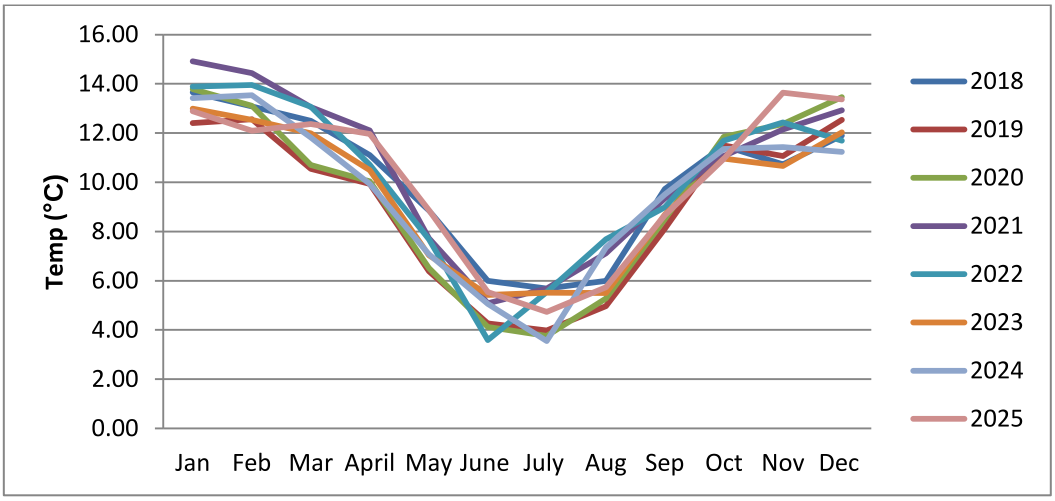


Figure 4.24: Temperature differences for the years 2018 to 2025

A decline in precipitation and an increase in temperature have been suggested by the RCP 8.5 model in the study region. The IPCC RCP 8.5 for 2018-2025 within the WEAP model has shown precipitation fluctuation with a 0.77% change, while temperature might change by 0.16%. A temperature rise of 0.16% was predicted from 2017 to 2025; 0.5% rise for the winter months and 0.2% rise for the summer months within the same period. The WEAP model has indicated that by the year 2025 there will be average BOD change of 2.9% while DO may decrease by 3%. However, an unexpected DO decrease of 1.3% was observed during the autumn months (March to May), and this might be due to expected warm winters. This is in conformity with a study by Hosseini *et al*. (2017), where mean monthly DO concentration decreased by about 1% as a result of climate change.

4.6 Chapter summary

It was determined through this study that 75% of the water quality parameters (pH, EC, Na, Ca, Mg, K, TDS, NO_3, and Cl) of the Khubelu wetland are within the WHO drinking water standards, whereas the remaining 25% (PO_4, BOD and COD) were beyond the WHO permissible standards, with DO being below the recommended value. Expected changes in rainfall and temperatures are likely to influence water quality because of the influence they have on the water physical, chemical and biological properties and processes. The study has illustrated that water in both the Khubelu wetland and Khubelu stream is unsuitable for human consumption. The WEAP model has determined that there might be an increase in BOD and decrease in DO due to predicted increase in temperature and decline in precipitation. This is because of the increase in the rates of reactions and processes which require oxygen for them to progress. Changes in climate are likely to have a significant effect on the quality of water in the Khubelu wetland. Furthermore, scenarios within the model incorporate factors that might change as a result of policy implementation due management of water bodies.

CHAPTER 5

RESULTS AND DISCUSSION: CHARACTERISING KHUBELU WETLAND SOILS

5.1 Introduction

This chapter presents results of the analyses carried out to determine the characteristics of Khubelu wetland soils. The chapter also looks at how the individual soil properties correlate with each other in an endeavour to determine whether they have been affected by anthropogenic activities. The chemical degradation index of the soil is presented at the end of the chapter.

5.2 Wetland soil characteristics

5.2.1 Soil texture

At 0 - 15 cm depth, sampling sites at the Khubelu wetland with the highest amounts of sand, silt and clay were GW2 (72.7%); GW8 (36.0%) and GW7 (22.7%) respectively, whereas sites with the lowest amounts of sand (50.7%), silt (16.0%), and clay (9.3%) were sites GW7 and GW8, GW4 and GW6, and GW2 respectively. At 0 - 15 cm depth, soil samples from sites GW2, GW4, GW5, GW6 and GW9 were classified as sandy loam, whereas samples from sites GW3 and GW8 were classified as loamy soils, with soil samples from site GW7 being sandy clay loam (Figure 5.1).

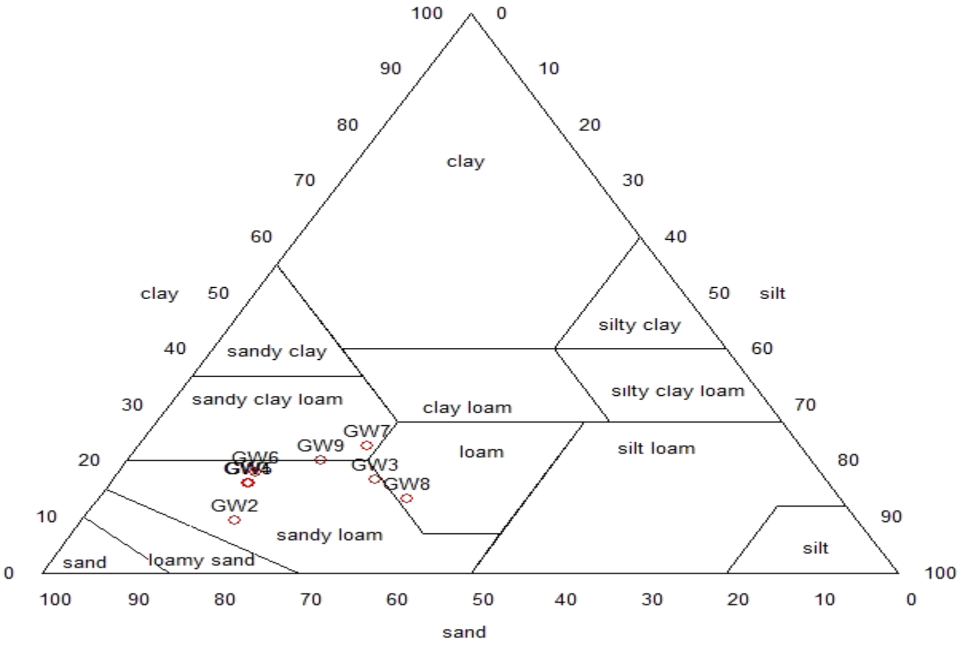


Figure 5.1: Textural classification of soil samples at depth 0 – 15 cm in Khubelu wetland

Across the wetland, the upstream region (GW2, GW3, GW4, and GW7), was dominated by sandy loam with the midstream region (GW6 and GW8) characterised by both sandy loam and loam soils, respectively, whereas downstream (GW5 and GW9), the soil texture was sandy loam.

At a depth of 15 - 30 cm in Khubelu wetland, sand content was highest at site GW3 (74.7%), while silt particles dominated soil samples at site GW6 (32.0%), with clay particles dominating at site GW2 (24.7%). Sand content in the soil samples was lower at GW5 than the other sampling points at 46.7%, while silt was lowest at GW2 (8.7%) and clay at GW3 (13.3%). At a depth of 15 - 30 cm across the upstream section of the wetland, the soil texture was sandy loam, with the midstream region characterised by both loam and sandy loam soils respectively. The two sites downstream the wetland were characterised by loam and sandy loam textures (Figure 5.2). Soils at this depth of the wetland were generally more clayey than the surface soils which is typical of most soil profiles.

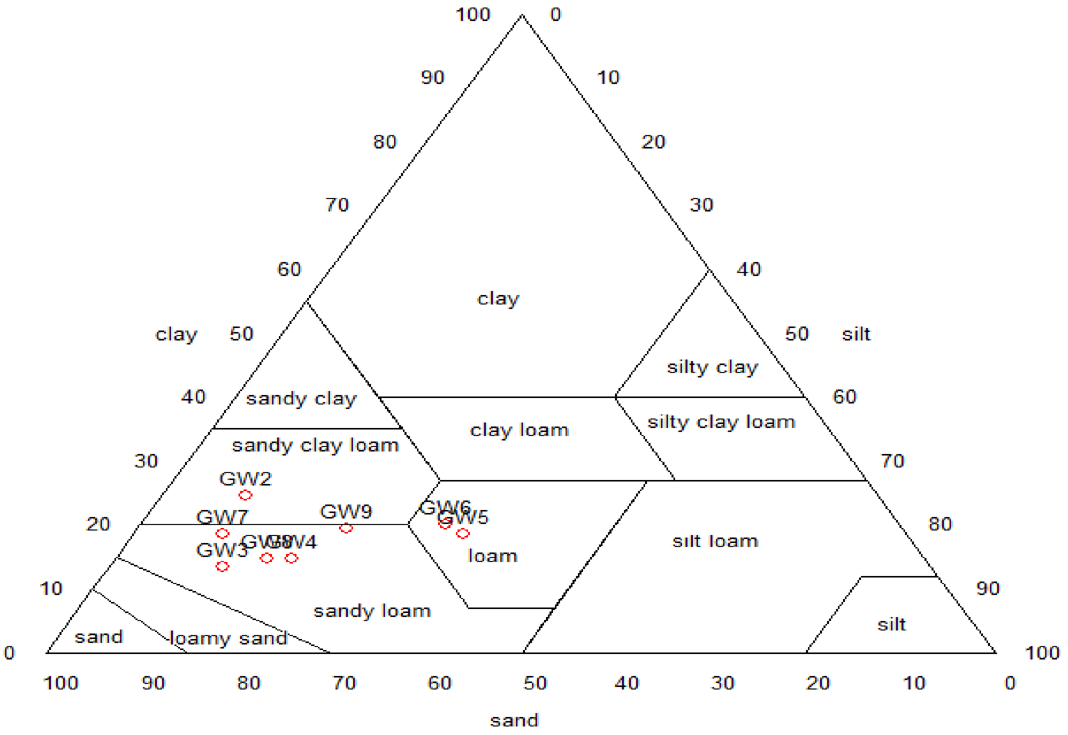


Figure 5.2: Textural classification of soil samples at depth 15 - 30 cm in Khubelu wetland

The soil textural triangle presented in Figure 5.3, shows that within the 30 - 45 cm depth of the Khubelu wetland, sandy soils dominated at site GW7 (80.0%), silt at site GW9 (33.3%), and clay at site GW2 (26.7%). Sand, silt and clay were lowest at sites GW9

(46.0%); GW7 (3.3%) and GW7 (16.7%) respectively. Textural classes at 30 - 45 cm were dominated by loam (4 sites) as in Figure 5.3, followed by sandy clay loam (3 sites) and sandy loam- GW7 (1 site). The textural classification of the soils shows increased quantities of clay and decrease in sand content with depth around the wetland. Loamy soils that dominate the wetland are generally characterised by good water drainage, and high plant-available water (Dymond *et al.,* 2016).

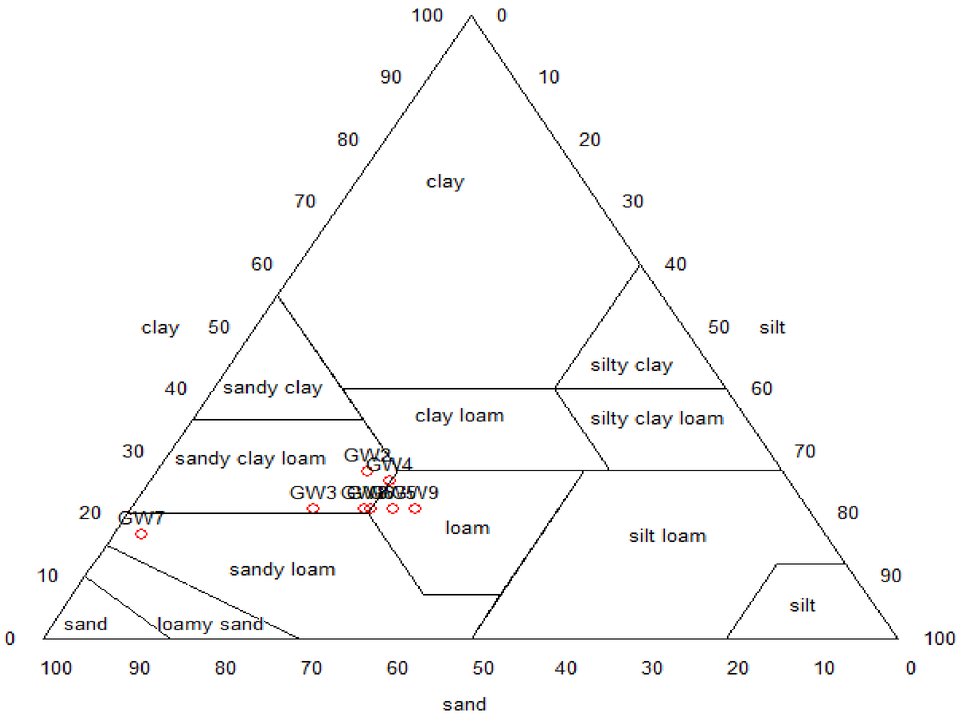


Figure 5.3: Textural triangle showing soil texture at depth of 30 - 45 cm in Khubelu wetland

Phapong wetlands are characterised by basaltic parent material (DWA, 2005; PEMconsult *et al.,* 2008). The parent material could therefore have led to dominance of sand over other soil textures in the wetland (Nnaji *et al.,* 2002; Obasi *et al.,* 2015). With sand dominating the soils, there is a likelihood of nutrient leaching from the wetland, rapid infiltration of water, poor water storage capacity and poor wetland soil fertility. Wetland soils are typically characterised as having high OM content and clay particles, both of which have high cation exchange capacity (Jackson *et al.,* 2014) that enhance removal of cations from water. Some of the samples have a reasonable amount of clay, which may contribute towards the retention of pollutants in the wetland soils, preventing their eventual release to receiving waters downstream. However, this ability is influenced by several other soil properties including its pH.

5.2.2 Wetland soil pH

The highest soil pH value around the wetland was 5.38 and this was recorded within the 0 - 15 cm soil depth at site GW5 whereas the lowest value of 4.79 was recorded at site GW3 within the 30 - 45 cm depth (Figure 5.4). In Lesotho, a similar range was recorded by Rasekoele (2016) in Khalo-La-Lithunya wetlands, with Olaleye (2019) showing a range of 4.69 to 5.44 for wetlands in Buthabuthe and Ha Matela. There was a decrease in soil pH with increasing soil depth at sites GW3, GW5, GW8, GW9, with no clear pattern observed at sites GW2, GW4, GW6 and GW7.

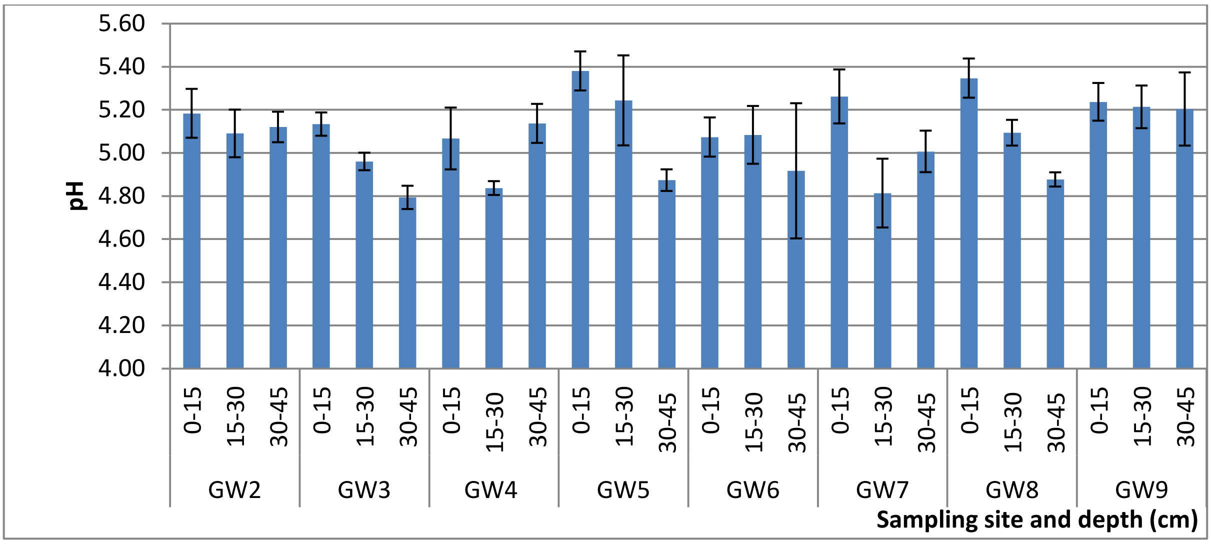


Figure 5.4: Variations of mean soil pH at different depths of the wetland

Results from ANOVA with Tukey's HSD Post Hoc test indicate that there were no differences in pH in soils at the different sites ($p = 0.29$) but mean pH of soils at a depth of 0 – 15cm were significantly higher than that at a depth of 30 – 45 cm ($p = 0.015$). Generally, wetland soils have low soil redox potential conditions due to oxygen depletion (Jackson & Drew, 1984; Greenway *et al.,* 2006) caused by the high degree of saturation of wetland soils. Under these anaerobic wetland conditions, OM becomes the terminal electron acceptor, breaking down into dissolved organic carbon. Microbial metabolism associated with accumulation of acetic acid and butyric acids, which occur under these conditions, could have led to low pH values observed in this study (Ponnamperuma, 1984). Furthermore, glycolysis reduces pH as alcohols and organic acids are formed through anaerobic processes (Mitsch & Gosselink, 2007). These conditions encourage the development of acidic conditions in soils, which may explain the acidic pH observed for the wetland soils.

Across the wetland, pH increased slightly from upstream to downstream at a depth of 0 - 15 cm and 15 - 30 cm, but no specific trend was observed within the 30 - 45 cm soil depth (Figure 5.5). The difference in soil pH from upstream to downstream the wetland was also insignificant (p = 0.07). The pH pattern observed from upstream to downstream of the wetland is consistent with those of a study by Yan *et al.* (2019), where pH was higher downstream and lower at the upstream region.

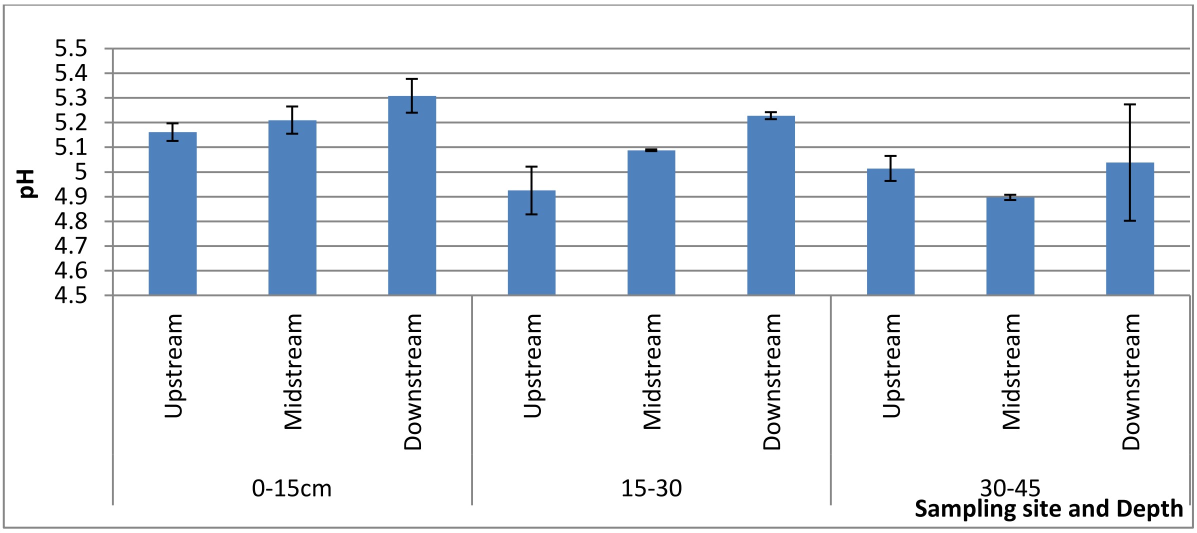


Figure 5.5: Variation of mean soil pH at different depths from upstream to downstream Khubelu wetland

Increase of pH downstream might be an indication that exchangeable bases (especially exchangeable K and Na) have leached with runoffs from the upper regions of the wetland to the lower regions (Tsui *et al*., 2004; Dias & Baptista 2015; Herbert *et al*., 2015; Osujieke *et al.,* 2018). Moreover, wetland inundation that leads to longer retention time of water in the downstream regions of the wetland might have contributed to absorption of the exchangeable bases, resulting in an increase in soil pH downstream (Reid & Mosley, 2015). The high concentration of exchangeable cations in the downstream wetland water justifies this. In general, the pH of the Khubelu wetland soils is acidic and might be unsuitable for plant growth as nutrient (phosphorus, calcium, nitrogen and magnesium) availability is optimum at pH levels of between 6 and 7 (Miah *et al.,* 2005; Jackson *et al.,* 2014). Jackson *et al.* (2014) further state that even microbial activity diminishes when soil pH is low. The low pH at the Khubelu wetland is likely to affect several processes in the wetland including inhibition of denitrification (Šimek *et al.,* 2002; Saleh-Lakha *et al.,* 2009). As a result, the stream water could be threatened with high nitrogen loads, which would ultimately cause high BOD. Other effects of low pH include increased availability of cations such as Al and Mn to a point where they may be toxic to wetland vegetation and organisms (Yang *et al*., 2015; Azam & Gazey, 2018). Excess Aluminium retards plant root growth (Kopittke *et al.,* 2016) and uptake of Ca and Mg, whereas levels of essential plant nutrients such as phosphorus are also lowered (Sumner & Yamada, 2002). Poor vegetation cover resulting from these inefficiencies would jeopardise nutrient and pollution removal by the wetland, ultimately affecting its water purification function. Furthermore, several authors have ascribed high phosphorus sorption to acidic conditions (Stumm & Morgan, 1996; Sato & Comerford 2005; Schoumans, 2015). With the prevailing pH conditions of the Khubelu wetland, it can be construed that the wetland might not be able to retain micronutrients (cations) that are required for plant growth. There might be leaching of nutrients downstream or down the soil profile making these nutrients unavailable for plant growth. These conditions would lead to poor vegetation cover that is highly significant for velocity reduction and uptake of pollutants. The water retention time required for effective functioning of processes like sorption would also be decreased. The Khubelu stream and other water bodies downstream of the wetland would thus be threatened by nutrient pollution. With predicted high temperatures, Dissolved Organic Carbon (DOC) is expected to show a negative impact on soil recovery from acidification (Evans, 2005), an effect that would cause an elevation of organic acidity and low soil pH. Menzies and Gillman (2003) have however observed that high temperatures in the range of 25 to 39°C are associated with denaturation of organic acids and would counteract acidification caused by DOC. Changes in pH conditions caused by changes in prevailing climatic conditions may however depend on the buffering capacity of the soil.

5.2.3 Wetland soil Electrical Conductivity

The highest EC value of 0.43 mS/cm was recorded within the 0–15 cm depth at site GW9 whereas the lowest value of 0.03 mS/cm was obtained within the 30–45 cm depth at site GW4 (Figure 5.6). There were no differences in EC of soils from one site to the other according to ANOVA analyses ($p = 0.03$ with Tukey's Post Hoc test) but soil EC at a depth of 0–15 cm was significantly higher than that at depths of 15–30 cm ($p = 0.008$) and 30–45 cm ($p = 0.001$). The EC values indicate that soils in the wetland were within the acceptable FAO range; with values below 4 mS/cm. Soils with EC above 4 mS/cm are considered saline and contribute towards reduced vegetation growth (Jamil *et al*., 2011; Paul, 2012).

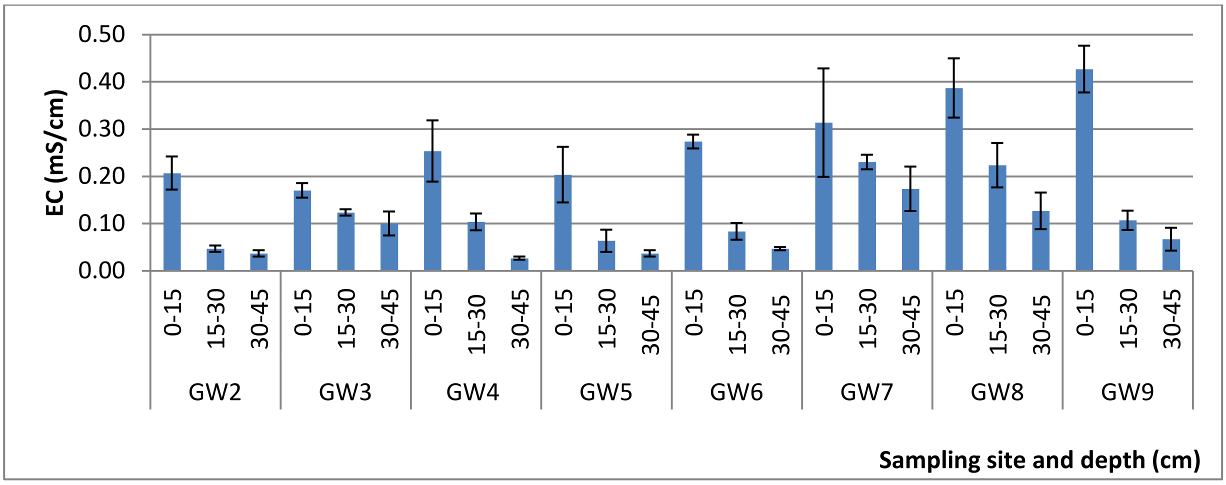


Figure 5.6: Mean soil EC at different depths of the wetland

Dissolved salts contained in soils in Khubelu wetlands might have been flushed out of the soil during rain events resulting in the observed low EC values. Similar observations have been made by Adugna and Abegaz (2015). Across the Khubelu wetland, a decrease in EC was observed with soil depth (Figure 5.7), and from upstream to downstream within the 0 - 15 cm and 30 - 45 cm depths. A similar trend was observed in a study by Raza *et al.* (2015) where soil EC decreased from 0.9 to 0.3 mS/cm within 10 - 30 cm and 30 - 60 cm soil depth respectively. There were however no significant differences in the EC of soils between the upstream, midstream and downstream sections of the wetland ($p = 0.19$).

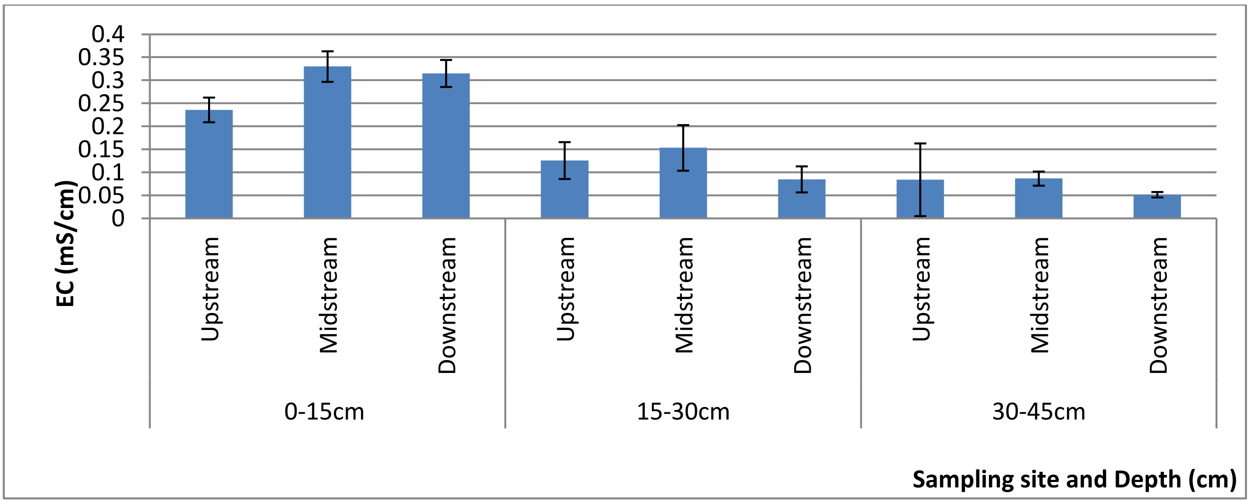


Figure 5.7: Variations of mean soil EC at different depths from upstream to downstream Khubelu wetland

5.2.4 Cation exchange capacity

Values for CEC of the wetland soils ranged from 3.72 meq/100g within 15 - 30 cm depth (GW3) to 4.19 meq/100g within 0 - 15 cm at GW9 (Figure 5.8). These CEC values fall within the range of the CEC values of quartz, a primary mineral that dominates sandy soils. The differences in CEC from one site to the other were insignificant ($p = 0.42$) but CEC values decreased with depth with soil CEC being higher at depths of 0 – 15 cm compared to CEC at depths of 0 – 30 cm ($p < 0.01$) and 0 – 45 cm ($p = 0.014$). A decrease in CEC with depth was observed at sites GW4, GW7, GW8 and GW9, with other sites showing an irregular pattern.

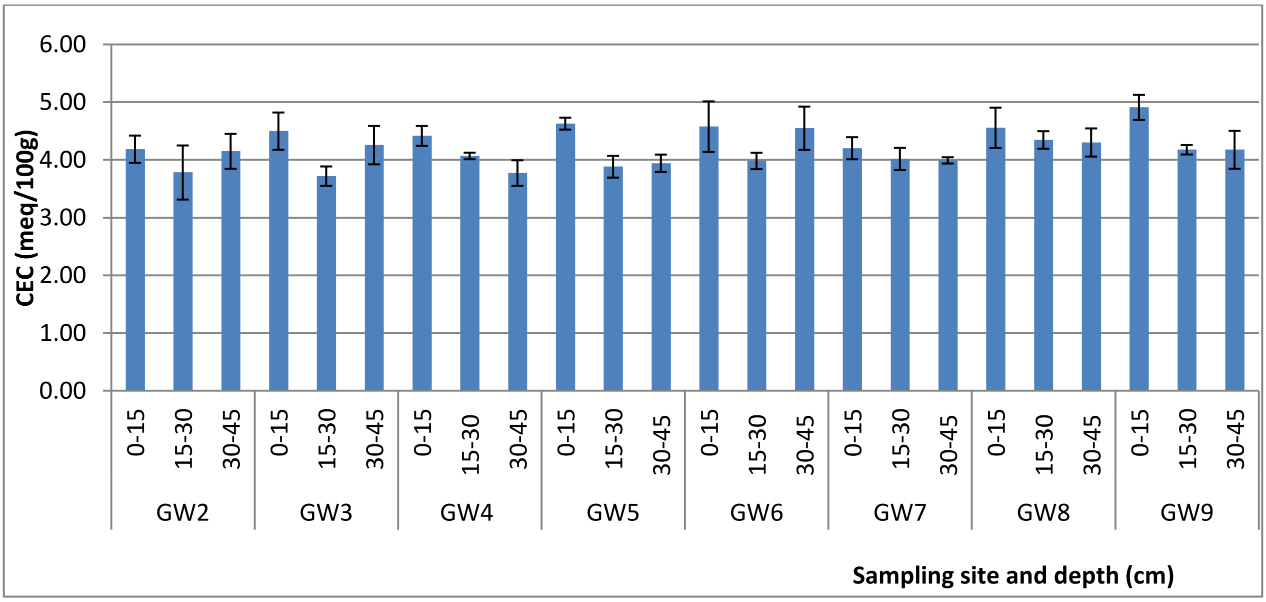


Figure 5.8: Variation of mean soil CEC at different depths of Khubelu wetland

Decreased CEC with soil depth in this study concurs with findings by Adugna and Abegaz (2015) and Osujieke *et al.* (2018). Though the CEC values decreased with depth, soil texture became more clayey with depth, which typically should have resulted in increase in CEC with depth, should the CEC have been contributed solely by soil texture. The observed pattern of CEC with depth of soils around the wetland may therefore indicate that the CEC of the wetland soils are not only determined by its soil texture, but other factors may contribute to the observed CEC. High CEC in surface soil is attributable to high OM content in this horizon of soil (Adugna & Abegaz, 2015; Osujieke *et al.,* 2018) and may be playing a significant role in the CEC of the soils around the wetland. The role of OM in the CEC of these soils is further justified by the fact that under acidic conditions, the CEC of organic matter would be low whereas in alkaline conditions its CEC is high as a result of the fact that it has pH-dependent charges. Under these conditions, its charge will vary from negatively charged to neutral to positively charged, depending on whether the soil is alkaline, neutral or acidic. The acidic nature of these soils would have resulted in lower negatively charged sites in the OM contained in the soils resulting in OM which varies with pH. Cation exchange capacity values showed no regular pattern downstream at 15 – 30 cm and 30 - 45 cm depths, but at 0 - 15 cm depth, the values for soil CEC increased downstream (Figure 5.9). ANOVA analyses also indicated no difference in soil CEC from upstream to downstream of the wetland (*p* = 0.11).

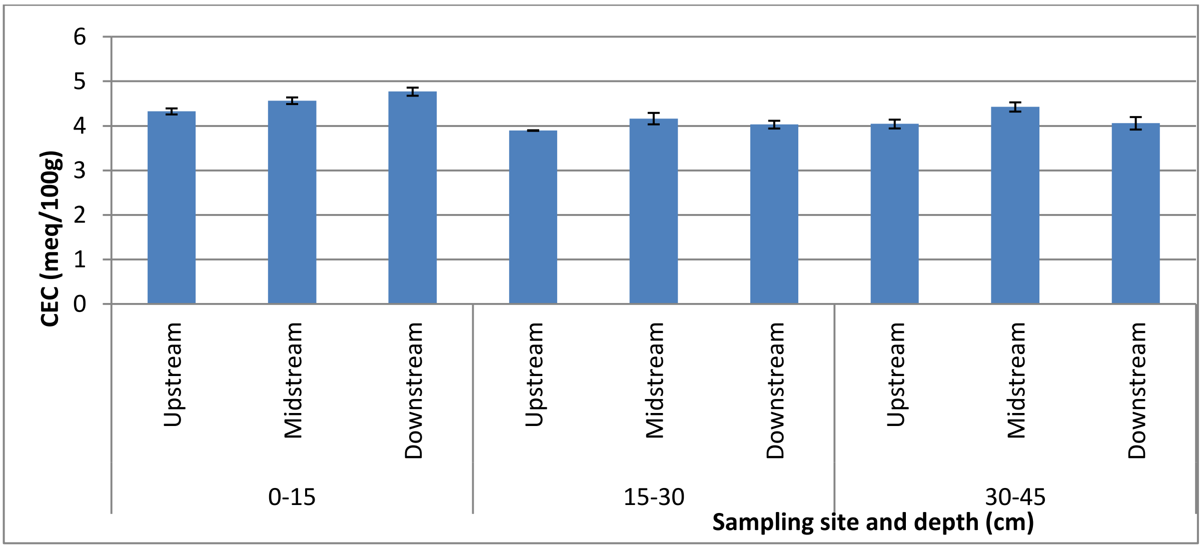


Figure 5.9: Variation of soil CEC at different depths from upstream to downstream of Khubelu wetland

Cation Exchange Capacity values indicate the ability of negatively charged soil particles to attract cations, retain them and supply these nutrients to vegetation when needed and also prevent them from entering the streams and rivers they supply. The CEC values of Khubelu wetland soils are low implying that the wetland soils have a low capacity to adsorb cations from solution and might fail to remove them from the wetland water before it is discharged into the Khubelu stream. Failure to retain nutrients that are highly essential for vegetation growth threatens the health of wetland flora as well as the water purification function of the wetland. Another possibility is that the wetland is dominated by sandy sediments and has low CEC. Changes in climatic variables may have an indirect impact on soil CEC through their impact on soil organic matter accumulation and chemical weathering. Excessive rainfall and predicted higher temperatures may increase the rate of chemical weathering of primary to secondary soil mineral, and a consequent increase in clay content in the soil; and this plays a significant role in soil CEC. In addition, these conditions would also affect the amount of organic matter accumulated in the soil which also affects CEC.

5.2.5 Soil total nitrogen and total carbon

The wetland had a mean maximum total nitrogen (TN) content of 2.38% at GW7 (15 - 30 cm) and a mean minimum of 0.39% at GW2 (30 - 45 cm), with a wetland average of 1.20%. There was a decrease in TN with depth at sites GW2, GW3, GW4, GW5, GW6, and GW9 (Figure 5.10) whereas sites GW7 and GW8 showed a fluctuation of TN content with depth. The differences in TN content with depth were significant (p = 0.05). TN values across the wetland varied from one site to the other (p = 0.00) and these differences were reflected in the pattern of TN from upstream to downstream the wetland. Total nitrogen values also increased with depth in the mid and lower areas of the wetland but fluctuated with depth upstream (Figure 4.11). A decrease in TN from topsoil towards lower horizons is in conformity with studies by Bai *et al.* (2005), Wang *et al.* (2016), Fekadu *et al.* (2017) and Osujieke *et al.* (2018). The decrease in TN with increasing depth could be attributable to rapid microbial activities in surface soils (Neff *et al*., 2003; Fekadu *et al.,* 2017; Osujieke *et al.,* 2018). Surface soils are also rich in organic matter which contains huge amounts or nitrogen compounds. The higher TN values observed at the 0 – 15 cm soil depth is therefore not unexpected.

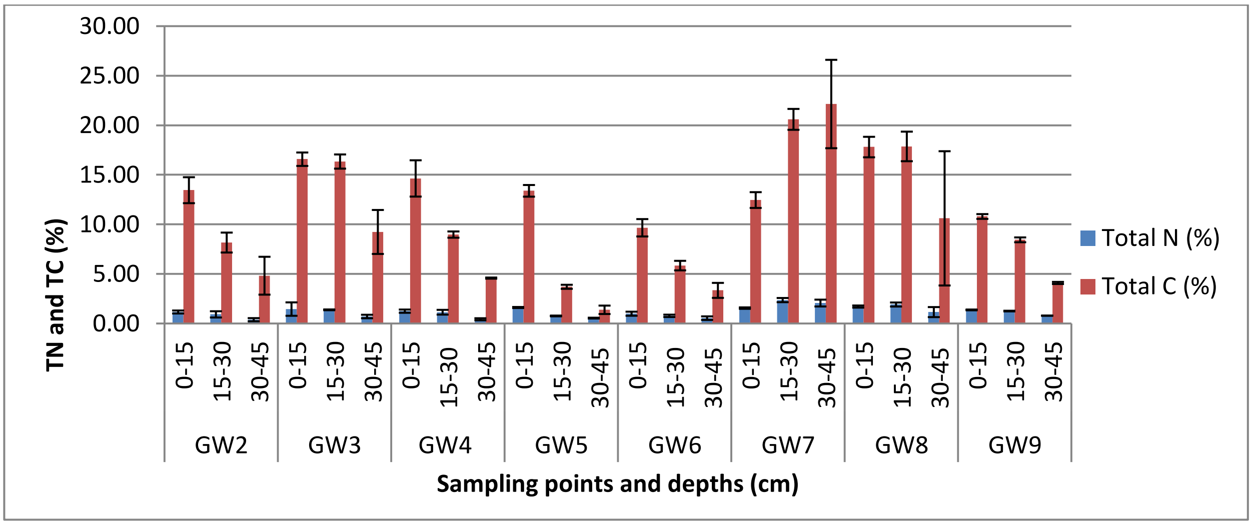


Figure 5.10: Variation of mean soil total nitrogen and total carbon with depth at Khubelu wetland

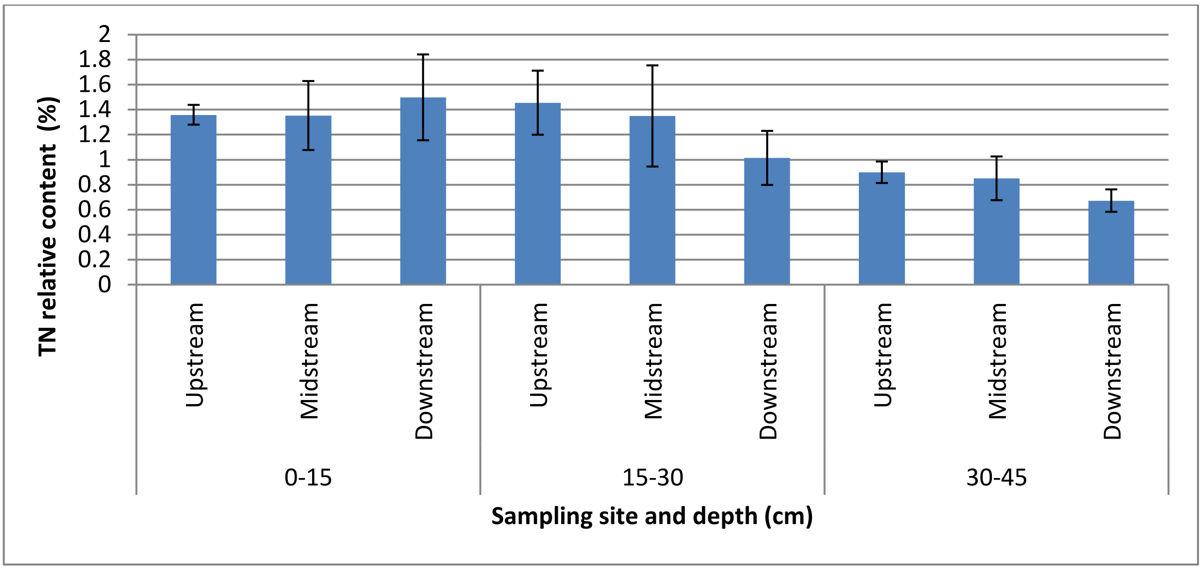


Figure 5:11: Variations of soil total nitrogen at different depths from upstream to downstream Khubelu wetland

The wetland site with the highest TC content (22.15%) was site GW7 at 30 - 45 cm depth whereas the lowest TC value (1.39%) was obtained in samples from a depth of 30 - 45 cm at site GW5 (Figure 5.10). There was a decrease in TC content with depth at sites GW2, GW3, GW4, GW5, GW6, and GW9. Sites GW7 and GW8 showed an irregular pattern of TC content with depth. Across the wetland, there was a decrease in TC content from midstream to downstream at 15 - 45 cm depth but not at the surface (Figure 4.12).

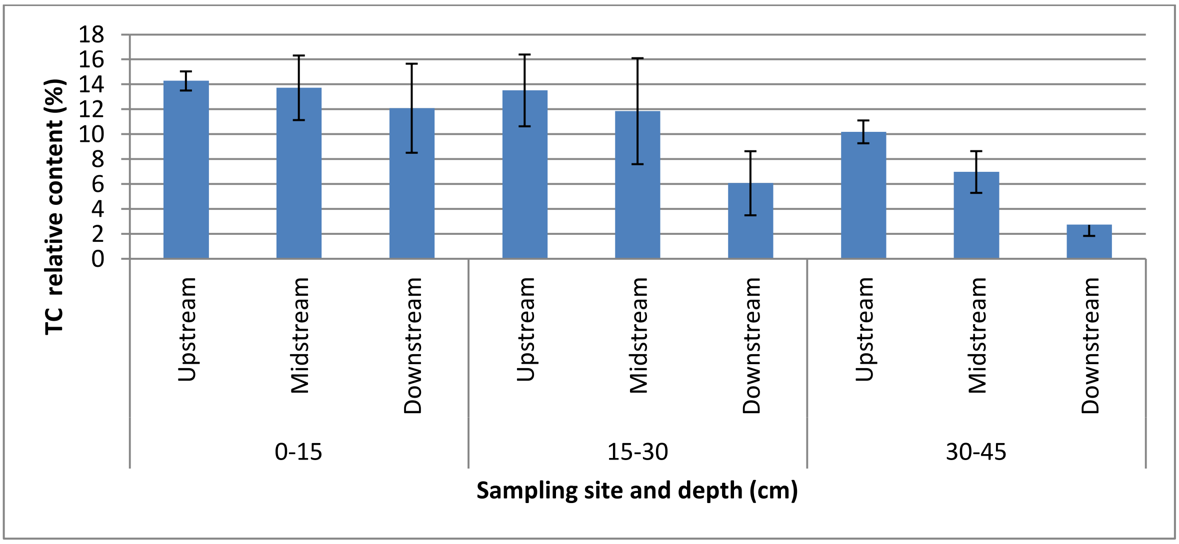


Figure 5.12: Variations of total soil carbon with depth from upstream to downstream Khubelu wetland

High TC content in topsoil is attributable to conversion of dead wetland plant litter and roots by microbial activity (Fang *et al.,* 2015). Carbon fixation by wetland vegetation through photosynthesis (Zhang *et al.,* 2019) also contributes towards high TC in topsoil as when these plants die, the sequestered carbon is returned to the top soil layer where the litter is dropped. Lower TC values at the >15cm depths might be due to poor transport of organic carbon to these depths (Harper & Tibbett, 2013). As observed with TN content, the content of TC in the wetland soils was lower downstream and this explains the poor vegetation cover observed at this area of the wetland.

5.2.6 Soil organic matter

The highest value for mean OM in the wetland soil (4.69%) was obtained in soils collected at a depth of 30 - 45 cm at site GW7, and the lowest (1.17 %) at the same depth but at site GW5 (Figure 5.13). Mean OM content of soils in the wetland was (2.67%). Interestingly, sampling sites GW5 and GW7 also had the lowest TC and highest TN, and within the same depths, which further highlights the relationship between soils TN, TC and OM. At sites GW2, GW3, GW4, GW5, GW6, and GW9, OM content in the soils decreased with depth whereas site GW7 showed an increase in soil OM content with depth. Organic matter content in soils at site GW8 fluctuated with depth as indicated in Figure 5.13.

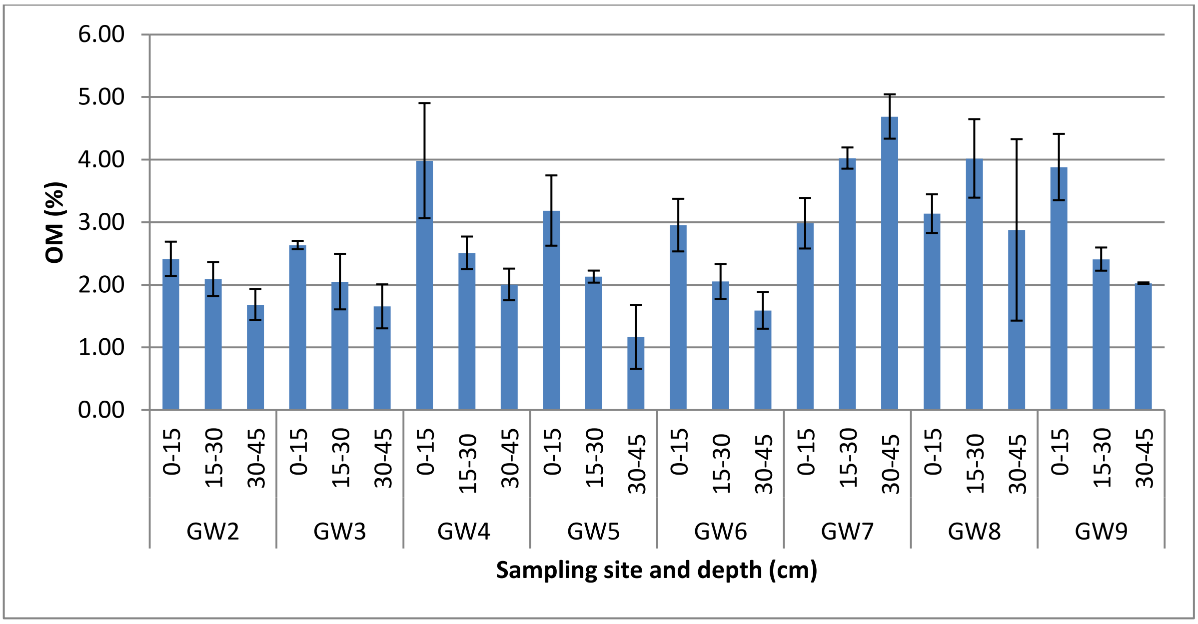


Figure 5.13: Variations of soil organic matter at different depths of Khubelu wetland

The content of OM in soils around the wetland varied with OM content in soils at site GW6 being significantly lower than OM content in soils from the other sites (p <0.01). The high OM at the surface soils has been attributed to plant roots, litter fall and microbial decomposition of these materials (Adugna & Abegaz 2015; Daniels *et al*., 2017). Across the Khubelu wetland, there was an increase in soil OM content downstream within the 0 -15 cm depth and a decrease within the 30 - 45 cm depth (Figure 5.14). At a depth of 15 - 30 cm there was no regular trend (Figure 5.14). For sandy loam soil, OM in the 0.5% to 1.0% range is classified as very low, whereas 2.5% and above reflect a very high OM content (NJAES, 2019). High OM content in wetland soils around Lesotho has been attributed to low temperatures (Schmitz & Rooyani, 1987), which impede microbial activity that are responsible for decomposing organic material. In addition, prolonged anaerobic conditions due to soil saturation in wetlands do not favour OM decomposition, which is seen to accumulate in these wetland environments (Jackson *et al.,* 2014).

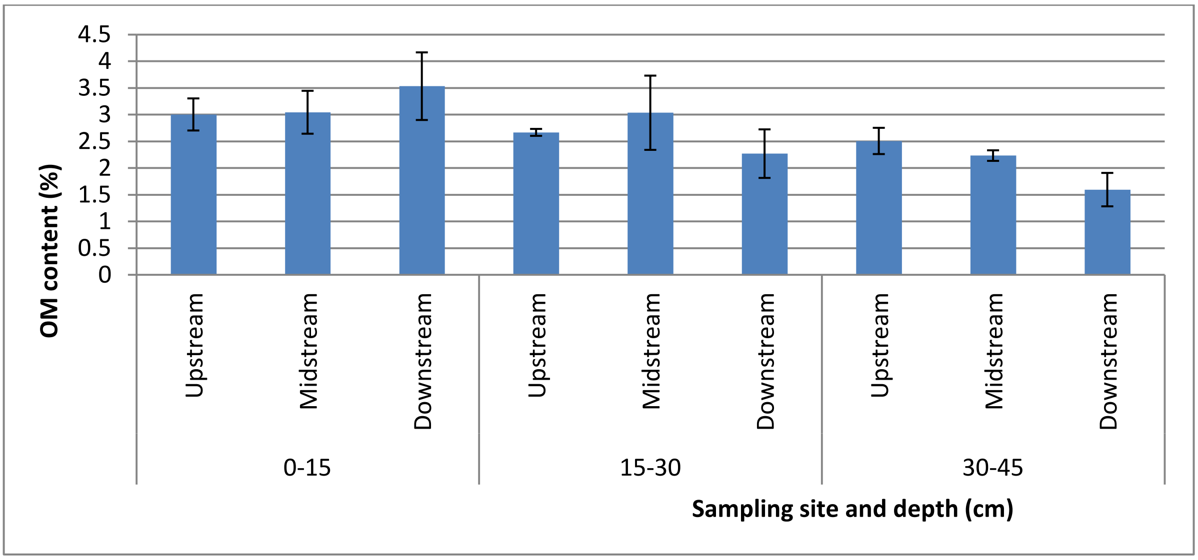


Figure 5.14: Variations of soil organic matter at different depths from upstream to downstream of the Khubelu wetland

The high OM content in the soil would assist the Khubelu wetland to adsorb nutrients and cations because of its contribution to density of negative charges, and consequently CEC (Ballantine *et al.,* 2011). High OM would also improve soil water-holding capacity (Brady & Weil, 1999), plant root development, and cation exchange capacity (Bruland & Richardson, 2005; Wolf *et al.,* 2011) in the Khubelu wetland, while significantly withholding nutrients before they could be leached either deeper into the soil or into the

Khubelu stream. In the event of low precipitation caused by climate change, the degree of saturation of the wetland soils would reduce creation of favourable conditions for aerobic micro-organisms that speed up OM decomposition (Inglett *et al.,* 2005). The wetland soil adsorption capacity would be reduced because less OM will accumulate, resulting in low retention of pollutants and nutrients. If the adsorption capacity and other sources of sinks are exceeded by the rate of delivery, this would further threaten downstream water quality. With the predicted increase in temperatures, soil microbial activity would be high, also leading to high OM decomposition (Higashida & Takao, 1986; Qiu *et al.,* 2005; Conant *et al.,* 2011). On a small scale, climatic variations have an impact on SOM, where it increases with an increase in precipitation and declining with increasing temperature (Ganuza & Almendros, 2003; Azlan *et al.,* 2012). From this perspective, it can be expected that OM will be low because of predicted increase in temperatures.

5.2.7 Exchangeable Ca, Mg, K, and Na in wetland soils

The highest mean value of exchangeable Ca (1.00 meq/100g) was obtained in soils from sites GW8 (15 - 30 cm) and GW9 (0 - 15 cm), with the lowest mean (0.69 meq/100g) observed in soils at GW5 within the 15 - 30 cm depths (Table 5.1).

Table 5.1: Mean exchangeable Ca variations at different soil depths around the wetland

	Soil Ca at different depths (meq/100g)		
Sampling site	0 – 15 cm	15 – 30 cm	30 – 45 cm
GW2	0.92	0.73	0.85
GW3	0.88	0.77	0.88
GW4	0.92	0.83	0.70
GW5	0.80	0.69	0.72
GW6	0.86	0.79	0.79
GW7	0.94	0.82	0.91
GW8	0.92	1.00	0.85
GW9	1.00	0.88	0.83

Within all the sampling points around the wetland, there was no regular trend followed by soil exchangeable Ca with depth, except at site GW9 where there was a decline in exchangeable Ca content with depth (Table 5.1). Across the wetland, there was also no regular trend of exchangeable Ca downstream except within the 30 - 45 cm depth where it decreased from 0.84 to 0.78 meq/100g (Figure 5.15). Exchangeable Ca in soils has been associated with the creation of positive charges onto which P may be adsorbed (Guppy, 2005; Duputel, 2013). However, the observed exchangeable Ca concentrations in the wetland soils are very low (lower than 250 to 500 meq/100g) and not likely to make any significant contribution towards the binding of P by these soils.

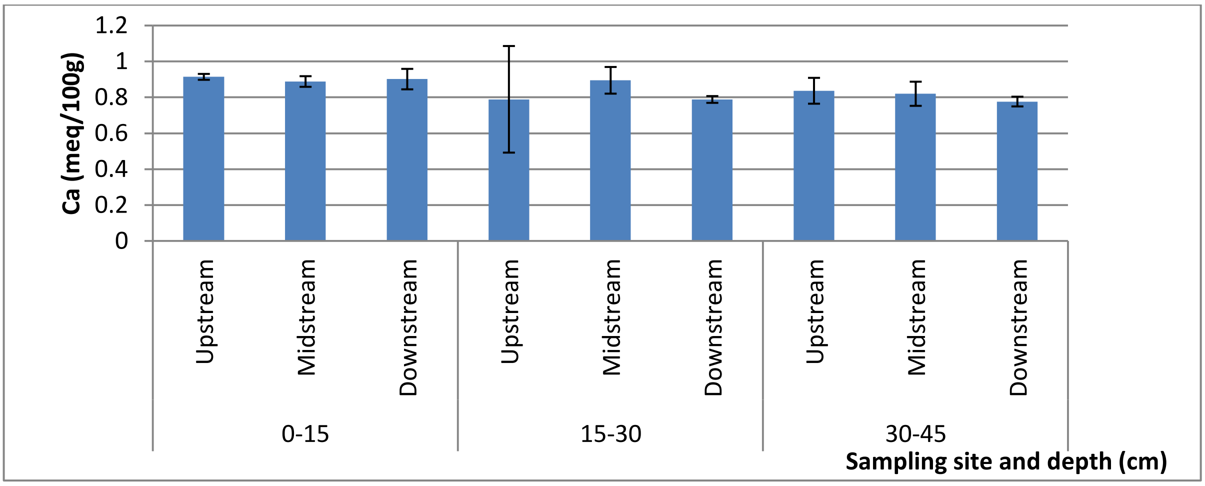


Figure 5.15: Variations of mean soil exchangeable Ca at different depths from upstream to downstream Khubelu wetland

Table 5.2: Variations of mean soil exchangeable Mg at different depths of Khubelu wetland

	Soil Mg at different depths (meq/100g)		
Sampling site	0 – 15 cm	15 – 30 cm	30 – 45 cm
GW2	2.36	2.37	2.35
GW3	2.35	2.38	2.36
GW4	2.35	2.37	2.36
GW5	2.35	2.34	2.35
GW6	2.36	2.37	2.34
GW7	2.37	2.35	2.35
GW8	2.35	2.36	2.37
GW9	2.36	2.35	2.36

The highest mean value of exchangeable Mg was 2.38 meq/100g observed at a depth of 15 - 30 cm at site GW3 and 0 - 15 cm at site GW9, whereas the lowest was 2.34 meq/100g at GW5 (15 - 30 cm) and GW6 (30 - 45 cm) with the wetland average of 2.36

meq/100g. Exchangeable Mg fluctuated with depth around the wetland (Table 5.2) and there was no regular trend from upstream to downstream within the 0 - 15 cm depth whereas at a depth of 15 - 30 cm, there was a decrease from upstream to downstream (Figure 5.16).

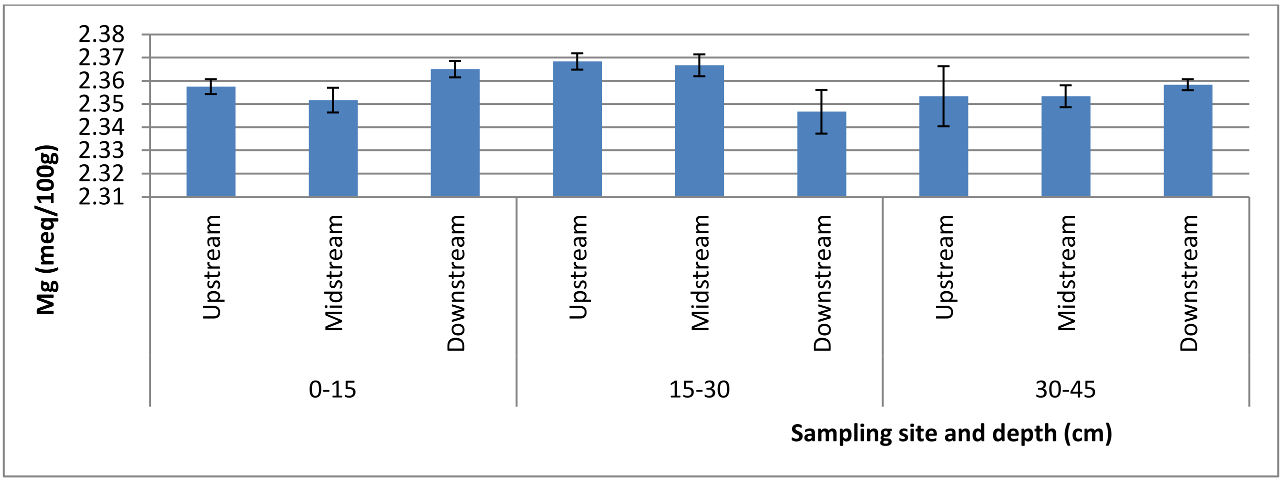


Figure 5.16: Variation of mean soil exchangeable Mg at different depths from upstream to downstream Khubelu wetland

For plant growth, magnesium below 0.5 meq/100g soil is classified as low; 0.5 - 2.5 meq/100g as medium and above 2.5 meq/100g of soil is high (Horneck *et al.,* 2011). Khubelu wetland soils therefore have medium Mg content that can support its vegetation.

Table 5.3: Variations of mean soil exchangeable K at different depths from upstream to downstream Khubelu wetland

Sampling site	Soil K at different depths (meq/100g)		
	0 – 15 cm	15 – 30 cm	30 – 45 cm
GW2	0.20	0.25	0.35
GW3	0.29	0.05	0.26
GW4	0.16	0.27	0.14
GW5	0.43	0.11	0.12
GW6	0.31	0.10	0.53
GW7	0.13	0.16	0.13
GW8	0.60	0.33	0.16
GW9	0.53	0.30	0.34

There was an increase in soil exchangeable K concentration with depth at site GW2, whereas the other sites did not show any regular trend (Table 5.3). The highest mean value for exchangeable K (0.60 meq/100g) was observed at site GW8 (0 - 15 cm), with the minimum value (0.05 meq/100g) recorded at site GW3 (15 - 30 cm). There was no trend followed by exchangeable K downstream within all the soil depths around the wetland (Figure 5.17).

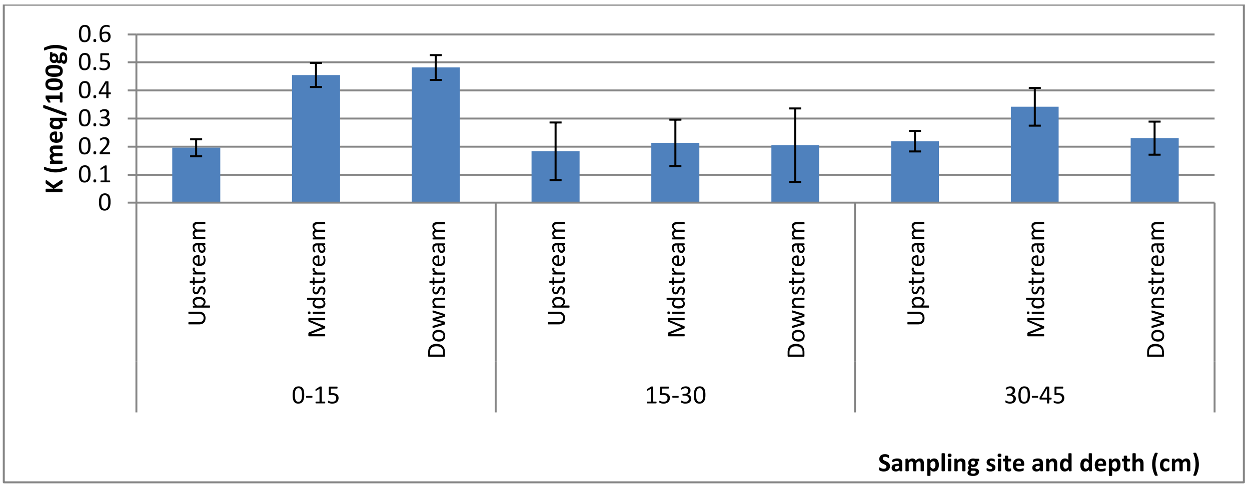


Figure 5.17: Variation of mean soil exchangeable K at different depths from upstream to downstream the wetland

Table 5.4: Variation of mean soil exchangeable Na at different soil depths around the wetland

Sampling site	Soil Na at different depths (meq/100g)		
	0 – 15 cm	15 – 30 cm	30 – 45 cm
GW2	0.71	0.43	0.61
GW3	0.98	0.52	0.76
GW4	0.98	0.60	0.57
GW5	1.05	0.74	0.74
GW6	1.05	0.72	0.89
GW7	0.76	0.68	0.60
GW8	0.69	0.66	0.93
GW9	0.99	0.64	0.65

Horneck *et al.* (2011) suggested that exchangeable K below 0.4 meq/100g is low and the 0.4-0.6 meq/100g range as medium. The wetland area in the study was dominated by low exchangeable K, with only three sites downstream (GW5, GW8 and GW9) showing medium values within the 0 - 15 cm depth. Mean value for exchangeable Na concentration in the wetland soils varied from 0.43meq/100g soil at GW2 (15 - 30 cm) to 1.05 meq/100g soil at GW5 (0 - 15 cm), and GW6 (0 - 15 cm), with a mean of 0.75 meq/100g soil. It showed a decrease from 0 - 15 cm depth, to the 15–30 cm depth of the soil. Exchangeable Na content in the soils around the wetland fluctuated with depth (Table 5.4).

Except at a depth of 15 - 30 cm where exchangeable Na increased from upstream to downstream, no definite pattern was observed across the wetland (Figure 5.18). Exchangeable Na has not been considered a major cation that supports plant growth (Raza *et al.,* 2015) and it is reputable for toxicity in some ecosystems (Kronzucker *et al.,* 2013). Among the exchangeable cations, Mg was predominant over Na, Ca, and K in the study area.

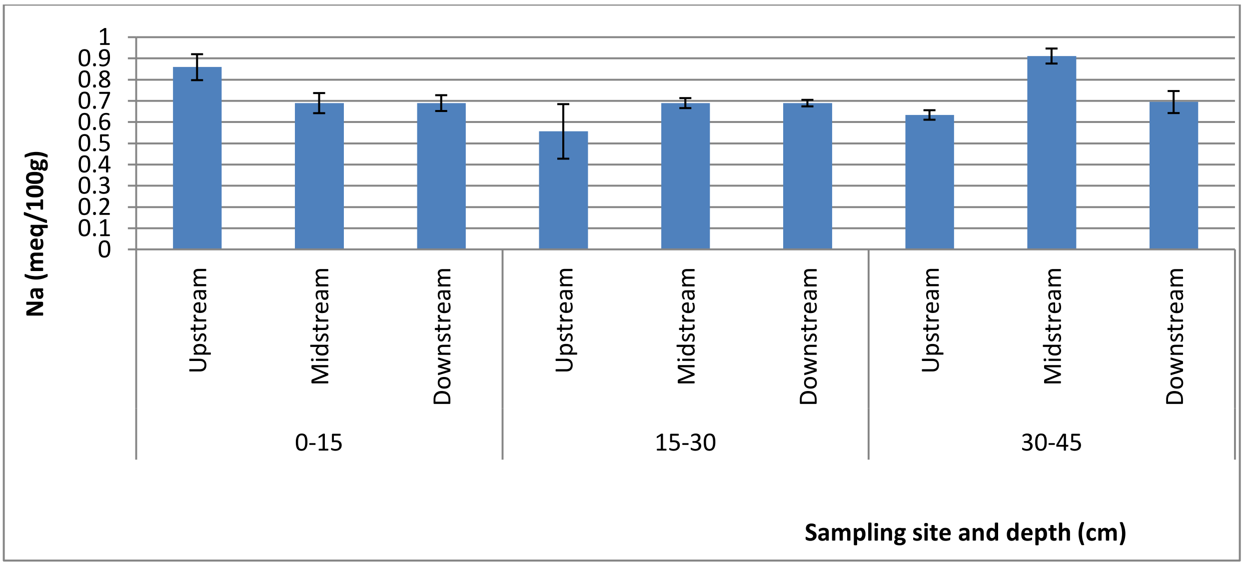


Figure 5.18: Variation of mean soil exchangeable Na at different depths from upstream to downstream Khubelu wetland

5.2.8 Available phosphorus

The highest amount of available P (0.65 mg/kg) was recorded at site GW7 (15 - 30 cm depth) and the lowest concentration (0.07 mg/kg) at sites GW2 (15 - 30 cm) and GW9 (0 - 15 cm) as shown in Figure 5.19. Values for available P fluctuated with depth at sites GW2, GW3 and GW7 whereas a decrease with depth was observed at sites GW4, GW5 and GW8. Sites GW6 and GW9 showed an increase in available P with depth. Available P decreased from upstream to downstream the wetland at depths of 0–30 cm but fluctuated at depths of 30–45 cm (Figure 5.20). Results from ANOVA indicated no difference in available phosphate levels in soils at different sites (*p* = 0.44), at different depths (*p* = 0.92) and from upstream to downstream (*p* = 0.82). In Lesotho, a decrease in available P downstream was also observed by Rasekoele (2016) in wetlands at Khalo-La-Lithunya. High available P within the 0 - 15 cm depth could be due to high content of OM, which has also been observed to be higher at this soil depth than at other depths studied, and to low pH (Sato & Comerford, 2005). Maluf *et al.* (2018) has ascribed adsorption of phosphorus onto clay at low pH. Phosphate can also become unavailable to plants if it precipitates with Ca forming dicalcium phosphate (DCP) (Shen *et al.,* 2011). It also typically adsorbs onto particles, and become unavailable in the presence of oxygen.

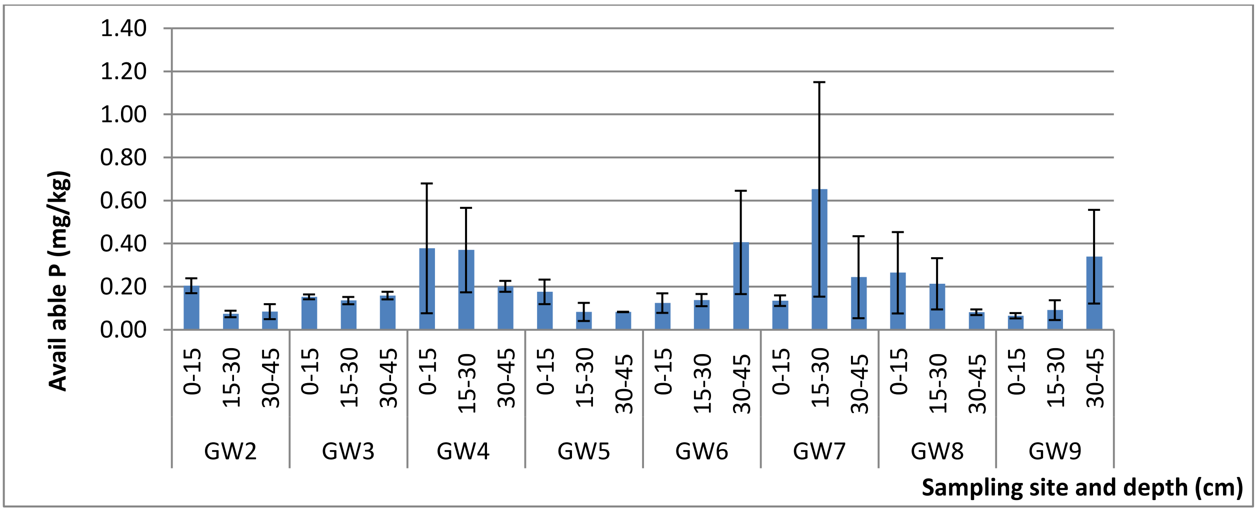


Figure 5.19: Variation of mean soil available P with depth around the wetland

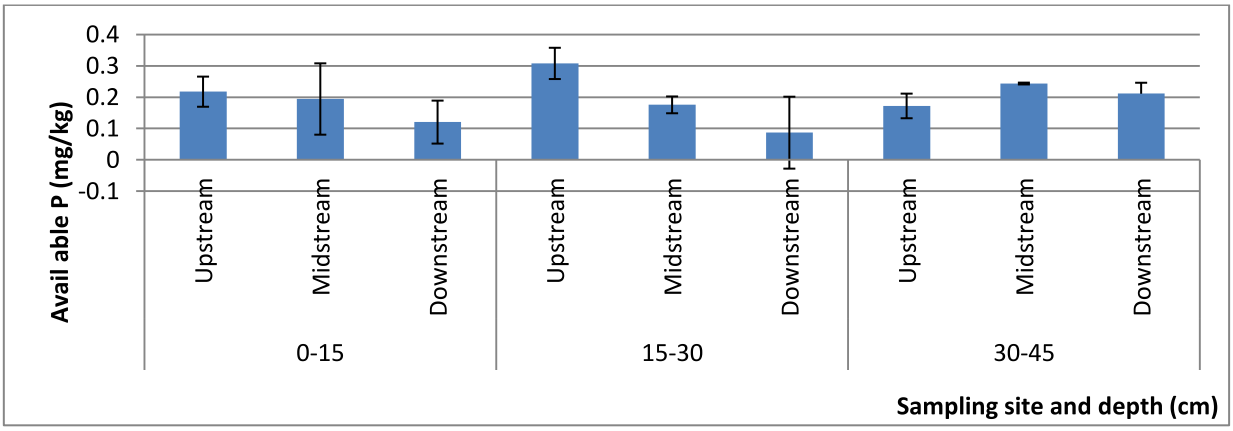


Figure 5.20: Variations of mean available P from upstream to downstream of the wetland at different depths

However, the content of exchangeable Ca observed in this study was too low to precipitate available P. Therefore, this leaves the possibility of absorption onto clay particles. The decrease in P concentration downstream further shows that the Khubelu stream will likely receive water less laden with it. However, low vegetation cover in the wetland due to decreased precipitation, as projected would, result in loss of available P into the stream, with a possibility of nutrient enrichment, and subsequent DO depletion since the stream would be eutrophic. The effect of climate change on soil P is indirect because P is usually contained in organic material. Any change in climate that affects soil OM is therefore likely to affect soil P content in the wetland, especially if there is no phosphate rich parent material around the catchment which can introduce P into the wetland.

5.3 Assessment of soil degradation at the Khubelu wetland

To determine the extent of soil degradation at the wetland, the chemical soil degradation index of the soils was determined. In doing so, the mean, minimum and maximum values of the various soil properties determined in this study for upstream, midstream, downstream, and for the entire study area, are presented in Tables 5.5 to Table 5.8. These values were subjected to a multivariate statistical technique, specifically Principal Components Analysis (PCA) with Varimax Rotation (Kaizer, 1958; Reyment & Joreskog, 1993; Allen, 2017) to reduce to data on the different soil properties analysed to a few principal components (Table 5.9) (Lima *et al.,* 2008). A total of four components from PCA with Eigenvalues above one were used in the determination of CDI of the samples.

Table 5.5: Means of soil chemical properties upstream Khubelu wetland

SITE	**pH**	**Avail P**	**Ca**	**Mg**	**K**	**Na**	**CEC**	**EC**	**T N**	**T C**	**OM**
GW2	5.13	0.12	0.83	2.36	0.99	1.13	3.43	0.81	1.22	5.12	2.04
GW3	4.96	0.15	0.84	2.36	0.2	0.75	4.16	0.13	1.18	14.06	2.11
GW4	5.01	0.32	0.82	2.36	0.19	0.71	4.09	0.13	0.94	9.4	2.83
GW7	5.03	0.34	0.89	2.35	0.14	0.68	4.07	0.24	2	18.4	3.9
MEAN	5.03	0.23	0.85	2.36	0.38	0.82	3.94	0.33	1.34	11.75	2.72
Max	5.13	0.34	0.89	2.36	0.99	1.13	4.16	0.81	2	18.4	3.9
Min	4.96	0.12	0.82	2.35	0.14	0.68	3.43	0.13	0.94	5.12	2.04

These four components accounted for 83.9% of the total variance observed in the soil properties. The component loadings of the different soil properties obtained from PCA analyses are indicated in Table 5.9. Loadings above 0.75 were classified as strong, those between 0.50 and 0.74 as moderate and component loadings between 0.30 and 0.50 as weak (Liu *et al.,* 2003). Only component loadings > 0.5 in components 1, 2, 3 and 4 were considered for further analyses (Liu *et al.,* 2003; Fathy *et al.,* 2012).

Table 5.6: Means of soil chemical properties midstream Khubelu wetland

SITE	**pH**	**Avail P**	**Ca**	**Mg**	**K**	**Na**	**CEC**	**EC**	**T N**	**T C**	**OM**
GW6	5.02	0.22	0.81	2.36	0.31	0.89	4.37	0.13	0.77	6.29	2.2
GW8	5.11	0.19	0.92	2.36	0.36	0.76	4.4	0.25	1.6	15.43	3.34
MEAN	5.07	0.21	0.87	2.36	0.34	0.83	4.39	0.19	1.19	10.86	2.77
Max	5.11	0.22	0.92	2.36	0.36	0.89	4.4	0.25	1.6	15.43	3.34
Min	5.02	0.19	0.81	2.36	0.31	0.76	4.37	0.13	0.77	6.29	2.2

Table 5.7: Means of soil chemical properties downstream Khubelu wetland

SITE	**pH**	**Avail P**	**Ca**	**Mg**	**K**	**Na**	**CEC**	**EC**	**T N**	**T C**	**OM**
GW5	5.17	0.11	0.74	2.35	0.22	0.85	4.15	0.1	0.98	6.16	2.16
GW9	5.22	0.17	0.91	2.37	0.39	0.76	4.42	0.2	1.14	7.78	2.77
MEAN	5.19	0.14	0.83	2.36	0.31	0.81	4.29	0.15	1.06	6.97	2.47
Max	5.22	0.17	0.91	2.37	0.39	0.85	4.42	0.2	1.14	7.78	2.77
Min	5.17	0.11	0.74	2.35	0.22	0.76	4.15	0.1	0.98	6.16	2.16

The first PCs accounted for 37.47% of total variation and soil properties with moderate to high loadings on this component were EC, TN, TC, OM and Ca (Table 5.9). The second component which accounted for 24.09% variance had CEC, Mg, K and pH as the soil properties with the highest loadings (Table 5.9). The third component which accounted for 14.55% of the variance had Na and available P with highest loadings (Table 5.9) and component 4 with 7.83% variance had pH as the soil property with the highest loading. Equations 3.5, 3.6 and 3.7 were used to determine the chemical degradation index of the soils around the Khubelu wetland as indicated in Table 5.10 to 5.13

Table 5.8: Means of soil chemical properties for the entire wetland area

SITE	**pH**	**Avail P**	**Ca**	**Mg**	**K**	**Na**	**CEC**	**EC**	**T N**	**T C**	**OM**
GW2	5.13	0.12	0.83	2.36	0.99	1.13	3.43	0.81	1.22	5.12	2.04
GW3	4.96	0.15	0.84	2.36	0.20	0.75	4.16	0.13	1.18	14.06	2.11
GW4	5.01	0.32	0.82	2.36	0.19	0.71	4.09	0.13	0.94	9.40	2.83
GW5	5.17	0.11	0.74	2.35	0.22	0.85	4.15	0.10	0.98	6.16	2.16
GW6	5.02	0.22	0.81	2.36	0.31	0.89	4.37	0.13	0.77	6.29	2.20
GW7	5.03	0.34	0.89	2.35	0.14	0.68	4.07	0.24	2.00	18.40	3.90
GW8	5.11	0.19	0.92	2.36	0.36	0.76	4.40	0.25	1.60	15.43	3.34
GW9	5.22	0.17	0.91	2.37	0.39	0.76	4.42	0.20	1.14	7.78	2.77
MEAN	**5.08**	**0.20**	**0.85**	**2.36**	**0.35**	**0.82**	**4.14**	**0.25**	**1.23**	**10.33**	**2.67**
Max	**5.22**	**0.34**	**0.92**	**2.37**	**0.99**	**1.13**	**4.42**	**0.81**	**2.00**	**18.40**	**3.90**
Min	**4.96**	**0.11**	**0.74**	**2.35**	**0.14**	**0.68**	**3.43**	**0.10**	**0.77**	**5.12**	**2.04**

Table 5.9: Component loadings of the different soil properties

Variable	**Component**			
	1	2	3	4
pH KCl	0.284	**0.510**	0.348	**0.642**
Avail P	-0.090	-0.417	**0.782**	-0.183
Ca	**0.687**	0.371	-0.088	-0.391
Mg	0.384	**0.708**	-0.385	-0.108
K	0.263	**0.701**	-0.025	-0.249
Na	0.204	0.178	**0.801**	-0.337
CEC	0.526	**0.792**	-0.088	-0.176
EC	**0.902**	0.179	0.254	0.123
TN	**0.897**	-0.209	0.022	0.249
TC	**0.853**	-0.367	-0.010	0.018
OM	**0.849**	-0.076	0.013	0.338
Eigenvalue	5.245	3.373	2.037	1.096
Total variance %	37.467	24.091	14.547	7.831
Cumulative variance %	37.467	61.558	76.105	83.936

Values for CDI indicated that the level of soil degradation around the wetland varied. Upstream, a CDI value of 3.42 to (Table 5.10) was obtained whereas midstream and downstream CDI values were 3.25 (Table 5.11) and 3.05 (Table 5.12), respectively. All these values are above the CDI threshold value of 2.0 for an undegraded wetland. The soil CDI for the whole wetland was determined as 3.29 (Table 5.13), which is also above 2.0, the threshold for undegraded soils. The wetland can therefore be classified as degraded according to Huang *et al.* (2012). A degraded wetland does not have fertile soil for vegetation support, nutrient and pollutant regulation (Benitez *et al.,* 2006).

Table 5.10: Chemical Degradation Index of upstream soil of Khubelu wetland

Soil Variable	Xij mean	Xi min	Xi max	Xij – Xi min	Xi max – Xi min	Q (Xi) Eq 3.6	Wi	Q(Xi) Wi	Q (Xi) Eq 3.7	Xi max - Xij	Q(Xi) Wi
CEC	3.94	3.43	4.16	0.51	0.73	0.70	0.79	0.55		0.22	
EC	0.33	0.13	0.81	0.2	0.68	0.00	0.91		0.71	0.48	0.64
TN	1.34	0.94	2	0.4	1.06	0.38	0.90	0.34		0.66	
TC	11.75	5.12	18.4	6.63	13.28	0.50	0.85	0.43		6.65	
OM	2.72	2.04	3.9	0.68	1.86	0.37	0.85	0.31		1.18	
Avail P	0.23	0.12	0.34	0.11	0.22		0.78			0.11	
Exchangeable Mg	2.36	2.35	2.36	0.01	0.01		0.71			0.00	
Exchangeable Na	0.82	0.68	1.13	0.14	0.45		0.80		0.69	0.31	0.55
Exchangeable K	0.38	0.14	0.99	0.24	0.85		0.70			0.61	
pH	5.03	4.96	5.13	0.07	0.17	0.41	0.51	0.21		0.10	
Exchangeable Ca	0.85	0.82	0.89	0.03	0.07		0.69		0.57	0.04	0.39
∑Q(Xi)						1.94	6.30	1.84	1.97	0.00	1.58
Total											1.84+1.58= 3.42
CDI= ∑Q(Xi) Wi = 3.42											

Table 5.11: Chemical Degradation Index of midstream soil of Khubelu wetland

Soil Variable	Xij mean	Xi min	Xi max	Xij – Xi min	Xi max – Xi min	Q (Xi) Eq 3.6	Wi	Q(Xi) Wi	Q (Xi) Eq 3.7	Xi max - Xij	Q(Xi) Wi
CEC	4.39	4.37	4.4	0.02	0.03	0.67	0.79	0.53		0.01	
EC	0.19	0.13	0.25	0.06	0.12	0.00	0.91		0.50	0.06	0.45
TN	1.19	0.77	1.6	0.42	0.83	0.51	0.90	0.45		0.41	
TC	10.86	6.29	15.43	4.57	9.14	0.50	0.85	0.43		4.57	
OM	2.77	2.2	3.34	0.57	1.14	0.50	0.85	0.42		0.57	
Avail P	0.21	0.19	0.22	0.02	0.03	0.67	0.78			0.01	
Exchangeable Mg	2.36	2.36	2.36	0	0	0.00	0.71			0.00	
Exchangeable Na	0.83	0.76	0.89	0.07	0.13	0.00	0.80		0.46	0.06	0.37
Exchangeable K	0.34	0.31	0.36	0.03	0.05	0.60	0.70			0.02	
pH	5.07	5.02	5.11	0.05	0.09	0.56	0.51	0.28		0.04	
Exchangeable Ca	0.87	0.81	0.92	0.06	0.11	0.00	0.69		0.45	0.05	0.31
∑Q(Xi)						2.17	6.30	2.12	1.42	0.00	1.13
Total											2.12 + 1.13 = 3.25
CDI= ∑Q(Xi) Wi= 3.25											

Table 5.12: Chemical Degradation Index of downstream soil of Khubelu wetland

Soil Variable	Xij mean	Xi min	Xi max	Xij – Xi min	Xi max – Xi min	Q (Xi) Eq 3.6	Wi	Q(Xi) Wi	Q (Xi) Eq 3.7	Xi max - Xij	Q(Xi) Wi
CEC	4.29	4.15	4.42	0.14	0.27	0.52	0.79	0.41		0.13	
EC	0.15	0.1	0.2	0.05	0.1	0.00	0.91		0.50	0.05	0.45
TN	1.06	0.98	1.14	0.08	0.16	0.50	0.90	0.45		0.08	
TC	6.97	6.16	7.78	0.81	1.62	0.50	0.85	0.43		0.81	
OM	2.47	2.16	2.77	0.31	0.61	0.51	0.85	0.43		0.30	
Avail P	0.14	0.11	0.17	0.03	0.06	0.50	0.78			0.03	
Exchangeable Mg	2.36	2.35	2.37	0.01	0.02	0.50	0.71			0.01	
Exchangeable Na	0.81	0.76	0.85	0.05	0.09	0.00	0.80		0.44	0.04	0.36
Exchangeable K	0.31	0.22	0.39	0.09	0.17	0.53	0.70			0.08	
pH	5.19	5.17	5.22	0.02	0.05	0.40	0.51	0.20		0.03	
Exchangeable Ca	0.83	0.74	0.91	0.09	0.17	0.00	0.69		0.47	0.08	0.32
∑Q(Xi)						2.03	6.30	1.92	1.42	0.00	1.13
Total											1.92+1.13 = 3.05
CDI= ∑Q(Xi) Wi= 3.05											

Table 5.13: Chemical Degradation Index of soils in Khubelu wetland

Soil Variable	Xij mean	Xi min	Xi max	Xij – Xi min	Xi max – Xi min	Q(Xi) Eq 3.6	Wi	Q(Xi) Wi	Q(Xi) Eq 3.7	Xi max - Xij	Q(Xi) Wi
CEC	4.14	3.43	4.42	0.71	0.99	0.72	0.79	0.57		0.28	
EC	0.25	0.10	0.81	0.15	0.71		0.91		0.79	0.56	0.71
TN	1.23	0.77	2.00	0.46	1.23	0.37	0.90	0.34		0.77	
TC	10.33	5.12	18.40	5.21	13.28	0.39	0.85	0.33		8.07	
OM	2.67	2.04	3.90	0.63	1.86	0.34	0.85	0.29		1.23	
Avail P	0.20	0.11	0.34	0.09	0.23	0.39	0.78			0.14	
Exchangeable Mg	2.36	2.35	2.37	0.01	0.02	0.50	0.71			0.01	
Exchangeable Na	0.82	0.68	1.13	0.14	0.45	0.00	0.80		0.69	0.31	
Exchangeable K	0.35	0.14	0.99	0.21	0.85	0.25	0.70			0.64	
pH	5.08	4.96	5.22	0.12	0.26	0.46	0.51	0.24		0.14	
Exchangeable Ca	0.85	0.74	0.92	0.11	0.18	0.00	0.69		0.39	0.07	0.27
∑Q(Xi)						3.42	6.30	1.76	1.87	0.00	1.53
Total											1.76+1.53 = 3.29
CDI= ∑Q(Xi) Wi= 3.29											

The wetland soil degradation might be due to overgrazing of vegetation within the wetland, which tends to leave the soil exposed further to external pressures like water erosion and harsh climate effects like heat and frosting. Poor wetland soil could imply that the soil has a reduced ability to retain pollutants and nutrients, making it easy for these components to be leached into the stream supplied by the wetland. The wetland soils might also not be able to support various processes such as nutrient cycling. With predicted climatic variations like increased temperatures, the wetland soil would be scotched resulting in further changes in wetland ecosystems coupled with loss of species. The ability of the wetland to perform its ecological function may be affected. Likewise, the potential for Khubelu wetland to remove nutrients and pollutants from discharge water would be reduced, causing a decline in the quality of water supplied into its stream.

5.4 Chapter summary

Khubelu wetland soil has a sandy loam texture. This textural class can support vegetation and retain OM. These properties aid in pollutant removal from water that must be discharged into the Khubelu stream. The soils are weakly acidic and non saline in nature. TN, TC and OM in the soil all decreased with increase in soil depth around the wetland. Exchangeable Ca, Mg, K and Na were higher in topsoil than in subsoil. The low CEC might make retention of nutrients and pollutants difficult. This would lead to leaching of cations and pollutants into the stream. The CDI of the wetland soils decreased from 3.42 to 3.25 (upstream to midstream) and 3.05 (downstream). However, the overall wetland soil CDI was determined to be 3.29 which was much higher than the maximum value of 2.0 that is reported for undegraded soils. The study has determined that the high CDI score might have been caused by external factors like overgrazing which exposed soil to gully erosion. However, climatic conditions, as predicted earlier in chapter four, may escalate the rate of soil erosion through vegetation cover loss. With predicted climatic variations which entail higher temperatures and low precipitation, the water pollution problems are also expected to escalate. The CDI is likely to be higher as well.

CHAPTER 6

RESULTS AND DISCUSSION: POTENTIAL OF KHUBELU WETLANDS TO PURIFY WATER

6.1 Introduction

In this chapter, the ability of the Khubelu wetland to purify water passing through it to streams is addressed. This function of the wetland is assessed by evaluating its ability to remove sediments, nutrients and organic compounds from the water. A description of the characteristics of the wetland is first presented and these are then used to determine the ability of the wetland to perform these different functions. 100% of the wetland is covered with emergent vegetation, 10% is deadstorage, and 40% is inundated with water. There are no areas of permanent open water or those with submerged vegetation in the wetland.

6.2 Characteristics of the Khubelu wetland

In the determination of the wetland's ability to purify water, the following wetland characteristics were evaluated: index for sediment removal (S_{sed}), wetland outlet constriction (V_{out}), wetland vegetation class ($V_{vegclass}$), area of wetland with herbaceous vegetation ($V_{understory}$), water storage ($V_{storage}$), area of wetland permanently inundated in water ($V_{effectarea1}$), percentage of wetland with clay and organic soil (V_{sorp}), percentage of wetland where conditions change between oxic and anoxic ($V_{effectarea2}$), adsorption (V_{sorp}), chemical precipitation (V_{pH}), and percentage of wetland with emergent vegetation ($V_{totemergent}$). A description of these wetland characteristics is presented below.

6.2.1 Wetland outlet constriction (V_{out})

Wetland outlet constriction determines how much water is held back within the wetland, thereby increasing the retention time of the water within the wetland. Wetland outlet constriction is described as unconstricted or slightly constricted, severely constricted or no channelised outlet (Adamus *et al*., 1991; Hruby *et al.,* 1999; Haering & Galbraith, 2010). These wetland outlet constrictions are scored as 0, 0.5, and 1.0 for unconstricted/slightly constricted, moderately constricted and severely constricted, respectively. The Khubelu wetland outlet was moderately constricted and was therefore given a score of 0.5 according to Hruby *et al.* (1999) classification. This outlet characteristic of the wetland implies that some of the water that gets into it during the rainy season is discharged into streams supplied by the wetland while some is retained. The removal of sediment, nutrients and pollutants by a wetland requires that the water be resident in the wetland for some time to allow absorption of nutrients and pollutants by the soil, and deposition of the sediment load transported by the water. A V_{out} score of 0.5 implies some pollutants and nutrients in the wetland water will be removed prior to its exit into the stream as they will be adsorbed onto soil or precipitated out of the water (Kovacic *et al.*, 2000; Withers & Jarvie, 2008).

6.2.2 Wetland vegetation class ($V_{vegclass}$)

The type of vegetation within the wetland was assessed with the help of the Cowardin vegetation class reference which describes vegetation classes as emergent, scrub/shrub, forest and aquatic bed (Cowardin *et al*., 1979). These different vegetation types are scored 1.0, 0.8, 0.3 and 0.0 for emergent, scrub/shrub, forest and aquatic bed vegetation, respectively (Cowardin *et al.,* 1979). Emergent vegetation covered 100% of the Khubelu wetland, and the wetland did not have scrub or shrub, forest and aquatic bed vegetation. The Cowardin classification gives emergent vegetation a score of 1 in the assessment of a wetland's ability to remove sediments because it is erect, and closer to the ground (Van De Valk, 1989; Faithful, 2015). This vegetation is also dense enough to reduce water velocity and filter out sediments. All these properties improve efficiency of a wetland to remove sediments and retain pollutants (Fisher & Acreman, 2004; DeBose *et al.,* 2014). The score for shrub and forest vegetation in the wetland was zero (0) as these vegetation types were absent from the AU. The score for $V_{vegclass}$ for Khubelu wetland was calculated according to equation 6.1 (Hruby *et al.,* 1999).

$$V_{vegclass} = \left(\frac{\%\, wetland\ with\ emergent\ vegetation}{100} \times 1\right) + \left(\frac{\%\, wetland\ with\ scrub}{100} \times 0.8\right) + \left(\frac{\%\, wetland\ with\ forest}{100} \times 0.3\right) + \left(\frac{\%\, wetland\ with\ aquatic\ bed}{100} \times 0.0\right) \qquad \textbf{(6.1)}$$

= (1 x1) + (0 % x 0.8) + (0% x 0.3) + (0% x 0.0)

$= (1 + 0 + 0 + 0)$

= **1**

This score indicates that the vegetation in the Khubelu wetland has a potential to reduce water velocity and trap sediments which would otherwise be carried with the water downstream.

6.2.3 Area of wetland with emergent vegetation ($V_{totemergent}$)

Direct observation of emergent vegetation species was done using Cowardin classification. According to this classification, areas with 100% cover are allocated 1, and other areas allocated proportional score as % of the wetland (Hruby *et al.,* 1999). The areal extent of emergent species in the wetland was estimated directly, and 100% of the wetland was covered with emergent vegetation, giving $V_{totemergent}$ a score of 1. This implied that water within the wetland was in contact with this vegetation type, which may sequester any available organics and toxic heavy metals from the wetland water. This type of vegetation also gives support to microbial population for decomposition of organic contaminants (Hruby *et al.,* 1999; Wantzen *et al.,* 2008). Stream water could therefore contain reduced amount of organic compounds due their decomposition in the wetland.

6.2.4 Area of wetland with herbaceous vegetation ($V_{understory}$)

Herbaceous understory is the vegetation present under a forest, which is about one metre above the ground. Herbaceous understory comprises herbaceous plants and grasses, forest, evergreens, deciduous and scrubs/shrubs. Herbaceous vegetation like emergent vegetation has a similar potential to trap some sediments (Gilliam, 2007). Wetland understory covered by herbaceous vegetation is scored 1, and proportionate areal coverage allocated thereafter (Hruby *et al.,* 1999) based on % coverage of the wetland. Equation 6.2 was used for the calculation of Vunderstory, utilising scores from % type of herbaceous vegetation forest, evergreen, deciduous and scrubs/shrubs. All the classes were not represented in the Khubelu wetland, and so were allocated percentage coverage of zero (0%) (Equation 6.2).

$$V\ understory\ \frac{(0.01\times 0\% forest/scrub)\times(forest+Evergreen+Deciduous+scrub)}{100} \qquad \textbf{(6.2)}$$

$$Vunderstory = \frac{[\,(0.01\times 0\,\%)\times(0+0+0+0)}{100}$$

$$= \mathbf{0.0}$$

With a score of 0.0 for the Khubelu wetland’s ability to trap sediments as a result of the presence of herbaceous understory is negligible.

6.2.5 Water storage ($V_{storage}$)

Water storage measures the volume of water that the wetland can store such that during the period when water is being retained, sediments are settling out (Wang *et al.*, 2014). This was achieved by first measuring livestorage, which is a measure of the volume of storage available during major rainfall events, followed by deadstorage, which represents the amount of water stored below the bottom of the wetland outlet. Equations 6.3 and 6.4 were used in the calculation of livestorage and deadstorage. When average depth of the two (livestorage and deadstorage) is equal to or greater than 1, a score of 1 is allocated. On the other hand, when the sum of the two is less than 1, scaling is done based on average depth. This, according to Hruby *et al.* (1999), was determined by dividing the average depth by one:

$V_{storage}$:

$$\boldsymbol{Livestorage} = Difference\ in\ elevation\ between\ the\ wetlands\ lowest\ point\ of\ outflow\ and\ annual\ inundation \times (0.67 \times D11.1) + (0.5 \times D11.2) + (1 \times D11.3) \quad \textbf{(6.3)}$$

Where:

Difference in elevation between wetland flood marks and wetland outlet = 1

D11.1 = cross section 1 of the wetland according to figure 6.1 = 1

D11.2 = cross section 2 of the wetland according to figure 6.1 = 0

D11.3 = cross section 3 of the wetland according to figure 6.1 = 0

Cross section 1 (Figure 6.1) best fits the cross section of the AU, and was scored 1

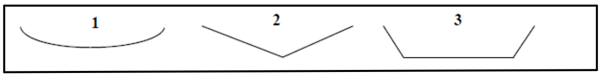


Figure 6.1: Possible cross sections of wetland.

The cross section of Khubelu wetland was similar to Figure 6.1 (1)

$$\boldsymbol{Livestorage} = \text{difference in elevation between AU flood marks \&}\ wetland\ outlet \times (0.67 \times \text{cross section 1}) + (0.5 \times \text{cross section 2}) + (1 \times \text{cross section 3})$$

$$Livestorage = 1 \times ((0.67 \times 1) + (0.5 \times 0) + (1 \times 0))$$

$$= \mathbf{0.67}$$

Deadstorage area was determined to be 10% from ArcGIS analyses

$$\text{Deadstorage} = \text{\% of wetland with permanent open water} \times 0.01 \times 2 \quad \textbf{(6.4)}$$

Where:

2 = the estimated average depth of permanent open water, and hence volume of storage (Hruby *et al.,* 1999).

$$Deadstorage\ =\ (10\,\%\ \times 0.01 \times 2)$$

$$= \mathbf{0.2}$$

Livestorage and deadstorage results were substituted in equation 6.5 for calculation of the wetland storage.

$$Vstorage\ = (livestorage\ +\ deadstorage)/1.0 \qquad \textbf{(6.5)}$$

$$= (0.67\ +\ 0.2)/1.0$$

$$= 0.87/1.0$$

$$= \mathbf{0.87}$$

The 0.87 score implies that water in the wetland had moderate residence time, which would enable sediments to be trapped according to Fennessy *et al.* (1994) together with pollutants that get attached to them, withholding them prior to water discharge into the Khubelu stream.

6.2.6 Area of wetland permanently inundated in water ($V_{effectarea1}$)

This represents an area from where sediments are removed from surface waters. Inundation period is reliant on several factors like a wetland's hydrogeologic setting, region's physiographic setting and climate (Mausbach & Richardson, 1994). From the ArcGIS analyses, 40% of the Khubelu wetland had permanent annual inundation. The area of wetland permanently inundated in water was therefore calculated as indicated in equation 6.6 (Hruby *et al*., 1999).

$$V_{effectarea1}\ =\ \frac{\%\ \text{area inundated}}{100} \qquad \textbf{(6.6)}$$

$$V_{effectarea1} = \frac{40}{100} \qquad = \mathbf{0.4}$$

This score shows that the wetland has a reasonable area from where sediments can be removed according to Johannesson *et al.* (2015).

6.2.7 Percentage of wetland with clay and organic soil (V_{sorp})

V_{sorp} is an indicator of the sorptive properties of the wetland soil. Phosphorus sorption is higher when soil has a high content of clay (Bridgham *et al.,* 2001) or organic matter

(Bruland & Richardson, 2006). Chapter five of the study has shown that the soils of the Khubelu wetland are sandy loam (59.1% sand, 18.7% silt and 22.2% clay), and this class has between 50% and 95% non-clay minerals. Wetland soil with less than 50% non-clay mineral is scored 1, those with between 50 and 95% non-clay mineral are given a score of 0.5, whereas those with non-clay mineral surface soils above 95% were given a score of zero (0) (Daniels *et al.,* 2010). A score of 0.5 was given to the Khubelu wetland since its non-clay mineral soil is between 50 and 95% as recommended by Hruby *et al.,* (1999).

V_{sorp} = **0.5**

This score implies moderate P sorption capacity of the soils in the wetland and hence minimal P release into the stream. A study by Pezeshki and DeLaune (2012) has shown that P release is also influenced by soil chemical changes, whereby flooded conditions with anaerobic conditions enable transportation of P deeper into soil or their release into subsurface water (Young & Ross, 2001; Amarawansha *et al.,* 2015). Phosphorus adsorption to clay is effective due to its high surface area (Withers & Jarvie, 2008; Rashed, 2013), and high amount of oxalate extractable aluminium and iron $(Al+Fe)_{ox}$ on surface soils (Schoumans, 2015).

6.2.8 Percentage of wetland where conditions change from oxic and anoxic ($V_{effectarea2}$)

The areas in the wetland that experience seasonal and annual flooding represent the areas where conditions are likely to change from oxic to anoxic. These areas indicate the extent to which nitrogen transformation would take place through nitrification and denitrification (Jordan *et al.*, 2003; Hermandez & Mitsch, 2007; Palta *et al.,* 2016). Nitrification is a microbial process that takes place during oxic conditions, converting ammonia into nitrites, and the nitrogen removal process is completed by nitrite-oxidising bacterium (nitrobacter) that converts the nitrites into nitrates (Wolfe & Lieu, 2001; Mitsch & Gosselink, 2007). According to Seitzinger *et al.* (2006) and Lamba *et al.* (2017), ammonium is hanged to nitrate during the oxic regime and conversion of nitrate to nitrogen gas (denitrification) occurs during anoxic conditions. The Khubelu wetland was 40% inundated with water for more than one month. There were no areas with permanent open water or those with open water covered with submerged vegetation and both scored 0 (Equation 6.7).

$$V_{effectarea2} = \frac{(\%\ of\ AU\ that\ is\ ponded\ or\ innundated\ for > 1\ month - (\%\ of\ AU\ with\ permanent\ open\ water + \text{Aquatic bed class}))}{100} \quad \textbf{(6.7)}$$

Where:

Aquatic bed class = open water covered by plants that grow on/above surface of the water OR floating leaf rooted vascular plants, and submerged mosses (Hruby *et al.,* 1999).

$$V_{effectarea2} = \frac{(40-(0+0))}{100}$$

$$V_{effectarea2} = \frac{40}{100}$$

$$V_{effectarea2} = \mathbf{0.4}$$

The score represents % area of the wetland that undergoes a shift between oxic and anoxic conditions. It also shows that moderate nitrogen transformation might take place since about 40% of the wetland was seasonally inundated (Daniels *et al*., 2010). In a study by Mubyana *et al.* (2003), low nitrogen values have been observed in the floodplain as a result of denitrification, signifying the effect of anaerobic conditions on nitrate conversion to volatile N oxides (Davidsson & Stahl, 2000). A score of 0.4 for Khubelu wetland indicates that some nitrogen contained in the wetland water would be lost to the atmosphere through denitrification, reducing nutrient pollution of the stream by the wetland. This further implies that there would be a potential to reduce pollution problems like eutrophication. However, if there are external sources of nitrogen into the wetland, then the wetland might become a nutrient source for the stream and not sinks (Gathumbi *et al.,* 2005).

6.2.9 Chemical precipitation (V_{pH})

pH plays a significant role in the precipitation of many toxic compounds out of water. Measuring the amount of contaminants that are removed from the wetland was guided by the level of pH in water within the wetland soil (Anderson & Nilsson, 2001; Mitsch & Gosselink, 2007). Apart from flooded conditions, chemical precipitation takes place when pH is below 5 (Mengel & Kirkby, 1982; Hruby *et al.,* 1999). However, there are toxic metals like lead that may precipitate out at pH above 9 (Hruby *et al.,* 1999). In Chapter 4, which addresses aspects of water quality in this study, pH of the Khubelu wetland interstitial water was measured and the average pH was 5.08. Low pH implies dissolution of many toxic metals and hence given a high score 1 (Mengel & Kirkby, 1982; Hruby *et al.,* 1999). A score of 1 is allocated when pH of interstitial water is below 4.5; 0.5 when pH is between 4.5 and 5.5 and 0 when pH is above 5.5 (Hruby *et al.,* 1999). The wetland's V_{pH} was thus allocated a score of 0.5 since the mean pH value of the interstitial water of the wetland was 5.08. The 0.5 score shows moderate ability of Khubelu wetland to retain toxic metals through precipitation, and the receiving stream may as a result have low concentration of toxic metals.

6.3 Water purification ability of Khubelu wetland

6.3.1 Potential to remove sediments

In this section, the wetland's potential to remove sediments through velocity reduction and pollutant filtration is determined. The wetland's characteristics and their scores, as described in section 6.2 of this chapter, are used as in equation 6.8 to determine its ability to remove sediments.

$$Index\ for\ removing\ sediment\ (S_{sed}) = (V_{storage} + V_{out} + V_{effectarea1} + V_{vegclass} + V_{understory}\ )x\ 2.56 \qquad (6.8)$$

Where:

$V_{storage}$ = average depth of both livestorage and deadstorage = 0.87

V_{out} = quantitative descriptors of outlet constriction = 0.5

$V_{effectarea1}$ = % of AU that is inundated = 0.4

$V_{vegclass}$ = % of AU in different Cowardin vegetation classes = 1.0

$V_{understory}$ = % AU area of herbaceous vegetation found under forest & shrub/scrub = 0.0

2.56 = factor utilised to normalise the scores (Daniels *et al.,* 2010) since for each evaluated function, the best performing wetlands of similar geomorphic settings (Hruby *et al.,* 1999; Daniels *et al.,* 2010) scores 10

Index for removing sediment = (0.87 + 0.5 + 0.4 +1.0 + 0.0) x 2.56

= (0.87 + 0.5 + 0.4 +1.0 + 0.0) x 2.56

= 2.77 x 2.56

= 7.09 ≃ **7**

A score of 7 indicates a moderate ability for the wetland to remove sediments on a scale where a score of 10 represents the highest level of performance (Hruby *et al.,* 1999; Daniels *et al.,* 2010). Sedimentation was observed upstream of the wetland (Figure 6.2), further showing that the wetland has a potential to remove sediments. Sediment retention was facilitated by vegetation cover that ensured velocity reduction of water

(Stevenson *et al*., 1988) as filtration took place. The sediment removal potential will ensure that pollutants absorbed/adsorbed on these sediments could also be removed in the process. This function is significant in improving water quality since sediments could have sorbed nutrients and toxic organics (Cooper *et al.,* 2000; Noe & Hupp, 2009). With predicted decline in precipitation, it might be expected that vegetation cover may not be adequate. This threatens sediment trapping and velocity reduction of water that runs through the wetland. If this happens, pollutants that would normally be trapped by vegetation would be transported into the Khubelu stream with discharge water. $V_{storage}$ and $V_{effectarea1}$ would also be lower, impacting negatively on the residence time and percentage of the wetland which is inundated. These would reduce the sedimentation process that enables pollutant removal. However, if mean annual precipitation decreases the volume of water will be minimal and consequently its kinetic energy may not be high enough to transport sediments. High temperature, on the other hand would lead to high evapotranspiration from vegetation; a process which would lead to wilting and eventual death of the plants. Loss of vegetation would thus impact negatively on sediment retention capacity of the wetland

Figure 6.2: Photo showing sedimentation upstream of the Khubelu wetland

6.3.2 Potential to remove nutrients

This section looks at the potential of the wetland to remove nutrients including phosphorus and nitrogen from interstitial waters. The potential to remove nutrients was determined according to recommendations by Daniels *et al.* (2010) using equation 6.9:

$$Index\ to\ remove\ nutrients = (S_{sed} + V_{sorp} + V_{effectarea2} + V_{out})x\ 2.56 \qquad (6.9)$$

Where:

S_{sed} = the index for removing sediment = 7.09/10 (10 being the scaling factor for S_{sed})

V_{sorp} = % of the wetland with clay soil and organic soil = 0.5

$V_{effectarea2}$ = the area of annual inundation – area of permanent exposed water = 0.4

V_{out} = constriction description of outlet characteristics = 0.5

2.56 = Factor utilised in order to normalise the score (Daniels *et al.,* 2010)

$$Index\ to\ remove\ nutrients = \left(\frac{7.09}{10} + 0.5 + 0.4 + 0.5\right) \text{x } 2.56$$

$$= (0.709 + 0.5 + 0.4 + 0.5) \text{ x } 2.56$$

$$= 2.109 \text{ x } 2.56$$

$$= 5.39$$

$$\pm \mathbf{5}$$

The Khubelu wetland index for removing nutrients from water is 5, and this score is an indication of average performance in nutrient removal (Daniels *et al.,* 2010). Water discharged from the wetland will have reduced levels of nutrients, delaying nutrient enrichment which would impact negatively on stream health. Negative impacts of nutrients leaching into the stream include DO depletion, increased BOD, ammonia toxicity and eventually eutrophication. Due to predicted shortages of rainfall, the percentage area inundated is likely to be low reducing the $V_{effectarea2}$ score. The lower area that is inundated would contribute towards low level of nutrient removal. OM decomposition is faster when temperatures are high, and low OM would lead to the release of nutrients from soil which would leach into the stream causing nutrient enrichment.

6.3.3 Potential to remove toxic organic and inorganic pollutants

This section presents the potential of the wetland to remove toxic organics through sedimentation, adsorption, precipitation and plant uptake. This was determined according to equation 6.10 (Daniels *et al.,* 2010).

$$Index\ for\ removing\ pollutants = \left(S_{sed} + V_{sorp} + V_{pH} + V_{totemergent} + V_{effectarea1}\right) \times 2.38 \qquad (6.10)$$

Where:

S_{sed} = wetlands index for removing sediments = 7.09/10 (10 being the scaling factor for S_{sed})

V_{sorp} = percentage of wetland with clay and organic soil = 0.5

V_{pH} = pH of interstitial water = 0.5

$V_{totemergent}$ = percentage area of emergent vegetation in the wetland = 1.0

$V_{effectearea1}$ = percentage of wetland that is annually inundated = 0.4

2.38 = Factor utilised in order to normalise the score (Daniels *et al.,* 2010)

$$Index\ for\ removing\ pollutants = \left(\frac{7.09}{10} + 0.5 + 0.5 + 1.0 + 0.4\right) \text{ x } 2.38$$

$$= (0.709 + 0.5 + 0.5 + 1.0 + 0.4) \text{ x } 2.38$$

$$= 3.06 \text{ x } 2.38$$

$$= 7.39$$

A score of 7.4 shows a moderate ability of the Khubelu wetland to remove pollutants from the water. The toxic organic compounds would therefore be retained by the wetland. Water discharged into the stream may likely contain low levels of toxic organics. Menzies and Gillman (2003) have associated an increase in soil pH with high temperatures due to organic acid denaturation. With expected rising temperatures, Khubelu soil pH is also likely to increase, decreasing precipitation of toxic organics from the wetland. Again, warmer temperatures are likely to increase toxin bioaccumulation (Spellman & Drinan, 2001; Malmqvist & Rundle, 2002), which might end up being leached into the stream if they are not sufficiently removed. The toxic organics will therefore end up in the Khubelu stream. Dehydration of 2:1 clay mineral would also be expected with higher temperatures, with resultant decrease in clay particles (Arocena & Opio, 2003). Low clay component of the Khubelu soil would lead to minimal removal of toxic organics through adsorption, with subsequent leaching into the stream. Low precipitation, on the other hand would lead to a reduced percentage of the wetland area that is annually inundated. This condition would reduce effective area for toxic organics' absorption together with the period of inundation. Furthermore, there would be invasion of non-hydrophobic vegetation which is not tolerant to the reducing wetland environment (Inglett *et al.,* 2005).

The results of the assessment of the wetland's ability to purify water indicate that the extent to which it can remove sediment, nutrients and pollutants from the wetland water varies; with index values of 7, 5, and 7.8 for the removal of sediments, nutrients and pollutants, respectively. The Khubelu wetland can be described as being more efficient in sediment and pollutant removal compared with nutrient removal. The implications of this are that a large amount of nutrients entering the wetland are likely to be discharged into receiving streams. These streams may therefore be at risk of undergoing eutrophication process, especially during the dry season when water movement is relatively low. Activities that result in the discharge of huge quantities of nutrients into the wetland should be closely monitored as there is a high risk of these nutrients being discharged into streams and rivers that are fed by the wetland. With predicted low precipitation, vegetation cover might not be rich enough to trap the sediments, threatening pollutant load in the stream. Climate predictions show a possible increase in temperature, and this would speed up the release of nutrients since decomposition processes of organic matter would be faster; also because of low OM to retain them. Low precipitation would lead to dying of aquatic macrophytes, spiking OM that would also decompose faster in a warm environment. There would be a gradual development of a new stable condition that differs from the natural wetland. The Khubelu stream is one of the tributaries of Senqu River supplying the Orange-Senqu River catchment. With the Khubelu stream being the headwaters of this catchment, the Lesotho government has a mandate to ensure its protection. Degradation of the wetland would further threaten its water purification function, further rendering the water discharged into the stream of poor quality.

6.4 Chapter summary

The results presented in this chapter indicated that the Khubelu wetland has a moderate potential to remove sediments through velocity reduction. Sediment removal will ensure that pollutants that might pass through the wetland are removed in the process, ultimately ensuring pollution reduction for water discharged into the Khubelu stream. Furthermore, the wetland showed a moderate ability to remove toxic organics through processes like adsorption, chemical precipitation and plant uptake. Its potential to remove nutrients is however rated as average. Though the Khubelu wetland has a potential to purify water that it discharges into its stream, there needs to be constant monitoring to ensure that the wetland does not deteriorate.

CHAPTER 7
SUMMARY, CONCLUSION & RECOMMENDATIONS

7.1 Introduction

In this chapter, a summary of the findings of the study, which have led towards the conclusions, are presented. Recommendations regarding the wetland conservation and protection measures that will ensure water and soil quality improvement are provided.

7.2 Summary of research

The aim of the study was to determine how climate change may affect water quality in Khubelu wetland and to understand how the possible effects may impact on the wetland's water purification ability. Specific objectives that guided the study were:

i. i. To determine the quality of water in Khubelu wetland and stream.
ii. To characterise the soil quality of Khubelu wetland.
iii. To assess the water purification function of the Khubelu wetland.
iv. To determine the effect of climate change on water quality of the Khubelu stream.

The conclusions of the research will be presented below, according to the objectives.
Water and soil from the Khubelu stream were sampled and their properties determined with a view of assessing the Water Quality Index and soil Chemical Degradation Index of the wetland. The wetland characteristics and its water purification function were also determined. A model was utilised to predict changes in water quality in the face of a changing climate. Values for DO in the wetland water were below the WHO limit of 5 mg/l in both the stream and wetland. Values for BOD, COD and phosphates in the stream and wetland were all within the limits of the WHO standards whereas EC was within the limit in the wetland but slightly above the recommended WHO level in the stream. The major cations (Mg, Na, Ca and K), TDS, nitrates, and Cl in the stream and piezometers, were within the WHO permissible levels. The study has revealed that there might be some degree of pollution in the wetland water according to values of the WQI.

The wetland soil was acidic and might impact negatively on vegetation growth. However, soil parameters like TC, TN and OM are within topsoil limits. All the exchangeable cations in the study area are higher in topsoil than subsoil. Soil CDI varied across the wetland and showed that the wetland was degraded since the CDI value for its soils was above the limit of 2. The study has shown that the wetland has a potential to remove sediments, nutrients and organic compounds and therefore has some capacity as a medium for purifying water. However, with escalating temperatures and declining discharge from the wetlands, there is a likelihood that the water quality may also decline, calling for integrated management of this scarce resource.

7.3 Conclusion

The conclusions of the research are presented according to the objectives stated above.

7.3.1 Water quality of Khubelu wetlands and stream

- The values obtained for WQI of both the stream and wetland indicate that the stream water is unsuitable for human consumption and the wetland water quality is very poor. Regarding livestock drinking, the water quality was acceptable for sheep and cattle according to FAO water quality standards.
- Variations of water parameters from the upper area of the wetland to the lower area have shown that levels were higher within the lower area in the proximity of the stream compared to the upper section of the wetland.
- Stream water quality was lower than that of the wetland, and this was mostly affected by parameters like PO_4, COD, BOD_5 and pH.
- Predicted increase in temperatures and decline in precipitation might lead to poorer water quality due to high evaporation that leaves concentrated pollutants, coupled with shortage of water which would dilute the pollutants.

7.3.2 Soil quality

- The wetland soil was acidic and may be unsuitable for vegetation growth.
- Soil pH, EC, TN, TC, OM and exchangeable Ca decreased with depth across the wetland.
- Low available phosphorus within the lower area of the wetland and high phosphates in the stream might imply that there are external sources of phosphates into the stream. It could also be possible that anoxia in wetland sediments caused P to be available and this helped it leach into the stream.
- The wetland soil CDI of 2.75 shows that the wetland is degraded.

- Low precipitation and high temperatures, as predicted, would likely cause faster decomposition of plant litter, further lowering even OM in topsoil.
- Water quality of the receiving stream could be threatened since pollutants will not be adequately retained by the wetland.

7.3.3 Potential to purify water

- The wetland has shown a potential to remove sediments, nutrients and pollutants which could affect water quality.
- The Khubelu wetland's ability to remove nutrients is however lowest among the three functions related to water purification, which implies that the streams supplied by the wetlands maybe at risk of pollution.
- With predicted high temperature and low precipitation, this water purification function might be lost due to low retention time of water, poor inundation of the wetland, and excessive evaporation of water, to mention a few.

7.3.4 Effect of climate change on water quality

The WEAP model has predicted that oxygen-depleting pollutants and other related pollutants that are driven by climate are highly likely to increase during the period 2018 to 2025. As a result, the stream water quality is likely to be poorer in the future. For animal drinking, it should be taken into consideration that the predicted increase in evaporation might result into high salinity and increase in other pollutants.

7.4 Contribution to knowledge

This is the first time such a comprehensive assessment of the Khubelu wetland has been carried out. Some of the contributions that this study has made to the available body of knowledge are highlighted below.

- In this study, it was revealed that the Khubelu wetland water is of very poor quality, whereas the stream water is unsuitable for direct use, implying that the water has to be treated prior to human consumption. This was achieved through determination of Water Quality Index and Chemical Degradation Index respectively. However, the water was of usable for all classes of animals.
- The wetland water and soil were characterised in order to evaluate their level of performance in water purification function.

  - It was further established that, with predicted changes in climatic variations, pollutants in the Khubelu wetland may not be trapped by vegetation and absorbed onto the soil due to vegetation cover loss and soil degradation respectively. This has further provided information on threats which may increase stream pollutant load. This phenomenon will render the stream water unsuitable for direct use by the Basotho nation and even by downstream users like the neighbouring countries (South Africa, Namibia and Botswana). Conventional treatment technologies would have to be employed since the water is polluted.
- In this study, a comprehensive method of wetland assessment was utilised, and this has never been done in previous studies of Lesotho and is therefore going to be a baseline for assessment of other wetlands in the country and other regions.
- The aspects of water purification which are most at risk have also been exposed through this study. Information is now available that indicates that the streams supplied by the wetland may be at risk of nutrient enrichment as the ability of the wetland to remove nutrients from the water is relatively low.
- The study has highlighted aspects of a palustrine wetland in Lesotho which was not previously available. The determination of water and soil quality was done, and this related to wetland water purification function and the implications of climate change. This may provide information that decision makers can now use to design programmes for the management of the wetlands in the face of changing temperature and precipitation patterns.
- The study, through the modelling of water quality, has further shown that the Khubelu wetland and stream may not be resilient to climatic variations. Projected increase in temperature and decrease in precipitation have been used, for the first time in this study, to model pollution levels of the Khubelu stream.

7.5 Recommendations

Based on the results of the study, the following recommendations are proposed:

- There needs to be continuous monitoring of the water quality as there are indications that its quality is at risk; a condition which might further be exacerbated by the predicted climate change. With the Khubelu stream being one of the tributaries of Senqu River (which also supplies nations like South Africa, Namibia and Botswana) close monitoring is necessary to avoid water-related crisis in these countries.

- Results from the study have indicated that the wetland has a low capacity to retain nutrients that are likely to affect the water quality of receiving streams. Strategies and programmes aimed at reducing the amount of nutrients introduced into the wetland need to be designed to reduce the risk of eutrophication that may occur as a result of nutrient enrichment.
- It is highly recommended that, for soil and water of good quality to be maintained in the wetland, implementation of environmental laws needs to be ensured and awareness campaigns carried out so that stakeholders would be aware of the impeding threats to the wetland, and how this might change with the predicted climate change.
- Studies such as this need to be carried out regularly so that the state of the wetland is known at all times.

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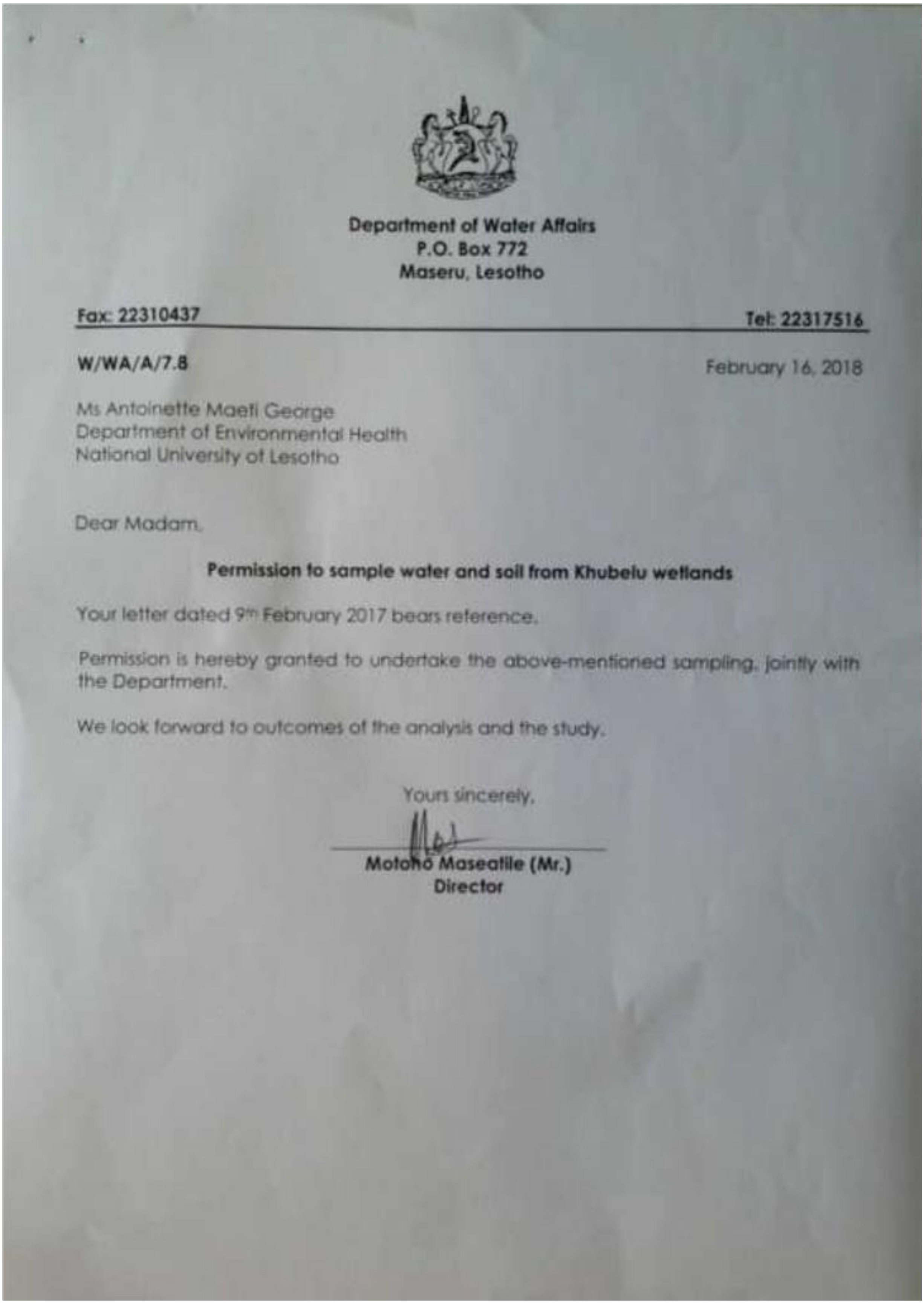
Appendix I: Department of Water Affairs Permission letter



Department of Water Affairs
P.O. Box 772
Maseru, Lesotho

Fax: 22310437 **Tel: 22317516**

W/WA/A/7.8 February 16, 2018

Ms Antoinette Maeti George
Department of Environmental Health
National University of Lesotho

Dear Madam,

Permission to sample water and soil from Khubelu wetlands

Your letter dated 9th February 2017 bears reference.

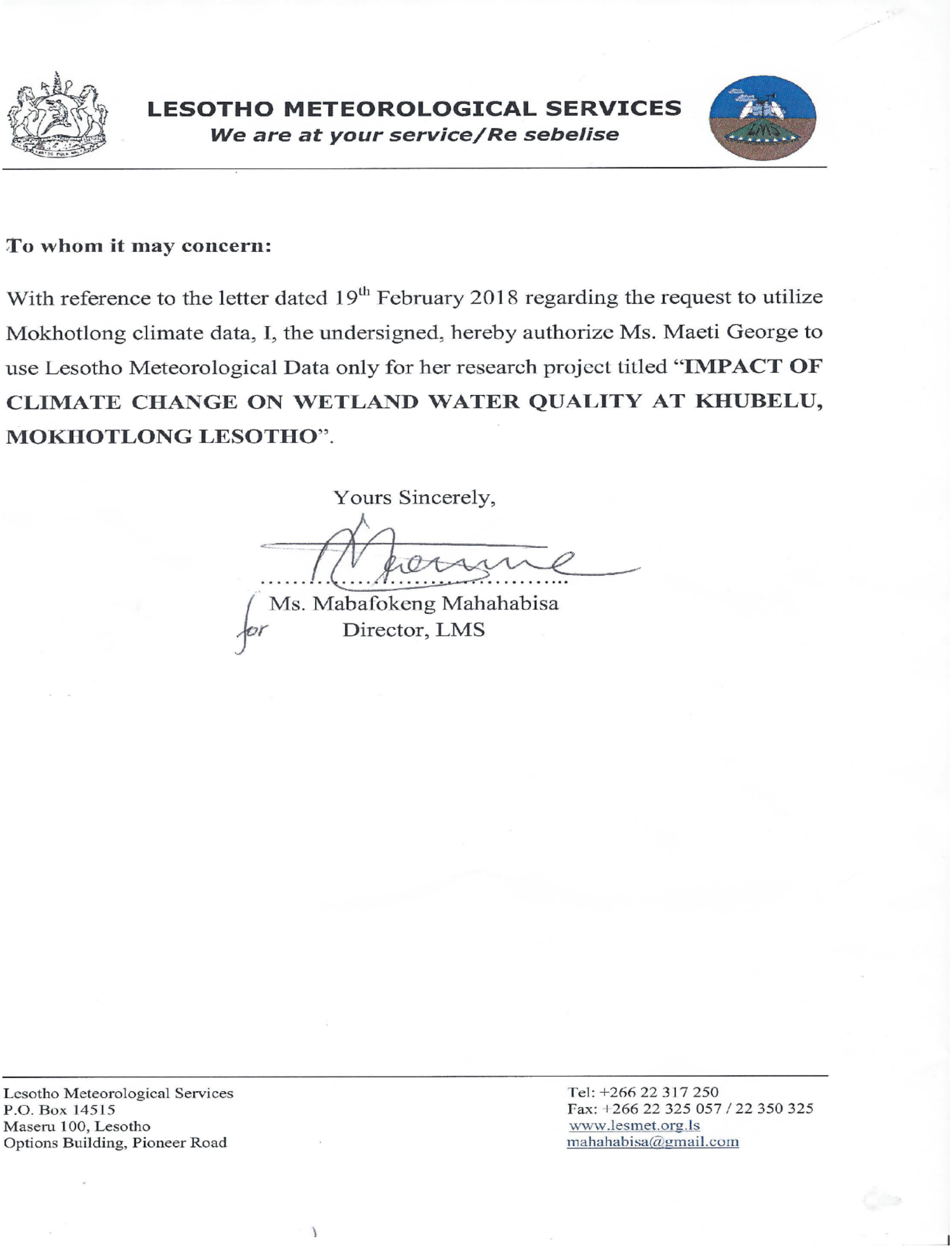
Permission is hereby granted to undertake the above-mentioned sampling, jointly with the Department.

We look forward to outcomes of the analysis and the study.

Yours sincerely,

Motoho Maseatile (Mr.)
Director

Appendix II: Lesotho Meteorological Service Permission letter



LESOTHO METEOROLOGICAL SERVICES
We are at your service/Re sebelise

To whom it may concern:

With reference to the letter dated 19th February 2018 regarding the request to utilize Mokhotlong climate data, I, the undersigned, hereby authorize Ms. Maeti George to use Lesotho Meteorological Data only for her research project titled "**IMPACT OF CLIMATE CHANGE ON WETLAND WATER QUALITY AT KHUBELU, MOKHOTLONG LESOTHO**".

Yours Sincerely,

……………………………………

Ms. Mabafokeng Mahahabisa
for Director, LMS

Lesotho Meteorological Services
P.O. Box 14515
Maseru 100, Lesotho
Options Building, Pioneer Road

Tel: +266 22 317 250
Fax: +266 22 325 057 / 22 350 325
www.lesmet.org.ls
mahahabisa@gmail.com

Appendix III: Seate Council permission letter

Seate J01 Community Council
P.O Box 493
Mapholaneng 520
21st march 2018

Dear Sir/Madam

Re: Permission to collect water and soil samples from Phapong wetland in Khubelu area for research purposes.

Seate Community Council has approved your request to collect water and soil samples from Phapong wetland as part of fulfillment for you to complete your research.

SEATE J01
COMMUNITY COUNCIL
2018 -03- 22
P.O BOX [illegible] MOKHOTLONG 500
LEKHOTLA [illegible] LA PUSO
[illegible] LA SEATE J01

....

Malefu Matolo (Ms)
Community Council Secretary

Appendix IV: UNISA Ethical Clearance Certificate

UNISA
university of south africa

UNISA GENERAL RESEARCH ETHICS REVIEW COMMITTEE

Date: 05/03/2018

Dear Ms George

Decision: Ethics Approval from 01/03/2018 to 28/02/2019

NHREC Registration # : REC-170616-051
ERC Reference # : 2018/CAES/42
Name : Ms AM George
Student # : 57643148

Researcher(s): Ms AM George
57643148@mylife.unisa.ac.za

Supervisor (s): Prof VM Ngole-Jeme
ngolevm@unisa.ac.za; 011-471-3878

Working title of research:

Impact of climate change on water and soil quality in Khubelo wetland, Mokhotlong Lesotho

Qualification: PhD Environmental Science

Thank you for the application for research ethics clearance by the Unisa CAES General Research Ethics Review Committee for the above mentioned research. Ethics approval is granted for a one-year period. After one year the researcher is required to submit a progress report, upon which the ethics clearance may be renewed for another year.

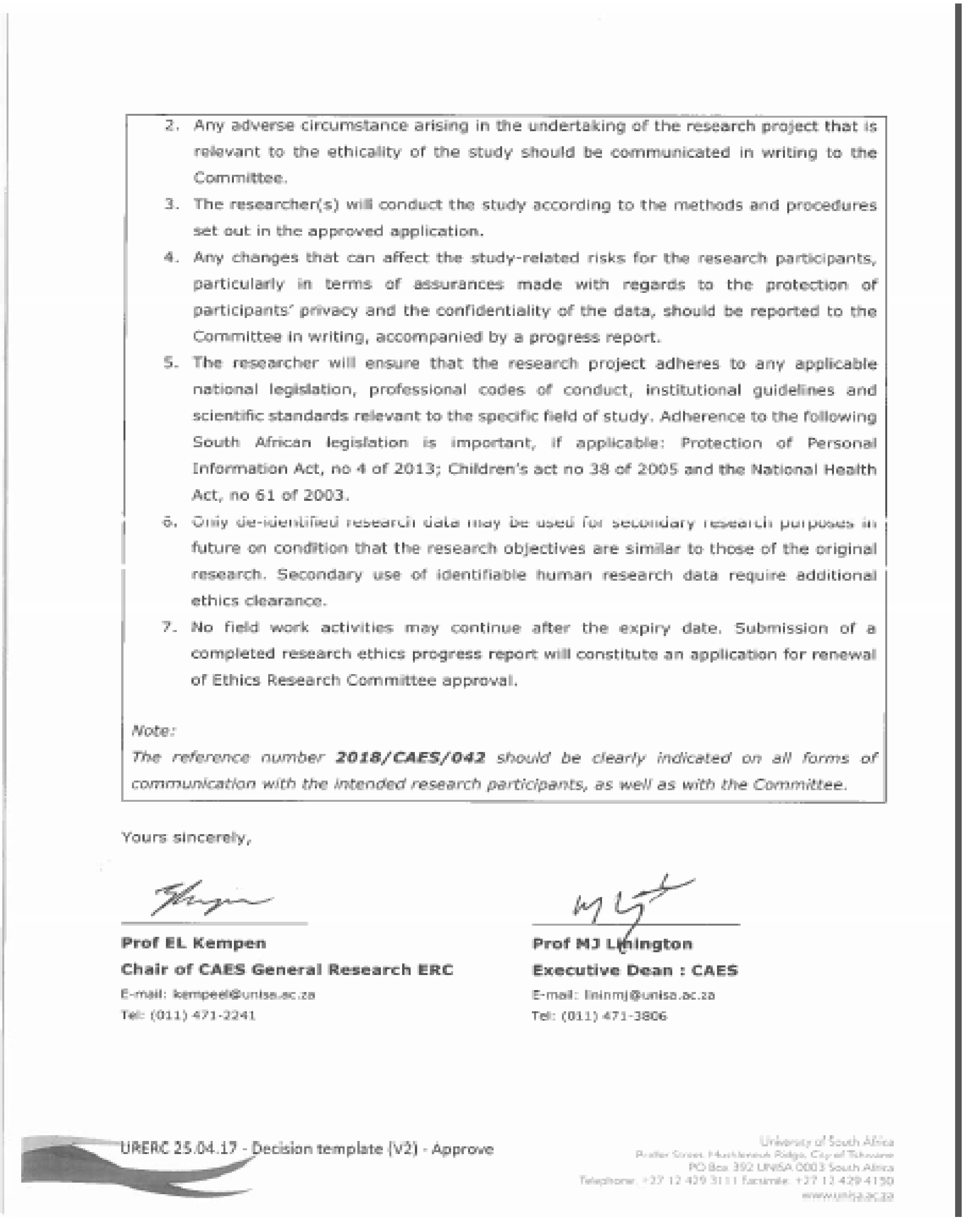
Due date for progress report: 28 February 2019

*The **low risk application** was **reviewed** by the CAES General Research Ethics Review Committee on 01 March 2018 in compliance with the Unisa Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment.*

The proposed research may now commence with the provisions that:

1. The researcher(s) will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.

University of South Africa
Preller Street, Muckleneuk Ridge, City of Tshwane
PO Box 392 UNISA 0003 South Africa
Telephone: +27 12 429 3111 Facsimile: +27 12 429 4150
www.unisa.ac.za



2. Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study should be communicated in writing to the Committee.
3. The researcher(s) will conduct the study according to the methods and procedures set out in the approved application.
4. Any changes that can affect the study-related risks for the research participants, particularly in terms of assurances made with regards to the protection of participants' privacy and the confidentiality of the data, should be reported to the Committee in writing, accompanied by a progress report.
5. The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study. Adherence to the following South African legislation is important, if applicable: Protection of Personal Information Act, no 4 of 2013; Children's act no 38 of 2005 and the National Health Act, no 61 of 2003.
6. Only de-identified research data may be used for secondary research purposes in future on condition that the research objectives are similar to those of the original research. Secondary use of identifiable human research data require additional ethics clearance.
7. No field work activities may continue after the expiry date. Submission of a completed research ethics progress report will constitute an application for renewal of Ethics Research Committee approval.

Note:
The reference number ***2018/CAES/042*** *should be clearly indicated on all forms of communication with the intended research participants, as well as with the Committee.*

Yours sincerely,

Prof EL Kempen
Chair of CAES General Research ERC
E-mail: kempeel@unisa.ac.za
Tel: (011) 471-2241

Prof MJ Linington
Executive Dean : CAES
E-mail: lininmj@unisa.ac.za
Tel: (011) 471-3806

Appendix V: Wetland Field Survey Guide

DATE: …………………………………

Air temp. (˚C)………………..

Coordinates: Lat:……………. Long…………………..

WEATHER CONDITIONS (mark with X)

Clear	Cloudy	Rain	Winds	Snow	Rain within last 12 to 24 hrs

Are climatic conditions typical of this time of the year? **Yes/No? ……………………….**

If No, explain under remarks section.

Identify wetland boundary

Wetland **Area** (km^2): …………….

Landform (slopey/terrace, etc): ……………………………….

Site map to show features like sampling points

1. Delineate wetland & Observe Assessment Unit
2. Find out area of AU= …………………
- Longest AU distance: **…………………**

3. Longest Stream length: **………………….**
4. Distance between piezometers
   a)………………….. c) …………………….. e) ……………………….
   b) ………………….. d) ……………………
4. Write down GPS coordinates for:
   a) **AU**: …………………………
   b) 7 piezometers from which water will be collected from, and
      GW 2: ……………………………..
      GW3: ……………………………..
      GW4: ……………………………..
      GW5: ……………………………..

GW6: ……………………………..
GW7: ……………………………..
GW8: ……………………………..
GW9: ……………………………..

c) soil sampled (3 FROM EACH PIEZOMETER)

d) Stream outlet

S1: ……………………………..
S2: ……………………………..

5. Fill in Habitat suitability; Vegetation cover & species richness; Macro & micro invertebrates; Soil type/texture; Hydrology:

Is there ANY SURFACE WATER?

a) Area of wetland inundated: ……………………………………………
b) Speed of water running out of outlet,
c) Any constriction towards outlet of wetland: YES/NO?
d) Depth of surface water: …………………

IF THERE IS NO SURFACE WATER, the following will be observed with coordinates:

a) water marks……………………..
b) drift lines………………………….
c) sediment deposits………………….
d) water stained leaves………………….
e) drainage patterns………………………..

Is the site significantly disturbed? Explain……………………………
Is vegetation……….., soil………………, or hydrology significantly disturbed?

VEGETATION

Type of vegetation	Names	**Dominant Species**	**% Vegetation Cover**

Remarks:			

HYDROLOGY SURVEY

	Piezometer 2	**Piezometer 3**	**Piezometer 4**	**Wetland Hydrology Indicators**
Depth of surface water				**Primary Indicators**: ☐ Inundated ☐ **X** Saturated ☐ Water marks ☐ Dirt lines ☐ **X** Sediment deposits ☐ Drainage patterns in wetlands **SECONDARY**: ☐ Oxidised root channels ☐ Water-stained leaves ☐ Local Soil survey data ☐ Other
Surface water movement (slow, fast, none)				
If no water, name hydrology indicators (water marks, drift lines, sediment deposits, water stained leaves, drainage patterns)				
Remarks:				

NB: A wetland may appear dry depending on the time of the year, precipitation amounts

Appendix VI: Guide used for Characterisation of wetland properties

MODELS: Adapted from Hruby *et al.* (1999)			
Sediment removal function: ability to reduce water **VELOCITY** (determined by retention time of water & vegetation structure near ground surface) Correction factor for area of sediment retention vs actual AU area ($V_{effect\ area1}$)	Depressional Outflow – Removing sediment		
	Process Velocity reduction	Variables $V_{storage}$	Measures/ indicators Average depth of both live & deadstorage
	Velocity reduction	V_{out}	Qualitative descriptors of outlet constriction
	Velocity reduction	$V_{effectareal}$	% of AU that is inundated
	Filtration	$V_{vegclass}$	% of AU in different Cowardian vegetation classes
	Filtration	$V_{understory}$	% area of herbaceous understory in AU
	INDEX: $\dfrac{V_{storage} + V_{out} + V_{effectareal} + V_{vegclass} + V_{understory}}{\text{Score from reference standard site}}$		
$V_{storage}$ = amount of storage (either live OR deadstorage). **Livestorage/ dynamic surface storage** being a measure of the volume of storage available during major rainfall events. **Deadstorage**: amount of water stored below the bottom of the outlet. Once			

deadstorage is filled, AU is not capable of store additional storm water. Thus, it is used to measure available water for storage. Residence time = storage/inflow volume.

FIELD WORK:

1. **Livestorage** = difference in elevation between bottom of outlet and ANY flood marks/ watermarks on vegetation/ along shore.
   Average depth of permanent open water = 2m
   Average depth of livestorage estimated at the outlet corrected by a factor representing the average cross section of the seasonally inundated areas in the AU.
2. Average depth of deadstorage = 2m × % of AU that is permanent open water

TOTAL STORAGE = **Av depth** × **area of AU**

$\mathbf{V_{out}}$ = Amount of constriction in surface outflow from AU

- **Unconstricted**/ slightly constricted: distance between low point of the outlet and inundation height (D28) is small (< 3-cm). scored a [0]
- **Moderately constricted**: outlet small enough to hold water back during wet season. Scored a [0.5]
- **Severely constricted**: small culverts/ heavily incised channels. Marks of inundation/ flooding a metre/ more above the bottom of outlet. ALSO, evidence of erosion on the downstream side of the outlet seen. Scored a [1].

$V_{effectareal}$: Area of the AU whereby sediment retention is expected to take place.

Summer inundation area: water marks, deposition lines and discolouration used to mark the area.

$V_{vegclass}$: % of ground in an AU that is covered by each of 4 Cowardin vegetation classes (emergent, shrub, forest, aquatic bed). Assumption is that 3 of the vegetation classes represent persistent vegetation.

Emergent veg [1]; shrub = [0.8]; forests [0.3] and aquatic bed [0] thus:

Score= fraction of AU with emergent × 1) + (fraction of AU with scrub/shrub × 0.8)+ fraction of AU with forest × 0.3)

$V_{understory}$: Areal extent of herbaceous vegetation under forested and scrub/shrub areas of AU.

Appendix VII: Wetland Observation Guide

WETLAND BUFFER (WITHIN 30m from wetland)

Excellent	**Good**	**Fair**	**Poor**
Natural vegetative cover		**X**	
Bank Stable- no erosion		**X**	
Undisturbed land			**X**

IMPACTS TO WETLAND

Animal grazing	**Quarrying**	**Clearing of vegetation**	**Dumping of sand, dirt, gravel**	**Fire**	**Roads construction/ Access roads**	**Other/Specify**
X						

VERTEBRATE PRESENCE

	Dung	**Tracks**	**Sightings (Estimate no.)**	**Burrows**	**Nests**
Cattle	**X**				
Horse					
Donkey					
Sheep	**X**	**X**			
Goat					
Ice rat		**X**		**X**	
Birds*					
Other/ specify					

***please specify species**

Observations of the wetland soil:

Are there any defined layers to the wetland soil? If so, describe.

Type……………………………………………………………………………………………

…………………………………………………

Depth

(cm/m)………………………………………………………………………………………

Are Hydric soils present? Yes………………………… No…………………………

What organisms are living in the soil?

Is there mottling (concentrated areas of red or yellow soil)?

………………………………………………………………………………………………

………………………………………………………………………………………………

………………………………………………………………………………

REMARKS:

Appendix VIII: Correlation matrix for water quality parameters in stream

Parameter	Temp	pH	EC	DO	Ca	Na	Mg	K	TDS	NO$_3$	PO$_4$	BOD	COD	Cl
pH	0.413	1.000												
EC	0.098	-0.600	1.000											
DO	0.018	0.452	-0.900	1.000										
Ca	0.759	-0.194	0.531	-0.441	1.000									
Na	0.732	-0.212	0.648	-0.491	0.898	1.000								
Mg	0.776	-0.142	0.353	-0.214	0.938	0.805	1.000							
K	0.365	-0.644	0.804	-0.563	0.744	0.871	0.655	1.000						
TDS	0.483	-0.429	0.430	-0.208	0.753	0.766	0.796	0.813	1.000					
NO$_3$	0.453	0.515	-0.099	0.254	-0.052	0.091	0.007	-0.102	-0.298	1.000				
PO$_4$	0.145	-0.027	0.660	-0.723	0.309	0.369	0.074	0.309	0.135	-0.160	1.000			
BOD	0.210	-0.306	0.762	-0.899	0.605	0.534	0.450	0.496	0.187	-0.081	0.489	1.000		
COD	-0.047	0.017	0.471	-0.455	-0.106	0.039	-0.288	0.073	-0.479	0.572	0.385	0.411	1.000	
Cl	-0.729	-0.035	-0.035	-0.253	-0.624	-0.477	-0.764	-0.380	-0.522	-0.356	0.148	0.010	0.162	1.000