



Spatial and Temporal Analysis of Water and Sediment Quality in Relation to Land-use in the Limpopo River Basin

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ABSTRACT

The Limpopo River Basin is an international river basin shared between Botswana, Zimbabwe, South Africa and Mozambique. This basin serves as an important water resource for social, economic and ecological functioning. The pressures on this subtropical savannah basin to supply the quantity and quality of water required for the basic human needs and natural ecology are inevitable. Rapid population growth across all four countries, and subsequently a growing economy is increasing the anthropogenic impacts, which are reflected in the water- and sediment quality. Therefore, it is important to manage and protect the basin in a sustainable manner for future utilisation. Although several studies have been conducted in the basin, limited data on the spatial and temporal distribution of water- and sediment quality in relation to land-use are available. Thus, this study aimed to determine the change of water- and sediment quality within the LRB, from 2021 to 2024, and link the changes with possible land-use activities.

To achieve the aims of the study *in situ* water quality parameters were measured, as well as nutrient and anion concentrations using ion chromatography, and element concentrations through quadrupole inductively coupled plasma-mass spectroscopy. These results were assessed against the fitness for water use values determined for the LRB according to the species sensitivity distribution model used in the 2013 Monograph study for the LRB, and the target water quality range values for water quality parameters. Additionally, Mauchino diagrams were used to present the ionic composition for each site and principal component analyses were performed to interpret the spatial and temporal water quality distribution. Furthermore, the sediment quality assessment included sediment grain size analysis, total organic carbon (TOC) measurements, and element analysis using ICP-MS. Grouped element charts were used to compare the 2021 and 2024 overlapping sites, whereas PCA plots were used to interpret the spatial and temporal sediment quality distribution for all the sites, as well as the overlapping sites. Lastly, the change in land-use/land-cover (LULC) classes were determined using the LULC data obtained from ESRI Sentinel-2 Land Cover Explorer for 2021 and 2024, whereafter it was analysed and associated with changes in water- and sediment quality.

The water quality assessment indicated elevated pH, electrical conductivity, dissolved oxygen, nutrient concentrations and some selected element concentrations. It was also observed that the nutrient concentrations were specifically higher in the upper region of the LRB, and elements such as zinc and copper throughout the whole basin. Additionally, most of the sites were dominated by higher alkalinity and high concentrations of major anions and cations. The sediment quality assessment indicated higher TOC during both years. Furthermore, the sediment grain size analysis indicated that most of the sites during 2021 and 2024 were dominated by coarse sand

and secondly, a combination of coarse and medium sand during 2021 and a combination of very coarse, coarse and medium sand during 2024. Some sites also indicated higher element concentrations due to anthropogenic impacts.

The LULC assessment indicated an increase in rangelands, crop fields and built areas from 2021 to 2024. The increase in LULC and the corresponding anthropogenic impacts on water quality were reflected in the increase in elements, as well as nutrients, salts and alkalinity at some overlapping sites. However, it must be noted that the element concentrations were higher in the sediment and lower in the water during 2021, whereas the element concentrations were higher in the water and lower in the sediment during 2024. This indicates the potential effect of higher rainfall from 2021 to 2024, potentially releasing the elements from the sediment during high flow events. Ultimately, the impacts of existing anthropogenic activities including agriculture, mining, urbanisation, sewage effluent and industrial runoff were evident. Consequently, further water quality deterioration was observed from 2021 to 2024, indicating the impacts of an increase in LULC.

Key terms: Anthropogenic impacts, land-use/land-cover, Limpopo River Basin, water quality, sediment quality.

LIST OF ABBREVIATIONS

As	Arsenic
BHNs	Basic Human Needs
Cd	Cadmium
Cr	Chromium
Cu	Copper
DO	Dissolved Oxygen
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
EWR	Ecological Water Requirement
EWRs	Ecological Water Requirements
FNASREC	Faculty of Natural and Agricultural Sciences Ethics Committee
GIS	Geographical Information System
Hg	Mercury
ICP-MS	Inductively Coupled Plasma-Mass Spectroscopy
INR	Institute of Natural Resources
IWRM	Integrated Water Resource Management
LIMCOM	Limpopo Watercourse Commission
LOD	Limit of Detection
LOQ	Limit of Quantification
LRB	Limpopo River Basin
LULC	Land use/Land cover
Ni	Nickel
NWA	National Water Act
NWRS	National Water Resource Strategy
NWU	North-West University
Pb	Lead

PES	Present Ecological State
RDM	Resource-Directed Measures
RQOs	Resource Quality Objectives
SDC	Source-Directed Controls
TOC	Total Organic Carbon
WHO	World Health Organization
WRG	Water Research Group
Zn	Zinc

KEY DEFINITIONS

Anthropogenic impacts refer to impacts on the natural environment caused by human activities such as pollution.

Aquatic Ecosystems includes any ecosystem in and around waterbodies.

Biological indicators/Biological responders are organisms that can provide information on the health of an ecosystem and/or indicate the effect that environmental stressors can have on an ecosystem through a response.

EcoClassification is the term used to describe the ecological classification process where the Present Ecological State (PES)/health of an aquatic ecosystem is determined.

Ecosystem drivers refer to the biophysical components of an ecosystem that affects the biological responders.

Ecosystem Health is a term used to describe the condition of an ecosystem as well as the productivity, diversity and the ability of an ecosystem to be resilient to changes.

Environmental flows/Ecological water requirements refer to the quantity and quality of water needed to sustain an aquatic ecosystem in a natural state.

Freshwater Ecosystems are ecosystems that occur in and around freshwater waterbodies.

Geology is the study of the Earth and the materials it consists of.

Geomorphology refers to the study of the formation and structure of landforms.

Hydrology is the study that focuses on the flow of water, the water cycle, water distribution and the properties thereof.

Non-point source pollution refers to pollution that cannot be linked to a specific source, but rather an area such as runoff.

Point source pollution refers to pollution that originates from one location linked to a specific source such as discharge pipes.

Risk regions are important sub-basin areas determined by socio-economic and transboundary issues.

Sediment quality refers to the condition of the sediment by assessing the physical (grain size) and chemical (elements) characteristics of the sediment.

Water quality refers to the condition of a water resource by assessing the physical-, chemical- and biological characteristics of the water resource.

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CHAPTER 1 GENERAL INTRODUCTION

1.1 Background

Freshwater resources of the Earth contribute only 0.01% to the world's water and covers a small percentage of 0.8% of the Earth's surface (Dudgeon *et al.*, 2006). In 2011 Wada *et al.* (2011) noted that during the previous decade the use of water has more than doubled. This is of concern as the small amount of fresh surface water resources supports approximately 10% of all described species globally (Sayer *et al.*, 2025). Fresh water and the freshwater biodiversity are important natural resources that is of economic, cultural and aesthetic value (Dudgeon *et al.*, 2006; Wada *et al.*, 2011). Unfortunately, freshwater ecosystems are threatened by climate change and anthropogenic impacts causing a loss in freshwater biodiversity (Dudgeon *et al.*, 2006; Mishra, 2023; Wang, 2024). Therefore, it is essential to assess and monitor the health of freshwater ecosystems to manage it in a sustainable manner for preservation and future utilisation.

The assessment of aquatic ecosystem health is prioritised globally with years of information in scientific literature focusing on the application of multiple methods (O'Brien *et al.*, 2016). Ecosystem health refers to the state of a natural system using reference or target conditions from a management perspective (Rapport *et al.*, 1998). There are various methods that can be used to assess the health of freshwater ecosystems, which includes biological indicators in isolation or in conjunction with chemical and physical parameters (O'Brien *et al.*, 2016; Vadas *et al.*, 2022). The review conducted by O'Brien *et al.* (2016) indicated that the majority of aquatic ecosystem health studies included a joint approach of using biological, physical and chemical indicators with more than 80% of the assessed studies using at least two types of indicators. Multiple indicators can provide more accurate results given that clear objectives are set with accurate predictions on how each indicator represent ecosystem health (O'Brien *et al.*, 2016). Therefore, to monitor the health of freshwater ecosystems, teams of aquatic ecologists, environmental scientists, and water quality experts have been working together for decades to assess freshwater ecosystems worldwide (Vadas *et al.*, 2022).

The indicators used to assess and monitor aquatic ecosystem health can be divided into ecosystem drivers and biological responders. In aquatic ecosystems, the major ecosystem drivers are hydrology, geomorphology and water quality (Haigh *et al.*, 2013). Biological responders however, can include fish, macroinvertebrates, zooplankton, phytoplankton, diatoms and riparian vegetation (Kleynhans, 2007; Su, 2021; Costa & Schneck; 2022).

Water quality is a key driver due to the cause-and-effect relationship between ecosystem drivers and biological responders. Changes in water quality due to seasonality, flow conditions, and anthropogenic influences can cause a positive or negative response in biological trends by affecting the local aquatic biota (Kleynhans, 2007). According to Omer (2020), water quality parameters can be categorised into three different types: biological-, physical-, and chemical parameters. Biological parameters comprise of bacteria, algae and viruses (Omer, 2020). Physical parameters include turbidity, temperature, colour, taste and odour, solids, and electrical conductivity (EC). Lastly, chemical parameters include pH, dissolved oxygen (DO), nutrients, metals, toxic organic compounds, toxic inorganic compounds and other elements.

While water quality is an important driver to aquatic ecosystem health, it is important to note that it only provides a relatively short-term indication of river health. Additionally, sediment analysis can provide a longer-term indication of aquatic ecosystem health when both the physical and chemical components are included (Erasmus, 2020). The chemical component can include metals, and the physical component can include particle size and organic carbon content (Iordache *et al.*, 2022). Fluctuations of elements in sediments and water can also be affected by temperature, pH and organic matter (Iordache *et al.*, 2022). Furthermore, the natural geology and different soil types across regions influence water quality conditions in the natural environment (Dickens *et al.*, 2021). Therefore, by using water- and sediment quality in conjunction, a more comprehensive overview of impacts on an aquatic ecosystems and changes from reference conditions can be observed.

Globally, severe water quality challenges are experienced and can be seen as one of the biggest challenges of the 21st century (Du Plessis, 2022). The major anthropogenic impacts on freshwater ecosystems are caused by agriculture, forestry, mining, urban runoff and other industries (Dallas & Day, 2004; Du Plessis, 2022; Gavrilas *et al.*, 2025). The effects of these anthropogenic activities can be monitored by assessing the above-mentioned water- and sediment quality parameters, focusing on both the physical and chemical components.

Agricultural activities including land preparation, irrigation, the use of fertilizers and pesticides, as well as livestock handling, affect water quality through point and non-point sources (Dallas & Day, 2004; Zahoor & Mushtaq, 2023). Surface runoff originating from eroded agricultural lands can lead to an increase in sediments, nutrients and organic waste within freshwater ecosystems, leading to changes in DO, EC and other parameters (Dallas & Day, 2004; Zahoor & Mushtaq, 2023). The rising population in the world is the main driver causing an increase in agricultural activities, putting pressure on the agricultural sector (Zahoor & Mushtaq, 2023). Additionally, forestry exhibits similar activities and impacts as the agricultural sector, with further effects

reducing light penetration, acidification and lower water temperatures due to tree shading (Dallas & Day, 2004). It is important to note that deforestation and forest landscape fragmentation can cause a decrease in the water quality condition, whereas an increase in forest cover can improve water quality, but it all depends on the specific water quality parameters (Qiu *et al.*, 2023).

The mining industry also impacts water quality worldwide and specifically in South Africa, since precious metals such as gold, uranium and coal have been mined in the country for decades (Dallas & Day, 2004). Effluents originating from mines can lead to acidification of downstream water bodies and cause an influx of metals, sulphates and other elements into the water (Dallas & Day, 2004; Wolkersdorfer & Mugova, 2022). Ultimately, changes in pH, EC and DO can be observed within water bodies near mines (Dallas & Day, 2004; Wolkersdorfer & Mugova, 2022). Furthermore, other industries, urban runoff and human waste can result in an increase in nutrients, metals, chemicals, organic matter and solids within surface water bodies (Dallas & Day, 2004). It is evident that industrial effluent and sewage waste is of big concern, with only 44% of wastewater originating from households being treated to specific standards or regulations (Du Plessis, 2022). Therefore, from a managing perspective it is important to have a strong governing body to enforce and regulate the appropriate rules and regulations to protect and preserve the water resources.

In South Africa, the national government is the custodian of the water resources (Haigh *et al.*, 2013). Thus, it is the responsibility of the appointed governing body, the Department of Water and Sanitation (DWS) to ensure that the water resources of South Africa are managed according to the National Water Act (NWA) 36 (1998), with the objectives of sustainable and equitable use of water. The NWA recognises that the water resources belong to the people and the importance of these resources to aquatic ecosystems. Additionally, aquatic ecosystems provide crucial ecosystem services to people, for example drinking water, biodiversity conservation, food and flood control (Haigh *et al.*, 2013). Therefore, the NWA (1998) ensures the management of water resources to supply the Basic Human Needs (BHN), as well as the Ecological Water Requirements (EWR). This can be achieved under the National Water Resource Strategy (NWRS) with two supplementary strategies including the use of Source-Directed Controls (SDC) and Resource-Directed Measures (RDM) (Haigh *et al.*, 2013). Source-Directed Controls refer to measures that contribute to the limits and constraints needed regarding the use of water and to achieve the relevant protection level. Furthermore, RDM refers to measures that take into the account the water resource quality, which include the quantity, quality, instream- and riparian habit, as well as the aquatic biota (Haigh *et al.*, 2013). Subsequently, the use of RDM involves the determination of the resource management class, ecoclassification, reserve determination and Resource Quality Objectives (RQOs) (Haigh *et al.*, 2013).

In accordance with the NWRS, mandated by the NWA (1998), the protection of water resources can be achieved through Integrated Water Resource Management (IWRM) (Haigh *et al.*, 2013). The IWRM approach is a management approach rooted in science that involves the planning and implementation process, that brings stakeholders together to determine the long-term social and ecological need of water, with the goal to meet the standards while keeping the economic- and ecological benefits (Haigh *et al.*, 2013). The use of IWRM can be implemented on a national and international scale.

The Limpopo River Basin (LRB) is shared by four countries namely, Botswana, Zimbabwe, South Africa and Mozambique. Therefore, the LRB management can become difficult as four different countries need to agree on a management plan to provide the water quantity and quality required for BHN and EWR, while maintaining the economic- and ecological benefits. Hence, the establishment of the Limpopo Watercourse Commission (LIMCOM). The LIMCOM agreement was signed in November 2003 in Mozambique (LIMCOM, 2025). Additionally, LIMCOM initiated a study to determine the Environmental flows required for the LRB (Dickens *et al.*, 2020). Environmental flow determination refers to the determination of the water quality and quantity needed to sustain a freshwater ecosystem (Gebreegziabher *et al.*, 2023). Water and sediment quality was included as important ecological drivers within the LRB during the aquatic ecosystem assessment process.

1.2 Problem statement and rationale for the research

The transboundary location of the LRB makes it difficult to manage the water resources, while keeping the economic and ecological benefits for all four countries. The total area of the LRB is approximately 408 000 km² resulting in the Limpopo River with a length of approximately 1 770 km (Kurugundla *et al.*, 2013). The Limpopo River originates in South Africa, creating the South Africa-Botswana- and South Africa-Zimbabwe borders and eventually reaching Mozambique where it enters the Indian Ocean (Kurugundla *et al.*, 2013).

The transboundary location of the LRB allows for cultural-, biodiversity- and natural resource richness (Dickens *et al.*, 2020). Consequently, the LRB is one of the most studied basins of southern Africa (Dickens *et al.*, 2020). This basin serves as home for approximately 20 million people providing water for BHN, social and economic opportunities (Dickens *et al.*, 2020). The economic activities that contribute to water usage in the basin include commercial forestry, mining, electricity generation, eco-tourism and other industries (Kurugundla *et al.*, 2013). Unfortunately, uneven distribution of development between the four countries causes an imbalance of water usage, with South Africa using the most water (Dickens *et al.*, 2020). Additionally, variability in climate and uneven distribution of precipitation resulted in droughts and floods causing food scarcity in areas with limited water (Kurugundla *et al.*, 2013; Magombeyi *et al.*, 2016; Dickens *et al.*, 2020). Therefore, it is important to manage the LRB for the benefit of all four countries.

Several studies of the LRB were conducted since the establishment of the Limpopo Watercourse Commission (LIMCOM) in 2003. These studies included: Joint Limpopo Scoping Study (LBPTC, 2010), Monograph reports on the Limpopo (INR, 2013) and the Resilience in the Limpopo Basin study (Gómez *et al.*, 2019). Following these studies, Dickens *et al.* (2020) did an analysis of the LRB and identified risk regions according to management objectives, source information and habitat availability. Risk regions can be seen as important sub-basin areas determined by socio-economic and transboundary issues (Dickens *et al.*, 2020). Furthermore, survey sites were selected within the risk regions to be assessed and used to determine the EWR required for the LRB, the current management tool for the LRB better known as environmental flow determination as stated by the Institute of Natural Resources (INR) (2013). This tool focuses on the quantity-, quality- and timing of the flow needed to sustain an aquatic ecosystem (INR, 2013).

Sufficient EWR data are available for the LRB, specifically in the South African regions due to NWA that require EWRs to be determined for all water resources, but there is an uneven distribution of useful data on the state of water resources in Botswana, Zimbabwe and Mozambique (INR, 2013). Although there are various studies indicating the impacts of land-use

on water resources and land-use conversions in Africa, limited data are available on the spatial- and temporal distribution of water- and sediment quality in relation to land-use within the LRB, which consists of smaller sub-catchments (Molekoa *et al.*, 2021). Although the implementation of EWRs as a management tool is sufficient, it is still important to understand the potential impacts land-use can have on the water- and sediment quality to set achievable management objectives for the LRB as part of the overall holistic management. Therefore, this study will focus to provide an overview of the water- and sediment quality in relation to land-use as well as the spatial and temporal analysis of water- and sediment quality in the LRB. This will be completed using data collected from joint basin surveys completed during 2021 and 2024.

1.3 Research questions, aim and objectives

Research Questions:

1. How did the water and sediment quality change in the LRB from 2021 to 2024?
2. What is the possible land-use activities that contributed to water- and sediment quality?

Aim:

- Determine the change of water- and sediment quality within the LRB from 2021 to 2024 and link potential changes with possible land-use activities.

Objectives:

- Determine the water quality and assess the fitness of water use according to the physical and chemical parameters.
- Determine the sediment quality according to the physical and chemical parameters.
- Analyse the change of water- and sediment quality within the Limpopo Basin from 2021 to 2024 and link it with possible land-use activities based on recorded activities, as well as recent geographical information system (GIS) maps.

1.4 Study area

The LRB is an international river basin shared between Botswana, Zimbabwe, South Africa and Mozambique spanning over approximately 412 938 km² (Knight, 2022). This basin is a subtropical savannah, with high rainfall variability. The rainfall ranges from 200 mm/year in the drier western parts to 600 mm/year in the eastern and lowland floodplain sections in Mozambique (Botai *et al.*, 2020). Furthermore, the eastern parts of the LRB in Mozambique are more susceptible to flooding

due to tropical and cyclones (Botai *et al.*, 2020). The high rainfall in the eastern section also contributes to high sediment loading in the lower section of the LRB (Botai *et al.*, 2020).

Different geological features can be seen throughout the basin with a variety of rock types from different ages and origin (Knight 2020; Knight 2022). There is a series of significant geological features in the LRB, including the Kalahari Craton, Limpopo Belt, Archaean Craton, Karoo System and Bushveld Igneous Complex (Schlüter, 2006). These different geological features are also present in the different rivers of the LRB and can be seen in the documented geological characteristics of the rivers in South Africa. The Marico and Crocodile rivers are located in mineral rich areas with sandy loam in the southern area and clay loam soils in the northern area, closer to the confluence with the Limpopo River (Du Preez *et al.*, 2018). Furthermore, the geological setting of Matlabas River contains sandstone bedrock due to the Matlabas Subgroup in the Waterberg Supergroup that include shale and mudstone (Dickens *et al.*, 2021).

The geology changes downstream of the Matlabas River and it can be seen in the Lephalala River where the geology consists of a rocky crustal formation at the base of the Waterberg formation, surrounded by the mineral rich Bushveld Igneous Complex (Dickens *et al.*, 2021). The Shingwedzi River, a tributary of the Olifants River consists mostly of granitic and gneissic rock due to the crystalline Basement Complex (Dickens *et al.*, 2021). Additionally, the Letaba River also serves as a tributary of the Olifants River, and the geology consists of granitic, gneissic, volcanic and sedimentary rocks (Dickens *et al.*, 2021). Conversely, the Olifants River, a tributary of the Limpopo River, consists of a complex geology that mostly comprise of granitic rock types (Dickens *et al.*, 2021).

The LRB was assessed under the guidance and needs of the LIMCOM, and the survey sites were distributed across the four different countries, covering the whole basin and relevant tributaries. Subsequently, the water- and sediment quality for the 2021 and the 2024 surveys were assessed and analysed for this study. The sampling sites, as well as the corresponding coordinates, system names and ecoregions for the sites sampled during 2021 and 2024 are provided in Table 1-1.

Table 1-1 Limpopo River Basin sampling sites, coordinates, system names and ecoregions for the sites sampled during 2021 and 2024.

Sampling Sites	Coordinates	River/Dam	Country	Sampling Year
CROCR	24°18'51.00"S 27° 2'46.10"E	Crocodile	South Africa	2021
MATL	24° 3'6.70"S 27°21'34.70"E	Matlabas	South Africa	2021
LEPHS	23° 8'28.60"S 27°53'6.10"E	Lephalala	South Africa	2021
MOGA	22°28'24.40"S 28°55'10.20"E	Mogalakwena	South Africa	2021
SANDR	22°23'57.40"S 30° 5'57.90"E	Sand	South Africa	2021
LUVU	22°26'40.00"S 31° 5'0.40"E	Luvuvhu	South Africa	2021 & 2024
SHINR	23°13'19.00"S 31°33'17.70"E	Shingwedzi	South Africa	2021
GLETL	23°40'37.50"S 31° 5'54.00"E	Letaba	South Africa	2021
LETA	23°45'30.00"S 31°22'11.90"E	Letaba	South Africa	2021
MAMBA	24° 5'11.10"S 31°15'3.40"E	Olifants	South Africa	2021
BALUL	24° 3'7.70"S 31°43'43.60"E	Olifants	South Africa	2021 & 2024
LIMP1	23°56'44.00"S 26°55'55.30"E	Limpopo	South Africa/Botswana	2021
LIMP2	22°27'18.70"S 28°54'6.30"E	Limpopo	South Africa/Botswana	2021
MAPU	22°10'47.65"S 29°24'31.53"E	Limpopo	South Africa/Botswana	2021 & 2024
LIMP3	24°30'0.72"S 33° 0'37.44"E	Limpopo	Mozambique	2021 & 2024
GMAR	24°42'20.66"S 26°25'24.95"E	Marico	South Africa	2024
NGOT	24°17'18.66"S 26°14'47.78"E	Ngotwane	Botswana	2024
LOTSW	22°41'9.57"S 28° 8'14.11"E	Lotsane	Botswana	2024
MOTL	21°51'48.03"S 27°45'8.21"E	Motloutse	Botswana	2024
LETSO	21°50'19.06"S 27°44'17.71"E	Letsibogo Dam	Botswana	2024
SHAS	21°34'7.36"S 28° 0'48.99"E	Shashe	Botswana/Zimbabwe	2024
UMZI	20°27'2.74"S 29° 7'50.84"E	Umzingwane	Zimbabwe	2024
MWENR	21°29'21.19"S	Mwenezi	Zimbabwe	2024

	30°47'22.35"E			
MWENG	21°57'6.25"S 31°26'21.67"E	Mwenezi	Zimbabwe	2024
ELEP	23°52'33.25"S 32°13'34.05"E	Olifants	Mozambique	2024
CCONR	22°25'34.27"S 31°18'26.35"E	Limpopo	South Africa/Botswana/Zimbabwe	2024

The 2021 field survey included the sampling of 15 sites in the LRB during May – July 2021 (Figure 1-1). The 15 sites that were sampled during the survey consisted of the following sites: Crocodile River (CROCR), Matlabas River (MATL), Lephalala River (LEPHS), Mogalakwena River (MOGA), Sand River (SANDR), Luvuvhu River (LUVU), Shingwedzi River (SHINR), two sites on the Letaba (GLETL and LETA) and Olifants (MAMBA and BALUL), as well as four sites on the mainstem Limpopo River (LIMP1, LIMP2, MAPU and LIMP3).

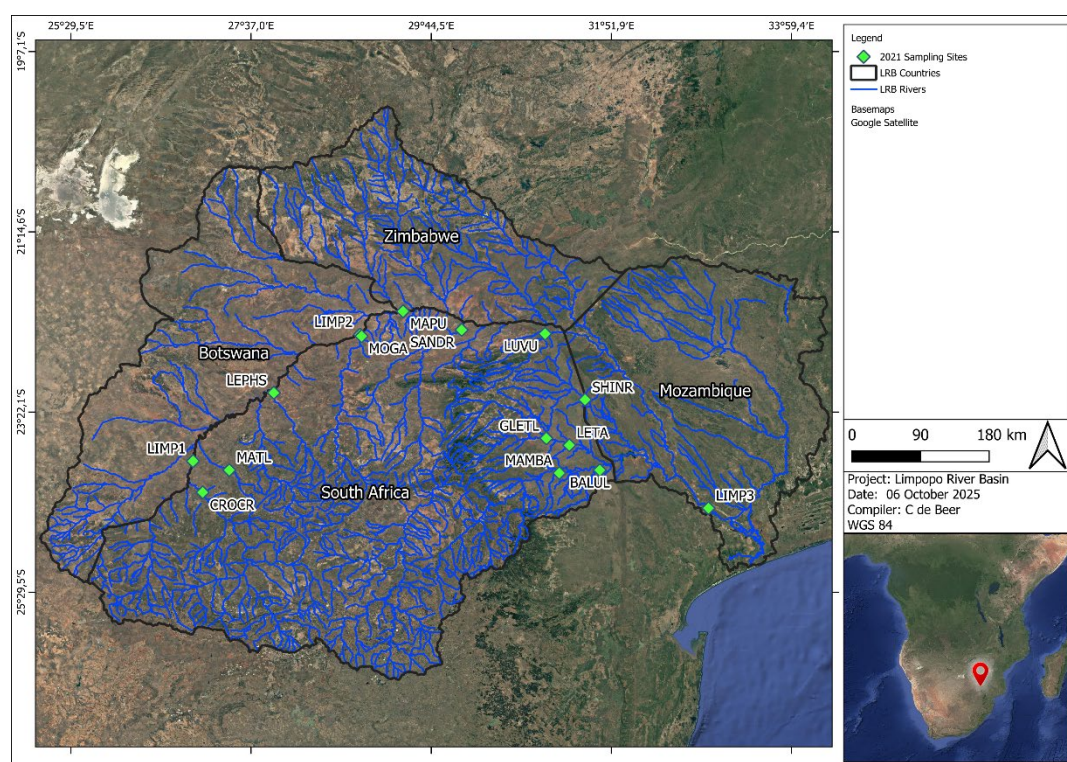


Figure 1-1 A map indicating the sampled sites during the 2021 field survey in the Limpopo River Basin.

During the 2024 field survey, 15 sites were sampled in the LRB during August – September 2024 (Figure 1-2). The 15 sites that were sampled during the survey consisted of the following sites: Marico River (GMAR), Ngotwane River (NGOT), Lotsane River (LOTSW), Motloutse River and Letsibogo Dam (MOTL and LETSD), Shashe River (SHAS), Umzingwane River (UMZI), two

sites on the Mwenezi River (MWENR and MWENG), Luvuvhu River (LUVU), two sites on the Olifants/Elephantes River (BALUL and ELEP), and three sites on the mainstem Limpopo River (MAPU, CCONR and LIMP3). It is important to note that the Olifants River and Elephantes River is the same system. In South Africa the system is referred to as the Olifants River and in Mozambique it is referred to as the Elephantes River. Overall, there are four sites that overlapped during the 2021 and 2024 surveys. These sites include MAPU, LUVU, BALUL and LIMP3 (Figure 1-3).

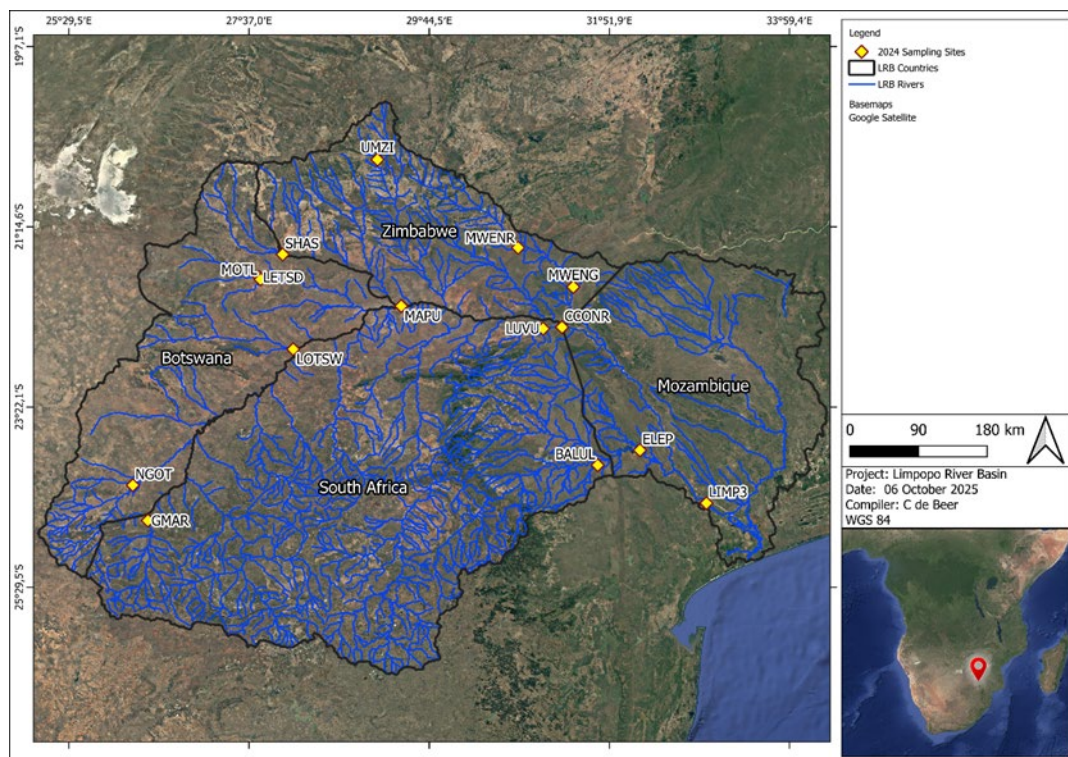


Figure 1-2 A map indicating the sampled sites during the 2024 field survey in the Limpopo River Basin.

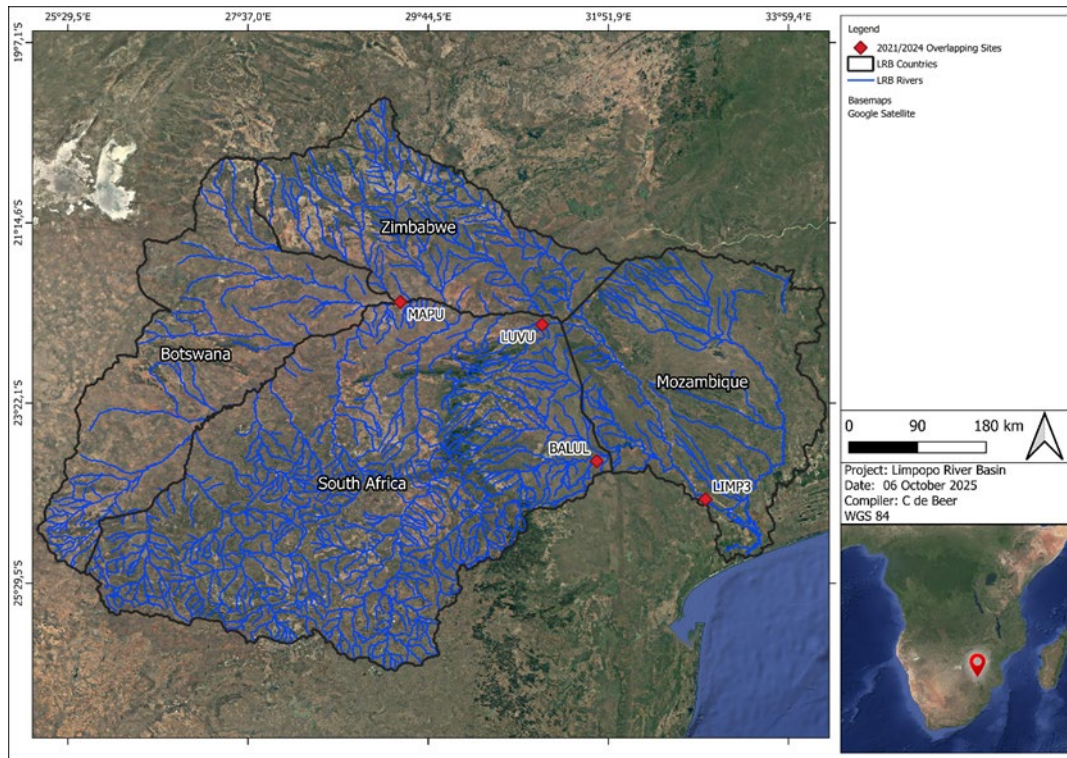


Figure 1-3 A map indicating the overlapping sites for the 2021 and 2024 field surveys in the Limpopo River Basin.

1.5 Limitations

Sites were not sampled seasonally. Therefore, water- and sediment quality that are provided for each year (2021 and 2024) were based on single surveys. This approach does not adequately account for variability, but it still provides an overview of the water quality and the potential effect of impacts on the water quality condition in the basin.

1.6 Potential contribution of the research

This study serves to give an overview of the water- and sediment quality within the LRB as well as the impact that land-use can have on water- and sediment quality. The research also contributes to a better understanding of water- and sediment quality as drivers of aquatic ecosystems and the impacts of land-use activities on it through the integration of water- and sediment quality in relation to land-use. Furthermore, this study supports international IWRM by assessing the water- and sediment quality within the transboundary LRB. Ultimately, the data provided by this study can contribute to the environmental flow determination and monitoring of the LRB, which will improve the water resource management in the transboundary basin.

1.7 Structure and outline of the dissertation

Chapter 1: General Introduction

A brief overview and introduction of the study, problem statement, research question, aims and objectives and study area are provided.

Chapter 2: Water Quality within the Limpopo River Basin

Chapter 2 includes the assessment of water quality, as well an assessment for the fitness of water use. A spatial and temporal analysis of water quality with the possible effects of land-use activities on the water quality in the LRB were also assessed.

Chapter 3: Sediment Quality within the Limpopo River Basin

Chapter 3 includes an assessment of sediment quality, as well as the spatial and temporal analysis of sediment quality with the possible effects of land-use activities on the sediment quality in the LRB.

Chapter 4: Conclusions and Recommendations

This chapter concludes the dissertation by reflecting back to the research questions and objectives and determining whether it was met during the study. Recommendations for future studies are also included in this chapter.

References

All the references cited in the dissertation are provided in this section.

CHAPTER 2 WATER QUALITY IN RELATION TO LAND-USE IN THE LIMPOPO RIVER BASIN

2.1 Introduction

Water is one of the most important resources to sustain life on earth (Molekoa *et al.*, 2021). This essential resource of globally economic, cultural and aesthetic value is not only utilised and important for aquatic ecosystems, but it is also a key component in the agricultural sector, forestry, mining and ultimately our basic human needs (BHN) (Dallas & Day, 2004; Dudgeon *et al.*, 2006; Wada *et al.*, 2011). Nevertheless, this important resource is under severe pressure due to increasing human populations, urbanisation and climate change, becoming one of the biggest challenges of the 21st century (Avtar *et al.*, 2011; Du Plessis, 2022). Additionally, anthropogenic impacts due to agriculture, forestry, urban runoff and other industries also contribute to the pressure on sustaining good water quality (Du Plessis, 2022; Gavrilas *et al.*, 2025). This is of great concern as both the water quality and quantity is affected (Molekoa *et al.*, 2021). Thus, emphasising the importance of managing water quality for sustainable and equitable use.

As previously discussed in Chapter 1, the Limpopo River Basin (LRB) is shared by four countries (Botswana, Zimbabwe, South Africa and Mozambique) and each country has specific ecological and economic needs. Thus, managing the international basin to the benefit of all stakeholders can become a technical and difficult task. Although difficult, it can be achieved through an integrated water resource management (IWRM) approach on an international scale (Haigh *et al.*, 2013). The participation of all stakeholders and assessment of the BHNs and EWRs can assist in managing the LRB to the benefit of all four countries.

The LRB supports close to 20 million people with more than 50% of the population originating from rural areas (Dickens *et al.*, 2020; Petrie *et al.*, 2015). Due to the higher population density in rural areas a significant proportion is involved in agriculture to sustain their food supply (Earle *et al.*, 2006). Contrastingly, an increase in urbanisation has also been observed leading to an increase in water allocation to both the social and economic sectors including agriculture, industry, municipality and power stations in the upper LRB (Petrie *et al.*, 2015; Kahinda *et al.*, 2016). Impacts and water usage in the middle region of the LRB include irrigation, mining, gold panning, tourism and other agricultural activities, whereas the lower regions of the LRB are mainly impacted by agricultural activities (INR, 2013). Additionally, other impacts include sand mining, domestic water supply, industrial water supply and wildlife ranching (INR, 2013).

Previous studies on the surface water quality in the Mokopane area, Limpopo, South Africa, in the Mogalakwena River and its tributaries indicated that the assessed sites have shown the deterioration of water quality from 2016 to 2019 and slightly better water quality during 2020 (Molekoa *et al.*, 2021). This study indicated that the better water quality observed in 2020 can be attributed to the lower human activities during the COVID-19 lockdown period. Thus, highlighting the impact of land-use/ land-cover (LULC). The Mogalakwena River is a tributary of the Limpopo River and joins the Limpopo River a few kilometres upstream of Mapungubwe. Therefore, it is expected that the deteriorated water quality in the Mogalakwena River will affect the water quality in the Limpopo River as well. Further, the majority of the physical and chemical parameters in the water samples indicated concentrations above the limits provided by the World Health Organisation (WHO) (Molekoa *et al.*, 2021). It was clear that the water quality in built-up areas was affected more than other areas (Molekoa *et al.*, 2021). Therefore, emphasising the relationship between anthropogenic activities and water quality. Molekoa *et al.* (2021) also indicated that anthropogenic activities such as wastewater discharge, industrial activities and mines contributed to the deteriorating of the water quality.

Historically the Olifants River in the LRB was heavily impacted through copper and phosphate mining on the banks of the Ga-Selati River with additional salt enrichment (sulphate and phosphate) that originated from effluent discharge (Riddell *et al.*, 2019). However, the governance of mining in the Olifants catchment and associated problems has improved, but it still suffers from point source pollution on occasion, such as the phosphate spill during 2013 (Marr *et al.*, 2017). The study conducted by Riddell *et al.* (2019) on the impacts of pollution on the aquatic ecosystems of the Kruger National Park (KNP) indicated that the higher concentrations of the water quality parameters measured in Olifants River affected the local fish and macroinvertebrate communities negatively. Additionally, land use activities in the Luvuvhu River such as poor agricultural activities, urbanisation, urban runoff and poor land use practises can cause water quality deterioration and possibly lead to water quality that is not suitable for future domestic use (Bapela, 2001). However, no major impacts were observed in the Luvuvhu River during the study conducted by Riddell *et al.* (2019), except for small scale agricultural activities possibly originating from Thohoyandou.

The impacts of anthropogenic activities on the water quality within the LRB are clear with urbanisation, mining, agriculture and industries being the leading activities that contribute to the impacts on water quality. Therefore, the aim this chapter was to assess the water quality status of selected sites for both the sampling years 2021 and 2024, as well as the spatial and temporal distribution of the water quality in relation to land use in the LRB.

2.2 Materials and methods

2.2.1 Field sampling

During the 2021 and 2024 field surveys, *in situ* water quality parameters were measured at the pre-selected sites in the LRB (Table 1-1), whereafter water samples were collected in pre-cleaned 250 mL poly-ethylene containers and frozen until analysis. The measurements were taken in current and out of current with the aid of a calibrated water quality multi-meter (WTW Multi 350I). The *in situ* parameters included dissolved oxygen (DO; mg/L), electrical conductivity (EC; $\mu\text{S}/\text{cm}$), pH and temperature ($^{\circ}\text{C}$). The water samples were stored in a freezer (-18°C) before further analysis in the laboratory. All samples and measurements were taken in triplicate for analysis (Erasmus *et al.*, 2020).

2.2.2 Water quality analysis

The collected water samples were removed from the freezer and left at room temperature to thaw. Thereafter, all the samples were analysed for nutrients (ammonium, nitrates, nitrites and ortho-phosphates) and anions (alkalinity, chloride and sulphate) using Ion Chromatography (IC) (Metrohm 940 Professional IC Vario) (Michalski, 2006).

Next, the samples were prepared for element analysis by filtering 200 mL through a cellulose nitrate filter ($0.45\ \mu\text{m}$, Sartorius Stedim Biotech), whereafter 2 mL nitric acid (HNO_3) (65% supra pure quality, Merck) was added to acidify the samples to an acid concentration of 1% (Erasmus *et al.*, 2020). The element concentrations in the water samples were determined using quadrupole inductively coupled plasma-mass spectroscopy (ICP-MS) (Agilent 7850 ICP-MS) by following the method described by Erasmus *et al.* (2020).

2.2.3 Assessment of fitness for water use

The water quality data were assessed, and the fitness of water use was determined for the sampled sites according to fitness for use categories developed for the 2013 Monograph study (Table 2-1) and the species sensitivity distribution (SSD) model used in the 2020 Water Quality Specialist Report (Table 2-2). The SSD models aims to determine suitable chemical concentrations to protect the species in the environment. This usually consists of a point estimate, which can be HC1 (hazardous concentration for 1% of the species), or the 99% protection level for the species. Additionally, a percentage level of certainty is also calculated where sufficient data are available (i.e. 95% certainty). The following fitness for water use categories were determined according to the classification scheme for selected water quality parameters and metal toxicants (Table 2-1 and Table 2-2):

- Good: Protection level of 99% with 50% certainty (HC1, 50).
- Tolerable: Protection level of 95% with 75% to 95% certainty (HC5, 5-25).
- Poor: Protection level of 95% with 50% to 75% certainty (HC5, 25-50).
- Unacceptable: Protection level of 95% with less than 50% certainty (HC5, >50).

Table 2-1 Recommended values for selected variables to classify the fitness for use of water.

Parameter	Good (Blue)	Tolerable (Green)	Poor (Amber)	Unacceptable (Red)	Sensitive use group
pH (lower)	6.5		<6.5		Domestic
pH (upper)	8.5		>8.5		Domestic
EC (µS/cm)	400	1500	3700	>3700	Irrigation & Domestic
SO ₄ (mg/L)	200	400	600	>600	Domestic
PO ₄ (mg/L)	0.025	0.075	0.125	>0.125	Aquatic
NO ₃ (mg/L)	0.7	1.75	3.0	>3.0	Aquatic

Table 2-2 Recommended concentration (µg/L) classes for metal toxicants based on the probability of affecting 5% of the species.

Element	Good <HC1/ (50)	Tolerable HC5 (5-25)	Poor HC5 (25-50)	Unacceptable >HC5 (50)
Ammonia	<682	683 – 1009	1010 – 2097	> 2097
Arsenic	<37.6	37.7 – 76.8	76.9 – 159.7	>159.7
Cadmium	<14.8	14.9 – 71.7	71.8 – 141.3	>141.3
Chromium	< 3157	3158 – 4543	4544- 6668	>6668
Copper	< 39.6	39.7 – 56.3	56.4 – 64.7	>64.7
Mercury	<11.1	11.2 – 16	16.1 – 19	>19
Zinc	<5	5.1 – 20.1	20.2 – 43.5	>43.5

The total ammonium was used to calculate the ammonia (NH₃) concentrations in the water quality samples using an Ammonia Calculator (Arain, 2025). The calculation was completed through a three-step calculation where the *pKa* value was determined and then used in the final calculation. The calculations were completed using the following formulas (Emerson *et al.*, 1975):

$$1. \text{ } pKa = 0.09018 + \frac{2727.92}{T}$$

$$2. f = 1/((10^{pKa-pH}) + 1)$$

$$3. [NH_3] = \alpha_1 \times [NH_4]$$

In the first calculation the pK_a value represents the ionisation constant of the ammonium ion and T represent the temperature in Kelvin. In the second calculation the fraction NH_3 and NH_4 is determined. The fraction is then used in the third calculation to calculate the NH_3 in Mg/L.

The water quality parameters that did not have fitness for use values/guidelines were compared to the Target Water Quality Range (TWQR) for South Africa developed by the Department of Water Affairs and Forestry (DWAF, 1996). The TWQR values are presented in Table 2-3. The TWQR provides values for different water uses and aims to protect and maintain aquatic ecosystem health.

Table 2-3 Target Water Quality Range values for the measured water quality parameters (DWAF, 1996).

Parameter	Value	Sensitive use group
DO (%)	80 - 120	Aquatic Ecosystems
Cl (mg/L)	< 600	Aquaculture
Alkalinity (mg $CaCO_3$ /L)	20 - 100	Aquaculture
Turbidity (NTU)	≤ 25	Aquaculture

2.2.4 Statistical analysis

Since the frequency of data collection was limited only descriptive statistics (mean, standard error) were applied. Mauchino diagrams, were created to illustrate a visual representation of the ionic (milli-equivalents per litre) composition in the water samples (CBBS, 2025). Mauchino diagrams were adapted from the original Maucha diagrams by Mike Silberbauer (Maucha, 1932; CBBS, 2025). These diagrams illustrate the ionic composition with a star symbol that present the anions (SO_4^{2-} , Cl^- , CO_3^{2-} , $NO_3^- + NO_2^-$ as N), cations (K^+ , Na^+ , Ca^{2+} , and Mg^{2+}) and total alkalinity (TAL) in different colours. Lastly, principal component analyses (PCA) were also performed to interpret the temporal and spatial water quality distribution. This was completed using Canoco 5 for Windows (v. 5.15) statistical package. Parametric data were log-transformed to ensure normality where necessary.

2.2.5 Land-use/ Land-cover

To determine the LULC for the LRB data was obtained from ESRI Sentinel-2 Land Cover Explorer (2025). The data were used in QGIS (version 3.34.11) to create LULC cover maps and to

determine the area covered (km²) that is categorised in nine different classes. These classes included water, trees, flooded vegetation, crops, built area, bare ground, snow/ice, clouds and rangeland. Lastly, the total area covered by each class was used to calculate the percentage cover as well as the differences between 2021 and 2024 in the LRB.

2.3 Results

The results included an overview of the water quality condition during 2021 and 2024. The ionic composition, element concentrations, as well as the spatial and temporal analysis results that were used to determine the water quality condition are indicated in this section. Lastly the changes in LULC are also included in this section.

2.3.1 Water quality overview for 2021

Overall, it can be seen that water quality perturbations were observed at all of the sampled sites. The pH data for the 2021 survey was found to be 'Good' according to the fitness for use for domestic use for most of the sites except for CROCR, LIMP1, MAPU, SANDR, MAMBA and BALUL that indicated elevated pH levels and were classified as 'Poor' (Table 2-4). The EC levels for most of the sites were 'Tolerable' for irrigation and domestic purposes, except for MOGA and SANDR that was classified as 'Poor', and MATL that were 'Unacceptable' due to elevated EC levels. Further, the SO_4 concentrations were all 'Good' for domestic use, except for MOGA, which were 'Tolerable' due to an increase in the SO_4 concentration. The PO_4 concentrations varied with seven sites ranging from 'Good' to 'Tolerable' and eight sites ranging from 'Poor' (MAPU, LUVU and BALUL) to 'Unacceptable' (CROCR, LEPHS, LIMP2, MOGA and SANDR) for the use of water by aquatic organisms. Additionally, the PO_4 concentrations indicated elevated levels in the upper reaches of the LRB in comparison with the lower reaches. Furthermore, the NH_3 concentrations were considered to be 'Good' for domestic use at all of the sampled sites. The NO_3 concentrations were 'Good' and 'Tolerable' for most of the sites, except for MATL, LIMP2 and BALUL that exhibited higher NO_3 concentrations.

Selected parameters (DO , Cl^- , alkalinity and turbidity) were compared to the TWQR (1996) values for South Africa. This was done due to limited water quality guidelines that are available for the LRB, specifically in the neighbouring countries (Table 2-4). The DO concentrations were within the acceptable range, except for CROCR, LIMP1, MOGA, MAPU, SANDR and MAMBA that indicated remarkably high DO concentrations. Further, site MOGA was the only site that indicated elevated Cl^- levels, above the TWQR value. Although site SANDR exhibited a Cl^- concentration below the TWQR, it must still be noted that the Cl^- concentration was well above the concentrations observed at the other sites. The alkalinity results indicated that 10 out of 15 sites were above the TWQR with high alkalinity. Lastly, only one site (CROCR), indicated high turbidity levels above the TWQR.

Table 2-4 Water quality results of the different variables analysed in the samples collected in the Limpopo River Basin (LRB) during the 2021 survey. The data are presented as mean $\pm$ standard error.

Element	CROCR	LIMP1	MATL	LEPHS	LIMP2	MOGA	MAPU	SANDR	LUVU	SHINR	GLETL	LETA	MAMBA	BALUL	LIMP3
pH	9.2 $\pm$ 0.03	8.7 $\pm$ 0.01	7.1	7.6 $\pm$ 0.04	8.5 $\pm$ 0.14	7.5 $\pm$ 0.27	8.8 $\pm$ 0.05	8.6 $\pm$ 0.07	8.3 $\pm$ 0.04	8.2 $\pm$ 0.06	8.3 $\pm$ 0.09	8.4 $\pm$ 0.44	8.8 $\pm$ 0.06	8.6 $\pm$ 0.02	8.13
EC (μ S/cm)	782 $\pm$ 11	837 $\pm$ 58	6855 $\pm$ 515	857 $\pm$ 2.0	936 $\pm$ 159	2415 $\pm$ 255	422 $\pm$ 1	2580	381	900 $\pm$ 31	1007	805 $\pm$ 427	1285.5 $\pm$ 7.5	547 $\pm$ 4.5	491.3
DO (mg/L)	10.8 $\pm$ 1.8	11.3 $\pm$ 0.6	9.3	9.4 $\pm$ 0.4	10.4 $\pm$ 0.1	12.8 $\pm$ 4.6	11.4 $\pm$ 0.5	16.2 $\pm$ 0.4	10 $\pm$ 0.2	9 $\pm$ 0.7	10.2 $\pm$ 0.6	9.7 $\pm$ 0.4	11 $\pm$ 0.4	10.2	13.71
DO (%)	121.4 $\pm$ 17	130.4 $\pm$ 8.2	107.5	106.8 $\pm$ 2.1	118.3 $\pm$ 2.3	154 $\pm$ 59.7	131.9 $\pm$ 2.3	200.9 $\pm$ 11.2	118.5 $\pm$ 4.2	99.9 $\pm$ 6.8	115.2 $\pm$ 6.7	113.2 $\pm$ 9.6	125.5 $\pm$ 2.4	109.5 $\pm$ 3.4	119
Temperature ($^{\circ}$ C)	22.4 $\pm$ 0.8	22.1 $\pm$ 0.8	22.3	21.6 $\pm$ 0.1	22.5 $\pm$ 0.3	23.6 $\pm$ 1.2	26 $\pm$ 0.9	27.7 $\pm$ 1.3	24.9 $\pm$ 0.5	21.5 $\pm$ 0.6	22.3 $\pm$ 0.2	22.7 $\pm$ 1.5	22.7 $\pm$ 0.1	20.3 $\pm$ 0.5	21.3
Cl (mg/L)	92.7 $\pm$ 2.1	81.3 $\pm$ 9.1	10.4 $\pm$ 1.1	10.7 $\pm$ 3.8	53 $\pm$ 8.7	603 $\pm$ 90.2	48 $\pm$ 2	444 $\pm$ 49.6	13.4 $\pm$ 0.31	87.3 $\pm$ 0.58	19.3 $\pm$ 2.52	28.3 $\pm$ 8.39	26 $\pm$ 2	32.7 $\pm$ 0.58	35.75 $\pm$ 13.1
SO ₄ (mg/L)	61 $\pm$ 1.0	58	1.3 $\pm$ 0.58	4.7 $\pm$ 1.2	14 $\pm$ 1.7	217 $\pm$ 65.3	33.3 $\pm$ 2.10	133 $\pm$ 3.5	4 $\pm$ 1	12 $\pm$ 1	14.7 $\pm$ 3.79	13 $\pm$ 1	69.7 $\pm$ 0.58	62.67 $\pm$ 0.58	35.5 $\pm$ 3.5
PO ₄ (mg/L)	0.15 $\pm$ 0.01	0.04 $\pm$ 0.02	0.05 $\pm$ 0.04	0.46 $\pm$ 0.32	0.24 $\pm$ 0.28	0.16 $\pm$ 0.01	0.1 $\pm$ 0.01	0.23 $\pm$ 0.3	0.1 $\pm$ 0.06	0.05 $\pm$ 0.04	0.03 $\pm$ 0.01	0.02 $\pm$ 0.01	0.01 $\pm$ 0.01	0.11 $\pm$ 0.08	0.03 $\pm$ 0.013
NH ₃ (μ g/L)	34.4	6.9	0.5	0.1	6.8	2.7	55.3	34.8	11	10.1	3.5	2	1.8	16.7	2.3
NH ₄ (mg/L)	0.08 $\pm$ 0.01	0.04 $\pm$ 0.01	0.07 $\pm$ 0.01	0.01 $\pm$ 0.001	0.06 $\pm$ 0.01	0.14 $\pm$ 0.13	0.18 $\pm$ 0.006	0.13 $\pm$ 0.06	0.1 $\pm$ 0.001	0.18 $\pm$ 3.4 $\times$ 10 ⁻¹⁵	0.05 $\pm$ 0.02	0.02 $\pm$ 0.001	0.01 $\pm$ 0.0006	0.12 $\pm$ 0.002	0.04 $\pm$ 0.007
NO ₃ (mg/L)	1.3 $\pm$ 0.45	1.33 $\pm$ 0.67	2.4 $\pm$ 0.2	0.9 $\pm$ 0.2	1.77 $\pm$ 0.4	0.93 $\pm$ 0.07	0.83 $\pm$ 0.4	1.63 $\pm$ 0.15	0.41 $\pm$ 0.06	0.86 $\pm$ 0.13	0.2 $\pm$ 0.09	0.27 $\pm$ 0.28	0.998 $\pm$ 0.85	1.97 $\pm$ 0.7	0.08 $\pm$ 0.003
NO ₂ + NO ₃ (mg/L)	1.31 $\pm$ 0.78	1.4 $\pm$ 0.67	2.4 $\pm$ 0.35	0.91 $\pm$ 0.35	1.9 $\pm$ 0.33	0.94 $\pm$ 0.12	0.84 $\pm$ 0.4	1.66 $\pm$ 0.24	0.41 $\pm$ 0.1	0.87 $\pm$ 0.23	0.21 $\pm$ 0.15	0.28 $\pm$ 0.29	1.01 $\pm$ 1.48	1.97 $\pm$ 1.21	0.08 $\pm$ 0.004
Alkalinity (mg/L CaCO ₃)	178.69	168.85	28.36	31.72	75.00	268.85	105.90	387.70	58.36	286.89	78.36	119.67	135.25	138.52	128.69
Turbidity (NTU)	35 $\pm$ 3.6	20 $\pm$ 1.0	4.67 $\pm$ 2.3	7.3 $\pm$ 0.58	9.7 $\pm$ 7.1	8 $\pm$ 3.0	15.3 $\pm$ 4.2	13.7 $\pm$ 2.9	8 $\pm$ 1.7	17.7 $\pm$ 2.08	11.7 $\pm$ 1.53	12.7 $\pm$ 2.89	13 $\pm$ 3	12 $\pm$ 1.73	15

Blue – Good; Green – Tolerable; Amber – Poor; Red – Unacceptable; Lavender – Outside TWQR range.

2.3.1.1 Ionic composition

The salt balance of the water samples showed that most of the sites were dominated by TAL (CO_3^{2-} and HCO_3^-), except for sites MOGA and SANDR (Figure 2-1). Secondly, Na^+ also contributed largely to the ionic composition at most of the sites except for sites MATL, LUVU, BALUL and LIMP3. Furthermore, Cl^- also contributed largely to the ionic composition at most of the sites and dominated at MOGA and SANDR where it indicated the highest concentrations of all the samples. The Mg^{2+} had a large contribution to the ionic composition at most of the sites with a slightly lesser presence of Ca^{2+} observed overall. It can also be seen that sites CROCR, LIMP1, MOGA, MAPU, SANDR, GLETL, MAMBA, BALUL and LIMP3 exhibited lower concentrations of SO_4^{2-} that contributed to the ionic composition of the sites. It was evident that all the sites exhibited low concentrations of NO_3^- and K^+ , except for sites MATL that indicated a higher concentration of NO_3^- and LIMP3 that indicated higher concentrations of K^+ that contributed to the ionic composition.

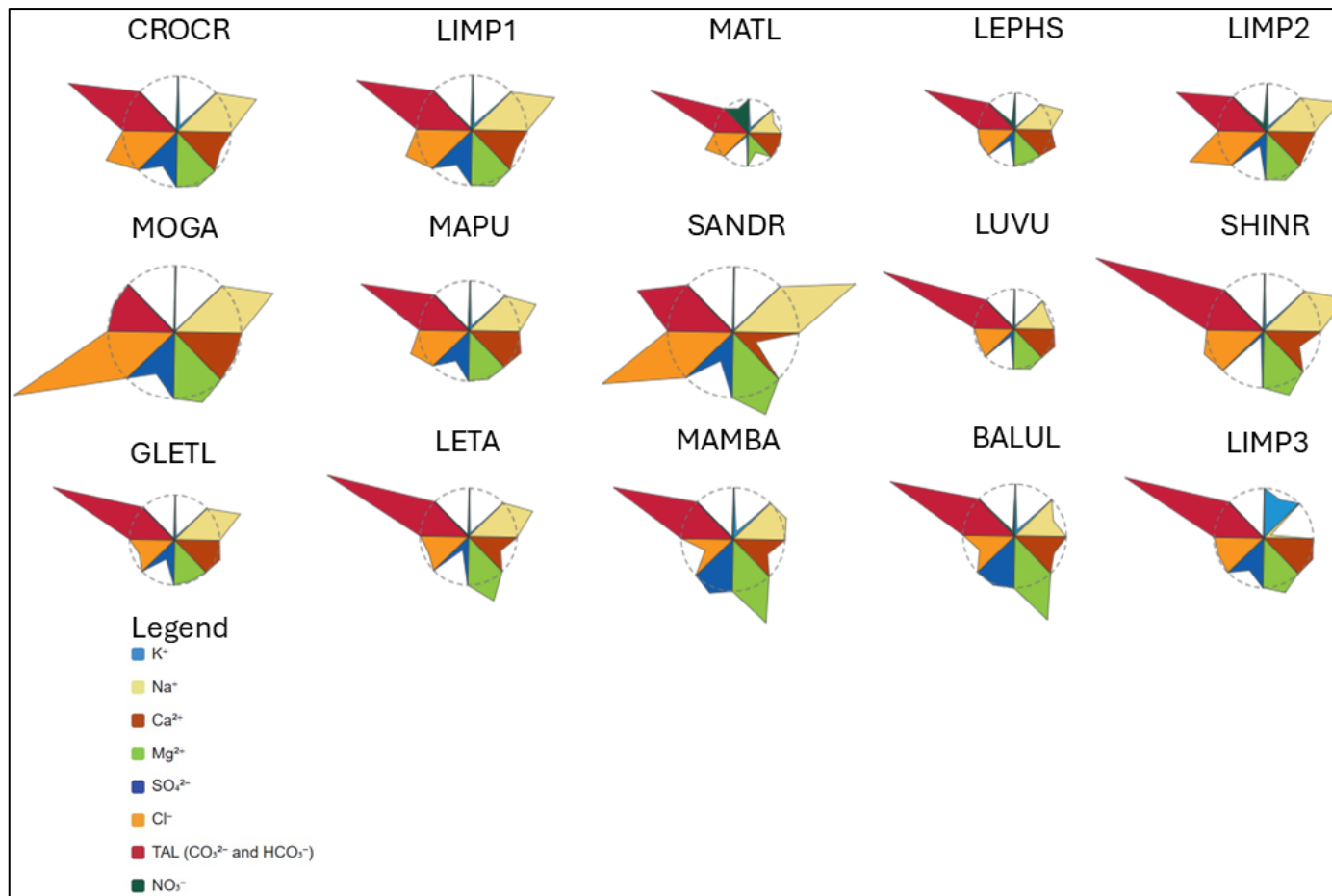


Figure 2-1 Salt balance of the 2021 water samples presented in Mauchino diagrams representing the Crocodile (CROCR), Matlabas (MATL), Lephalala (LEPHS), Mogalakwena (MOGA), Sand (SANDR), Luvuvhu (LUVU), Shingwedzi (SHINR), two sites on the Letaba (GLETL and LETA) and Olifants (MAMBA and BALUL), as well as four sites on the mainstem Limpopo (LIMP1, LIMP2, MAPU and LIMP3).

2.3.1.2 Element concentrations

The trace element concentrations measured in the water samples can be seen in Table 2-5. The concentrations at the sites ranged between 0.08 (LUVU) – 1.66 (CROCR) µg/L for As, <0.001 (MAPU and LIMP3) – 0.04 (SANDR) µg/L for Cd, 0.08 (MOGA) - 5.39 (LUVU) µg/L for Cr, 0.76 (LEPHS) – 5.61 (LIMP2) µg/L for Cu, 0.02 (LIMP2) – 38.54 (LUVU) µg/L for Hg, 0.97 (LIMP3) – 26.14 (LUVU) µg/L for Ni, <0.001 (MAPU and LIMP3) – 0.21 (GLETL) µg/L for Pb and 1.99 (LETA) – 17.35 (LIMP2) µg/L for Zn.

The majority of the metal concentrations were well within the fitness for water use limits and therefore, the sites were classified as 'Good' for aquatic organism to use Table 2-5. The Zn concentrations were mostly 'Good', except for sites MATL, LEPHS, LIMP2, MAPU, LUVU and SHINR that indicated higher Zn concentrations, specifically LIMP2. Furthermore, relatively constant Ni and Pb concentrations were observed at the sites, except for LUVU that indicated considerably higher Ni concentrations.

Table 2-5 The trace element concentrations (µg/L) in the water samples collected from the Limpopo River Basin during the 2021 survey. The data are presented as mean ± standard error.

Element	CROCR	LIMP1	MATL	LEPHS	LIMP2	MOGA	MAPU	SANDR	LUVU	SHINR	GLETL	LETA	MAMBA	BALUL	LIMP3
As	1.66 ± 0.003	1.56 ± 0.01	0.27 ± 0.02	0.14 ± 0.01	0.5 ± 0.04	0.51 ± 0.01	0.5 ± 0.03	0.88 ± 0.02	0.08 ± 0.01	0.55 ± 0.02	0.29 ± 0.01	0.37 ± 0.03	1.09 ± 0.02	0.93 ± 0.01	1.1 ± 0.06
Cd	0.02 ± 0.01	0.01 ± 0.01	0.03 ± 0.01	0.01 ± 0.01	0.03 ± 0.01	0.02 ± 0.003	<0.001	0.04 ± 0.02	0.02 ± 0.01	0.02 ± 0.002	0.01 ± 0.004	0.01 ± 0.003	0.01 ± 0.01	0.02 ± 0.01	<0.001
Cr	0.20 ± 0.04	0.15 ± 0.06	0.29 ± 0.12	0.24 ± 0.04	0.41 ± 0.16	0.08 ± 0.02	0.23 ± 0.05	0.16 ± 0.02	5.39 ± 8.84	0.26 ± 0.09	0.18 ± 0.02	0.39 ± 0.42	0.31 ± 0.18	0.26 ± 0.07	0.09 ± 0.006
Cu	1.98 ± 0.14	1.54 ± 0.3	1.62 ± 0.11	0.76 ± 0.08	5.61 ± 2.13	1.49 ± 0.4	1.92 ± 0.35	1.91 ± 0.11	0.97 ± 0.11	1.75 ± 0.33	1.51 ± 0.16	1.75 ± 0.51	1.33 ± 0.32	1.48 ± 0.18	0.9 ± 0.03
Hg	<LOD	<LOD	<LOD	<LOD	0.02	<LOD	<LOD	<LOD	38.54 ± 65.18	<LOD	0.08 ± 0.09	<LOD	<LOD	<LOD	<LOD
Ni	4.17 ± 0.21	3.93 ± 0.1	1.68 ± 0.18	1.16 ± 0.06	3.21 ± 0.19	3.21 ± 0.2	2.6 ± 0.23	2.59 ± 0.16	26.14 ± 42.36	2.88 ± 0.04	1.15 ± 0.21	1.31 ± 0.02	1.23 ± 0.11	1.96 ± 0.07	0.97 ± 0.05
Pb	0.06 ± 0.02	0.04 ± 0.01	0.08 ± 0.05	0.01 ± 0.02	0.11 ± 0.04	0.05 ± 0.004	<0.001	0.16 ± 0.12	0.03	0.2 ± 0.09	0.21 ± 0.25	0.19	<LOD	0.06 ± 0.01	<0.001
Zn	4.12 ± 1.32	2.68 ± 0.49	8.78 ± 1.85	5.35 ± 0.83	17.35 ± 11.05	4.89 ± 3.23	5.43 ± 3.90	3.48 ± 0.98	5.84 ± 3.30	5.28 ± 0.49	2.95 ± 1.19	1.99 ± 0.57	2.55 ± 0.55	3.06 ± 1.14	2.54 ± 0.74

Blue – Good; Green – Tolerable.

2.3.1.3 Spatial distribution of water quality variables for 2021

This PCA biplot describes 50.57% of the variation in the data, where 29.71% is displayed on the first axis and 20.86% is displayed on the second axis (Figure 2-2). The sampling sites SANDR, MOGA, CROCR and LIMP1 exhibited higher levels for most of the elements (Cd, Cu, Ni, Pb and As), major anions and cations ($\text{NO}_2 + \text{NO}_3$, Cl^- , SO_4 , alkalinity and turbidity) and physico-chemical parameters (temperature, DO and pH). Further, LIMP2, MATL, LEPHS and LUVU were characterised by higher levels of some elements (Zn, Cr and Hg), PO_4 and EC. Along the second axis, separation can be seen due to higher levels of elements (Cd, Cu and Ni), major anions and cations ($\text{NO}_2 + \text{NO}_3$ and Cl^-) and physico-chemical parameters (temperature and DO) at sites SANDR and MOGA. However, CROCR and LIMP1 had higher levels of major anions, cations (SO_4 , alkalinity and turbidity), As and pH. Further separations on the second axis are due to LIMP and MATL that exhibited higher EC, PO_4 and Zn levels where LEPHS and LUVU had higher concentrations of Cr and Hg.

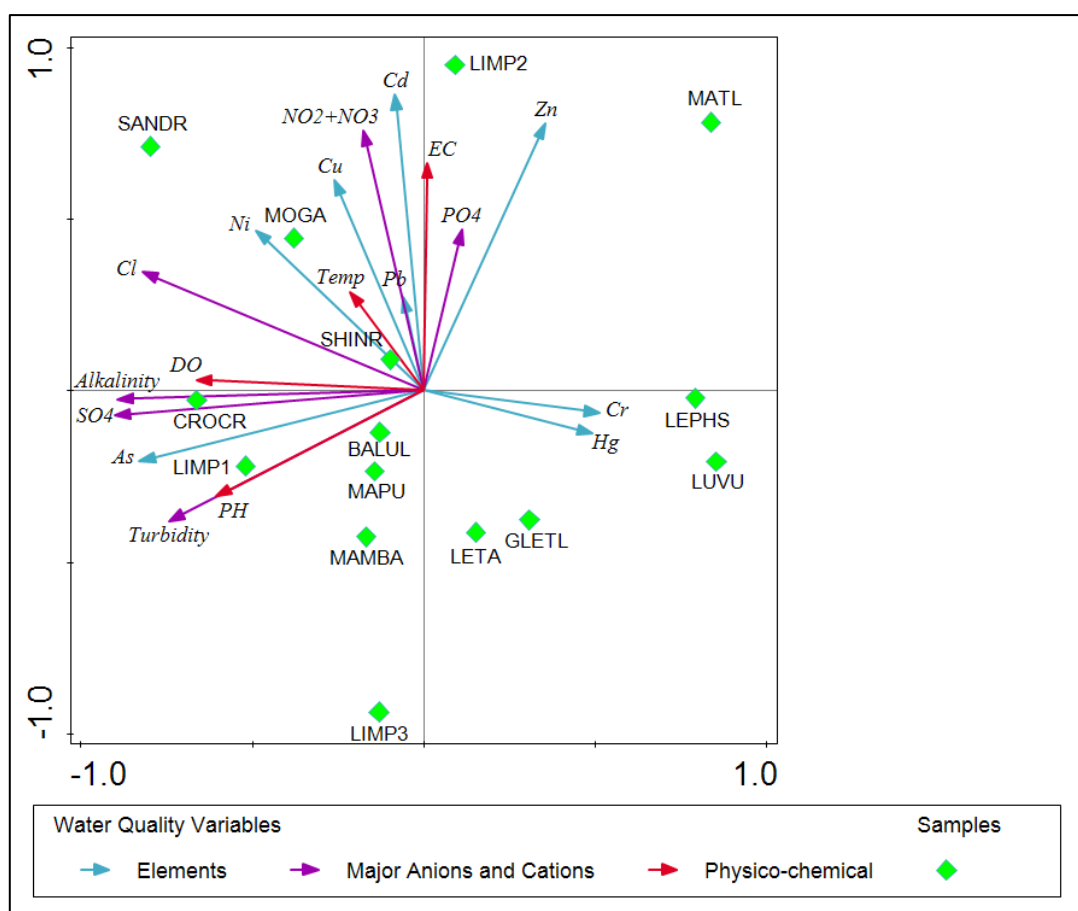


Figure 2-2 A PCA biplot indicating the different element, major anion and cation, and physico-chemical concentrations at the 2021 Limpopo River Basin sampling sites. This PCA biplot describes 50.57% of the variation in the data, where

29.71% is displayed on the first axis and 20.86% is displayed on the second axis.

2.3.2 Water quality overview during 2024

The water quality data were compared to the values stipulated for the fitness of water use and it was determined that according to the pH levels the water was 'Good' for domestic use at most of the sites, except for LETSD and BALUL that were considered to be 'Poor' due to an increase in pH (Table 2-6). The EC concentrations at most of the sites were classified as 'Tolerable', whereas sites LOTSW, LETSD, MWNER, WMENG, LUVU and CCONR were 'Good'. Furthermore, the SO₄ concentrations observed in the LRB were considered to be 'Good' for domestic use at all of the sites. Contrastingly, the PO₄ concentrations varied at the sites ranging from 'Good' at LIMP3 to 'Tolerable' at SHAS, MWENG, LUVU, CCONR, and BALUL. Additionally, there were three sites that were classified as 'Poor' (GMAR, LETSD and MWENR) and six sites that were classified as 'Unacceptable' (NGOT, LOTSW, MOTL, UMZI, MAPU and ELEP) to be utilised by aquatic organisms. It was noted that most of the elevated PO₄ concentrations were observed in the upper section of the LRB. Lastly, the NO₃ concentrations were 'Tolerable' for aquatic use at most the sites, except for NGOT that indicated to be 'Unacceptable' due to a high NO₃ concentration.

Table 2-6 exhibits the additional parameters (DO, Cl⁻, alkalinity and turbidity) compared to the TWQR values for South Africa. The additional water quality parameters are compared to TWQR values due to limited water quality guidelines for the LRB. The DO concentrations were within the acceptable range, except for LOTSW that exhibited a low DO saturation and LUVU, BALUL, ELEP and LIMP3 that indicated elevated DO saturation. Further, all the sites indicated Cl⁻ levels well within the TWQR guideline value. The alkalinity results indicated that 11 out of 15 sites were above the TWQR with high alkalinity. Lastly, six sites (GMAR, LOTSW, MOTL, LETSD, UMZI and MWENR), indicated high turbidity levels above the TWQR.

Table 2-6 Water quality results of the different variables analysed in the samples collected in the Limpopo River Basin (LRB) during the 2024 survey. The data are presented as mean $\pm$ standard error.

Element	GMAR	NGOT	LOTSW	MOTL	LETSD	SHAS	UMZI	MAPU	MWENR	MWENG	LUVU	CCONR	BALUL	ELEP	LIMP3
pH	6.8 $\pm$ 0.006	6.47 $\pm$ 0.02	7.86 $\pm$ 0.03	8.31 $\pm$ 0.01	8.51 $\pm$ 0.009	7.93 $\pm$ 0.03	8.19 $\pm$ 0.08	7.91 $\pm$ 0.01	7.52 $\pm$ 0.09	6.83 $\pm$ 0.06	8.19 $\pm$ 0.03	7.96 $\pm$ 0.09	8.53 $\pm$ 0.01	8.15 $\pm$ 0.003	8.41 $\pm$ 0.005
EC (μ S/cm)	681 $\pm$ 0.58	1166.33 $\pm$ 0.67	254 $\pm$ 0.58	824.33 $\pm$ 218.6	192.57 $\pm$ 1.39	498.33 $\pm$ 7.36	435.33 $\pm$ 3.33	588.67 $\pm$ 2.73	171.13 $\pm$ 0.32	278 $\pm$ 0.58	178.33 $\pm$ 2.80	195.6 $\pm$ 4.35	670 $\pm$ 0.58	423.03 $\pm$ 3.03	490.33 $\pm$ 11.67
DO (mg/L)	7.43 $\pm$ 0.09	9.05 $\pm$ 0.17	5.65 $\pm$ 0.85	8.12 $\pm$ 0.81	10.01 $\pm$ 0.28	9.08 $\pm$ 0.3	9.05 $\pm$ 0.55	8.86 $\pm$ 0.44	8.88 $\pm$ 0.04	9.71 $\pm$ 0.37	11.3 $\pm$ 0.29	9.44 $\pm$ 0.36	13.04 $\pm$ 0.05	11.24 $\pm$ 0.18	12.52 $\pm$ 0.18
DO (%)	85 $\pm$ 1.15	94.97 $\pm$ 1.39	50 $\pm$ 10.97	88.33 $\pm$ 3.33	117.33 $\pm$ 6.23	92 $\pm$ 3.51	96.3 $\pm$ 9.84	104.4 $\pm$ 0.81	100.87 $\pm$ 1.62	103.73 $\pm$ 1.75	125.13 $\pm$ 5.66	98 $\pm$ 10.6	130.5 $\pm$ 0.26	120.23 $\pm$ 0.39	127.23 $\pm$ 1.13
Temperature ($^{\circ}$ C)	19 $\pm$ 0.58	13.4 $\pm$ 0.06	18.17 $\pm$ 0.32	21.57 $\pm$ 1.12	24.2 $\pm$ 0.53	25.9 $\pm$ 0.46	18.63 $\pm$ 0.52	22.53 $\pm$ 1.12	21.07 $\pm$ 0.03	17.2 $\pm$ 0.1	25.2 $\pm$ 0.12	20.03 $\pm$ 0.58	14.33 $\pm$ 0.15	20.2 $\pm$ 0.06	22.83 $\pm$ 0.30
Cl (mg/L)	4.08 $\pm$ 0.36	67.42 $\pm$ 7.26	4.76 $\pm$ 0.18	45.43 $\pm$ 9.89	2.22 $\pm$ 0.24	6.6 $\pm$ 0.09	9.01 $\pm$ 0.30	64.05 $\pm$ 1.47	8.8 $\pm$ 0.15	17.66 $\pm$ 0.35	12.84 $\pm$ 1.78	10.4 $\pm$ 1.87	38.38 $\pm$ 8.02	25.87 $\pm$ 1.42	23.15 $\pm$ 5.02
SO ₄ (mg/L)	6.88 $\pm$ 0.66	20.55 $\pm$ 1.09	1.26 $\pm$ 0.002	7.6 $\pm$ 3.06	2.41 $\pm$ 0.15	1.07 $\pm$ 0.02	67.23 $\pm$ 0.49	27.31 $\pm$ 1.56	2.08 $\pm$ 0.01	3.5 $\pm$ 0.04	2.03 $\pm$ 0.09	1.86 $\pm$ 0.13	53.47 $\pm$ 10.18	44.99 $\pm$ 2.22	37.2 $\pm$ 7.26
PO ₄ (mg/L)	0.09 $\pm$ 0.009	1.55 $\pm$ 0.15	0.92 $\pm$ 0.14	0.18 $\pm$ 0.02	0.12 $\pm$ 0.02	0.04	0.29 $\pm$ 0.15	0.23 $\pm$ 0.05	0.08 $\pm$ 0.03	0.05 $\pm$ 0.02	0.04 $\pm$ 0.01	0.07 $\pm$ 0.02	0.04 $\pm$ 0.02	0.35 $\pm$ 0.07	0.02 $\pm$ 0.007
NH ₃ (μ g/L)	1.1	2.1	225	1.5	68.9	25.5	30.2	28.8	8.1	1.2	60.5	25.6	37.4	28.4	58.7
NH ₄ (mg/L)	0.51 $\pm$ 0.002	4.19 $\pm$ 0.39	0.84 $\pm$ 0.06	0.03 $\pm$ 0.007	0.4 $\pm$ 0.003	0.5 $\pm$ 0.03	0.56 $\pm$ 0.01	0.79 $\pm$ 0.08	0.51 $\pm$ 0.007	0.51 $\pm$ 0.01	0.63 $\pm$ 0.04	0.65 $\pm$ 0.08	0.5 $\pm$ 0.01	0.51 $\pm$ 0.009	0.51 $\pm$ 0.002
NO ₃ (mg/L)	1.08 $\pm$ 0.03	12.44 $\pm$ 0.08	0.98 $\pm$ 0.01	1.04 $\pm$ 0.06	1 $\pm$ 0.01	1.06 $\pm$ 0.02	1.01 $\pm$ 0.01	1.05 $\pm$ 0.01	1.18 $\pm$ 0.004	1.0 $\pm$ 0.01	0.99 $\pm$ 0.01	1.04 $\pm$ 0.01	1 $\pm$ 0.004	1.07 $\pm$ 0.005	1.03 $\pm$ 0.02
NO ₂ + NO ₃ (mg/L)	1.13 $\pm$ 0.02	20.39 $\pm$ 1.57	1.36 $\pm$ 0.02	1.09 $\pm$ 0.04	1.05 $\pm$ 0.03	1.09 $\pm$ 0.02	1.06 $\pm$ 0.03	1.07 $\pm$ 0.02	1.23 $\pm$ 0.01	1.02 $\pm$ 0.01	1.0 $\pm$ 0.01	1.06 $\pm$ 0.02	1.02 $\pm$ 0.004	1.08 $\pm$ 0.007	1.05 $\pm$ 0.02
Alkalinity (mg/L CaCO ₃)	141.71	160.05	115.04	233.41	93.36	205.07	135.04	155.05	78.36	106.7	68.36	56.69	146.71	106.7	100.03
Turbidity (NTU)	28 $\pm$ 5.1	11.33 $\pm$ 1.86	315.33 $\pm$ 10.67	42.33 $\pm$ 17.68	29.33 $\pm$ 9.24	11.67 $\pm$ 1.20	32.67 $\pm$ 16.33	7.33 $\pm$ 0.67	25.67 $\pm$ 7.06	6.0 $\pm$ 1.16	1.67 $\pm$ 0.33	22.0 $\pm$ 5.51	10.0 $\pm$ 0.58	3.67 $\pm$ 1.20	10.67 $\pm$ 2.96

Blue – Good; Green – Tolerable; Amber – Poor; Red – Unacceptable; Lavender – Outside TWQR range.

2.3.2.1 Ionic composition

The Mauchino diagrams, which represents the ionic composition of the sampled sites, indicated that most of the sites were dominated by TAL, except for NGOT and MOTL Figure 2-3. Secondly, it can be seen that Ca^{2+} contributed largely to most of the sites and less at NGOT, MOTL and LETSD. The Mg^{2+} concentrations also contributed largely to the ionic composition at most of the sites and less at NGOT, MOTL and LETSD. Furthermore, Na^+ was also present in higher concentrations at all of the sites except for GMAR, LOTSW, LETSD and UMZI. It was also observed that Cl^- was present in lower concentrations at the majority of the sites except MAPU that exhibited a higher concentration. The SO_4^{2-} concentrations were also low at most of the sites and only UMZI, BALUL, ELEP and LIMP indicated a degree of SO_4^{2-} contribution to the ionic composition at the various sites. Lastly, it can be seen that all the sites exhibited low concentrations of NO_3^- and K^+ , except NGOT that indicated a higher concentration of NO_3^- that contributed to the ionic composition.

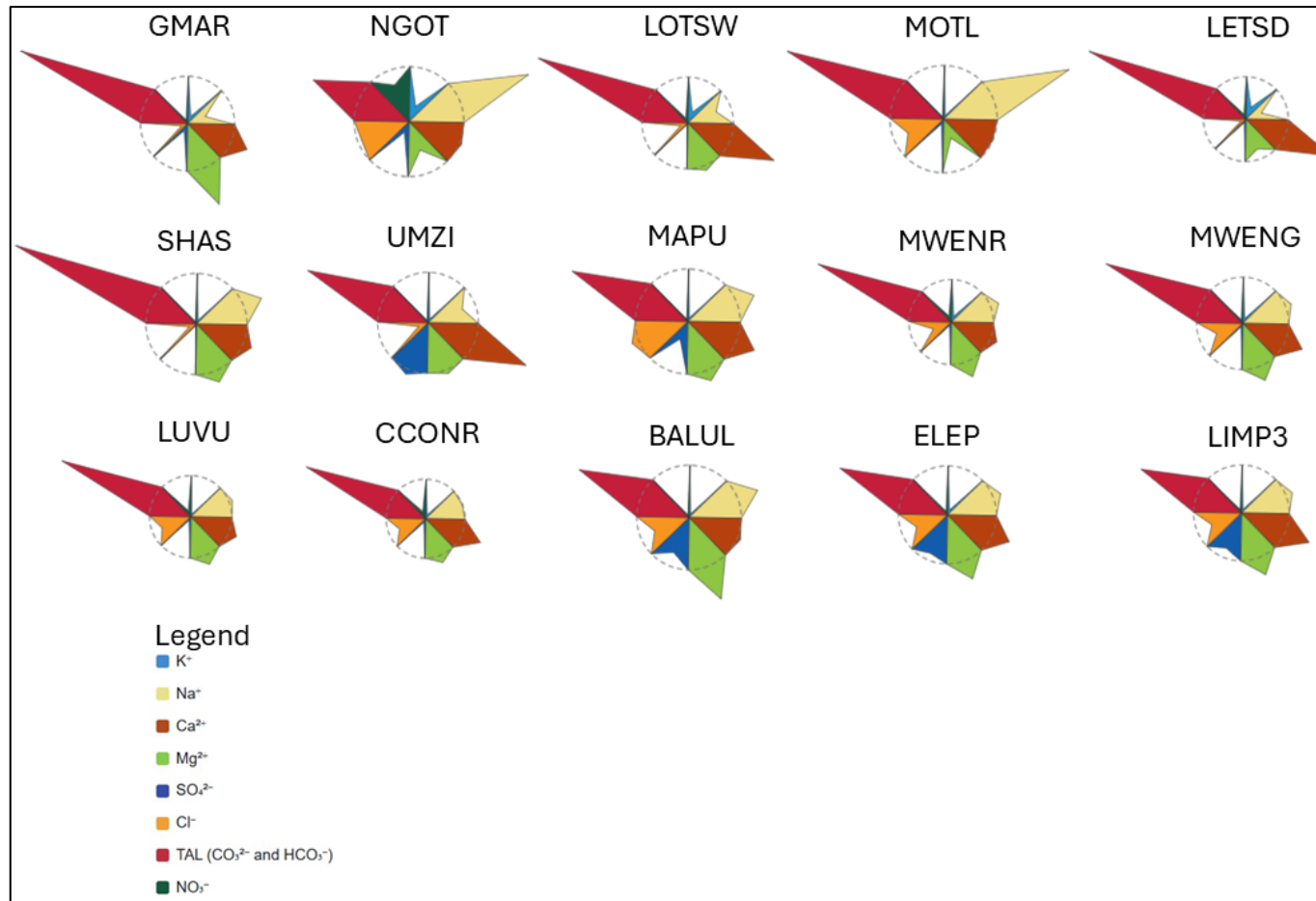


Figure 2-3 Salt balance of the 2024 water samples presented in Mauchino diagrams representing the Marico (GMAR), Ngotwane (NGOT), Lotsane (LOTSW), Motloutse and Letsibogo Dam (MOTL and LETSD), Shashe (SHAS), Umzingwane (UMZI), two sites on the Mwenezi (MWENR and MWENG), Luvuvhu (LUVU), two sites on the Olifants/Elephantes (BALUL and ELEP), and three sites on the mainstem Limpopo (MAPU, CCONR and LIMP3).

2.3.2.2 Element concentrations

The trace element concentrations measured in the water samples taken at each site can be seen in Table 2-7. The measured concentrations ranged between 0.17 (LUVU) – 1.9 (NGOT) µg/L for As, 0.04 (ELEP) – 0.31 (BALUL) µg/L for Cd, 2.78 (GMAR) – 3.21 (LOTSW and UMZI) µg/L for Cr, 14.16 (SHAS) – 17.06 (LOTSW) µg/L for Cu, 0.21 (GMAR, LOTSW, UMZI and MWENR) – 0.19 (NGOT) µg/L for Hg, 0.13 (LIMP3) – 7.95 (NGOT) µg/L for Ni, 0.63 (MOTL and ELEP) – 5.81 (BALUL) µg/L for Pb and 11.82 (MWENG) – 114.07 (MWENR) for Zn.

The majority of the metal concentrations were within the recommended fitness for use values and therefore, the sites were classified as 'Good' for aquatic organisms to use. The Zn concentrations were mostly 'Tolerable', except for sites GMAR and MWENR which indicated higher Zn concentrations and was classified as 'Unacceptable'. Furthermore, relatively constant Ni and Pb concentrations were observed at the sites, except for NGOT and BALUL that indicated considerably higher Ni and Pb concentrations respectively.

Table 2-7 The trace element concentrations (µg/L) in the water samples collected from the Limpopo River Basin during the 2024 survey. The data are presented as mean ± standard error.

Element	GMAR	NGOT	LOTSW	MOTL	LETSD	SHAS	UMZI	MAPU	MWENR	MWENG	LUVU	CCONR	BALUL	ELEP	LIMP3
As	0.66 ± 0.07	1.9 ± 0.06	0.59 ± 0.03	0.65 ± 0.28	0.30 ± 0.02	0.68 ± 0.04	1.76 ± 0.02	0.97 ± 0.04	0.31 ± 0.01	0.24 ± 0.01	0.17 ± 0.005	0.25 ± 0.08	0.93 ± 0.12	1.06 ± 0.03	0.78 ± 0.08
Cd	0.08 ± 0.01	0.17 ± 0.04	0.07 ± 0.02	0.06 ± 0.01	0.14 ± 0.04	0.08 ± 0.02	0.19 ± 0.06	0.23 ± 0.07	0.19 ± 0.06	0.29 ± 0.02	0.21 ± 0.08	0.11 ± 0.03	0.31 ± 0.14	0.04 ± 0.003	0.26 ± 0.04
Cr	2.78 ± 0.12	2.97 ± 0.03	3.21 ± 0.09	3.02 ± 0.15	2.82 ± 0.03	2.83 ± 0.03	3.21 ± 0.20	2.89 ± 0.03	3.04 ± 0.16	2.91 ± 0.01	2.84 ± 0.04	3.09 ± 0.12	3.11 ± 0.04	2.90 ± 0.01	3.01 ± 0.09
Cu	14.89 ± 0.5	14.82 ± 0.22	17.06 ± 0.44	14.78 ± 0.54	14.97 ± 0.41	14.16 ± 0.40	14.45 ± 0.17	14.25 ± 0.17	15.35 ± 0.09	14.84 ± 0.15	15.49 ± 0.52	15.98 ± 0.42	15.97 ± 0.40	14.99 ± 0.28	16.24 ± 0.13
Hg	0.21 ± 0.2	0.19 ± 0.01	0.12 ± 0.001	0.17 ± 0.01	0.13 ± 0.001	0.13 ± 0.01	0.12 ± 0.001	0.15 ± 0.01	0.12 ± 0.01	0.17 ± 0.03	0.15 ± 0.004	0.13 ± 0.003	0.14 ± 0.0003	0.13 ± 0.002	0.13 ± 0.01
Ni	4.22 ± 0.07	7.95 ± 0.39	4.0 ± 0.08	4.09 ± 0.64	3.43 ± 0.07	3.66 ± 0.10	3.13 ± 0.05	3.82 ± 0.11	3.69 ± 0.05	3.41 ± 0.02	3.46 ± 0.49	3.25 ± 0.10	4.11 ± 0.21	3.64 ± 0.04	0.13 ± 0.01
Pb	0.80 ± 0.07	1.50 ± 0.58	0.81 ± 0.22	0.63 ± 0.01	1.25 ± 0.19	0.73 ± 0.24	1.69 ± 0.66	3.42 ± 1.31	2.64 ± 1.41	3.34 ± 0.98	2.73 ± 0.78	1.76 ± 0.56	5.81 ± 1.33	0.63 ± 0.03	3.35 ± 0.11
Zn	54.9 ± 6.41	15.20 ± 1.23	15.50 ± 1.40	15.45 ± 2.19	19.03 ± 7.60	13.22 ± 1.48	20.15 ± 6.15	15.64 ± 1.23	144.07 ± 2.50	11.82 ± 0.18	16.75 ± 4.08	14.03 ± 1.12	14.90 ± 1.64	17.37 ± 4.62	15.98 ± 3.05

Blue – Good; Green – Tolerable; Red – Unacceptable.

2.3.2.3 Spatial distribution of water quality variables during 2024

The PCA biplot describes 51.62% of the variation in the data, where 30.94% is displayed on the first axis and 20.68% is displayed on the second axis (Figure 2-4). The sampling sites SHAS, LETSD, MWENR and CCONR exhibited higher levels for the elements (Zn and Cu), and physico-chemical parameters (temperature and pH). Furthermore, NGOT was characterised by higher concentrations of selected elements (Hg, Ni and As), EC and major anions and cations (PO_4 , $\text{NO}_2 + \text{NO}_3$ and alkalinity). Along the second axis separation can be seen due to higher levels of turbidity at sites LOTSW and GMAR, whereas LUVU had higher pH levels and LIMP3 had higher levels of DO and elements (Pb and Cd). Additionally, it can also be seen that BALUL had elevated levels of major anions and cations (SO_4 and Cl^-), DO and selected elements (Pb and Cd).

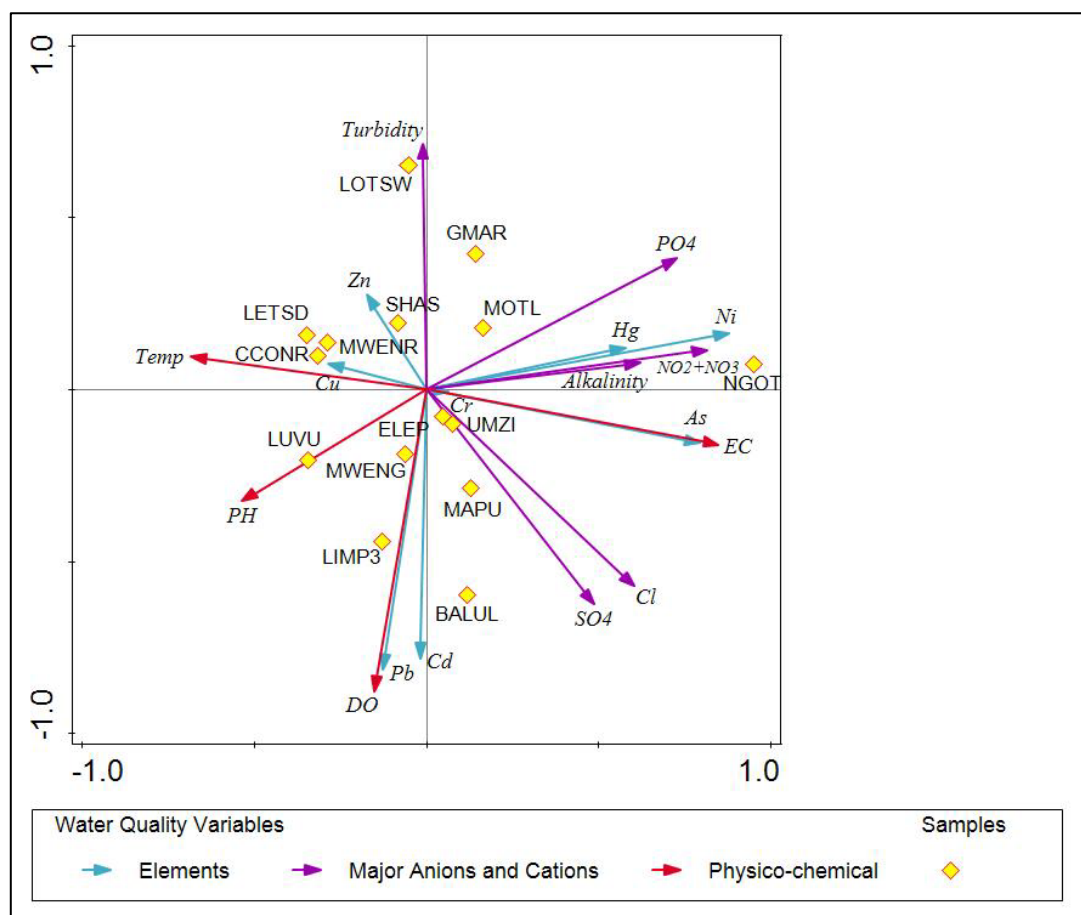


Figure 2-4 A PCA biplot indicating the different element, major anion and cation, and physico-chemical concentrations at the 2024 Limpopo River Basin sampling sites. This PCA biplot describes 51.62% of the variation in the data, where 30.94% is displayed on the first axis and 20.68% is displayed on the second axis.

2.3.3 Spatial and temporal analysis of water quality for the 2021 and 2024 overlapping sites

2.3.3.1 Water quality variables

The 2021 survey aimed to assess the mainstream of the LRB, whereas the 2024 survey aimed to assesses the tributaries of the LRB. Thus, only four sites were sampled during both years, which were considered for the spatial and temporal analysis. The PCA biplot describes 83.96% of the variation in the data, where 50.5% is displayed on the first axis and 33.46% is displayed on the second axis (Figure 2-5). In the PCA biplot it can be seen that most of the element concentrations (Hg, Cr, Ni, Zn, Pb, Cd and Cu) increased from 2021 to 2024. Site LUVU is characterised by Hg and Cr, whereas LIMP3, MAPU and BALUL indicated to have higher levels of Zn, Ni, Cu, Cd, Pb. Furthermore, it can also be seen that the temperature was higher at LUVU during both the sampling year 2021 and 2024.

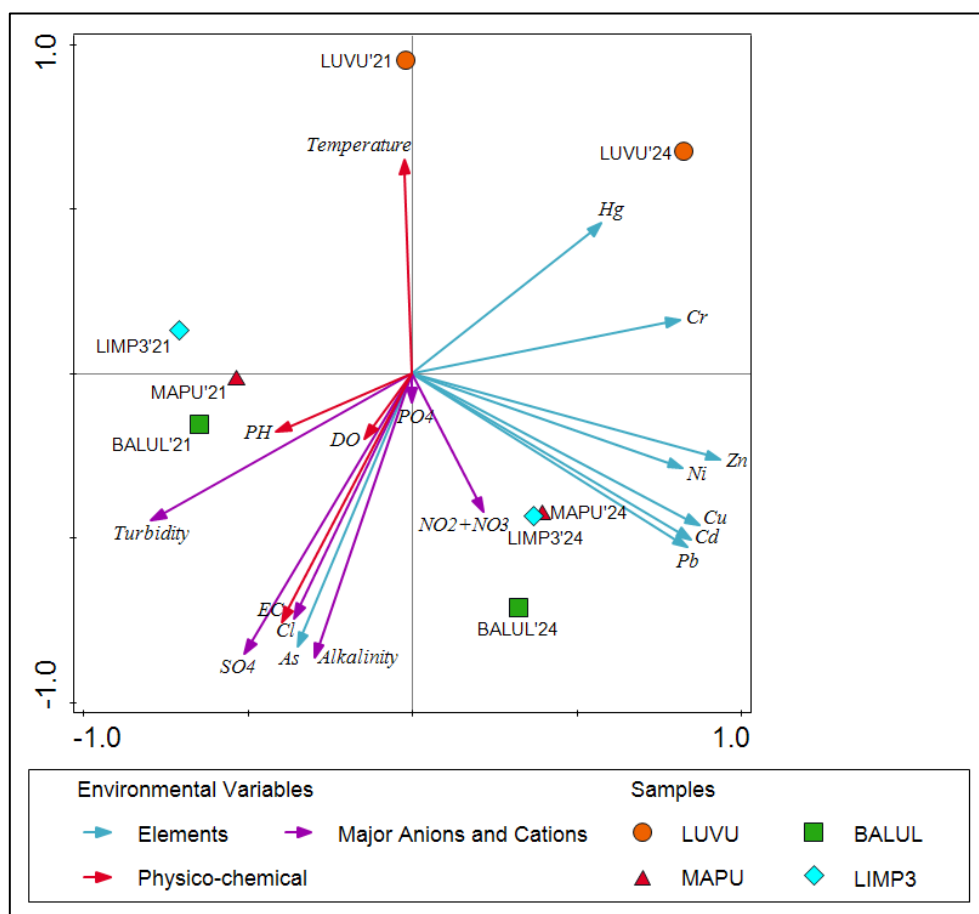


Figure 2-5 A PCA biplot indicating the different element, major anion and cation, and physico-chemical concentrations at the 2021 and 2024 overlapping sites in the Limpopo River Basin. This PCA biplot describes 83.96% of the variation in the

data, where 50.5% is displayed on the first axis and 33.46% is displayed on the second axis.

2.3.3.2 Elements

The difference in element concentrations in the water samples for the overlapping sites between 2021 and 2024 are presented in Figure 2-6. The bars in the charts represents a visual comparison of the mean element concentrations. All of the element concentrations at site MAPU were higher during 2024 and therefore indicating an increase in element concentrations from 2021 to 2024. Similar trends were observed for LUVU where As, Cd, Cu, Pb, and Zn increased from 2021 to 2024 (Table 2-5, Table 2-7 and Figure 2-6). Lastly, both sites, BALUL and LIMP3 also indicated an increase in concentrations for all of the elements, except for As (Table 2-5, Table 2-7 and Figure 2-6).

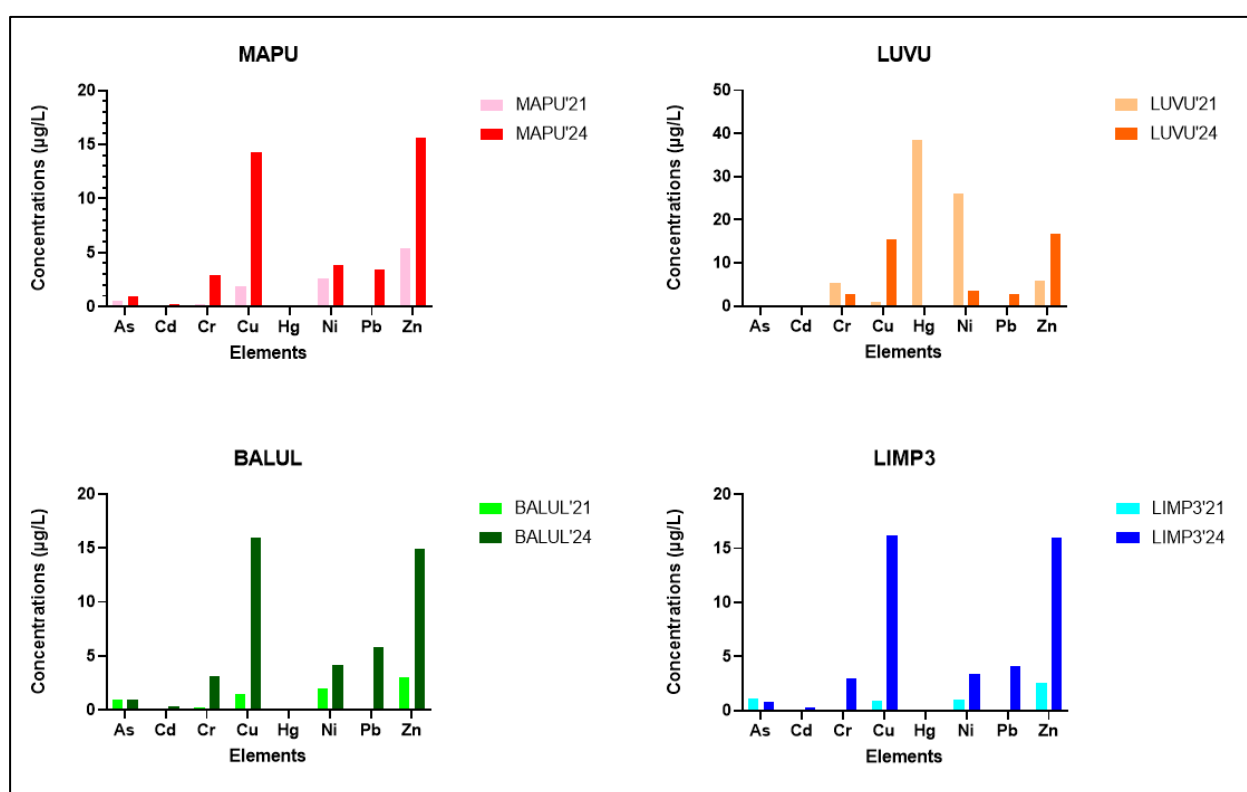


Figure 2-6 Visual comparison of the mean element concentrations (µg/L) at the overlapping sites (MAPU, LUVU, BALUL and LIMP) in the Limpopo River Basin between 2021 and 2024.

2.3.4 Land-use/Land-cover during 2021 and 2024

From Table 2-8 and the LULC maps (Figure 2-7 and Figure 2-8) it can be seen that the LRB is dominated by rangeland and tree areas. However, an increase in rangeland (5.14%) and a decrease in tree cover (5.52%) was observed from 2021 to 2024. A slight increase in crops (0.42%) and built areas (0.15%) between 2021 and 2024 was also observed. Lastly, water, flooded vegetation, bare ground, snow/ice and clouds were present in low coverage during both years. A decrease in water (0.1%), flooded vegetation (0.09%) and bare ground (0.01%) was observed from the year 2021 to 2024, whereas the cloud cover was approximately the same and a slight increase in snow/ice (0.00001%) cover was observed.

Table 2-8 The Land-use/Land Cover classes, area (km²) and coverage (%) for 2021 and 2024, as well as the calculated difference between 2021 and 2024.

LULC Class	2021		2024		Area (km ²) difference	Coverage (%) difference
	Area (km ²)	Coverage (%)	Area (km ²)	Coverage (%)		
Water	1832.03	0.443	1409.32	0.342	-422.71	-0.1
Trees	192029.39	46.657	169325.27	41.142	-22704.12	-5.52
Flooded vegetation	585.9	0.142	223.89	0.054	-362.01	-0.09
Crops	21262.32	5.166	22998.87	5.588	1736.55	0.42
Built Area	11805.03	2.868	12400.11	3.013	595.08	0.15
Bare ground	334.29	0.081	307.26	0.075	-27.03	-0.01
Snow/Ice	0.04	0.00001	0.08	0.00002	0.04	0.00001
Clouds	0.04	0.00001	0.02	0.00001	-0.02	0
Rangeland	183737.46	44.642	204901.12	49.786	21163.66	5.14
Total	411577.51	100	411565.9286	100	-11.5814	0

Increase in LULC highlighted in yellow.

Decrease in LULC highlighted in blue.

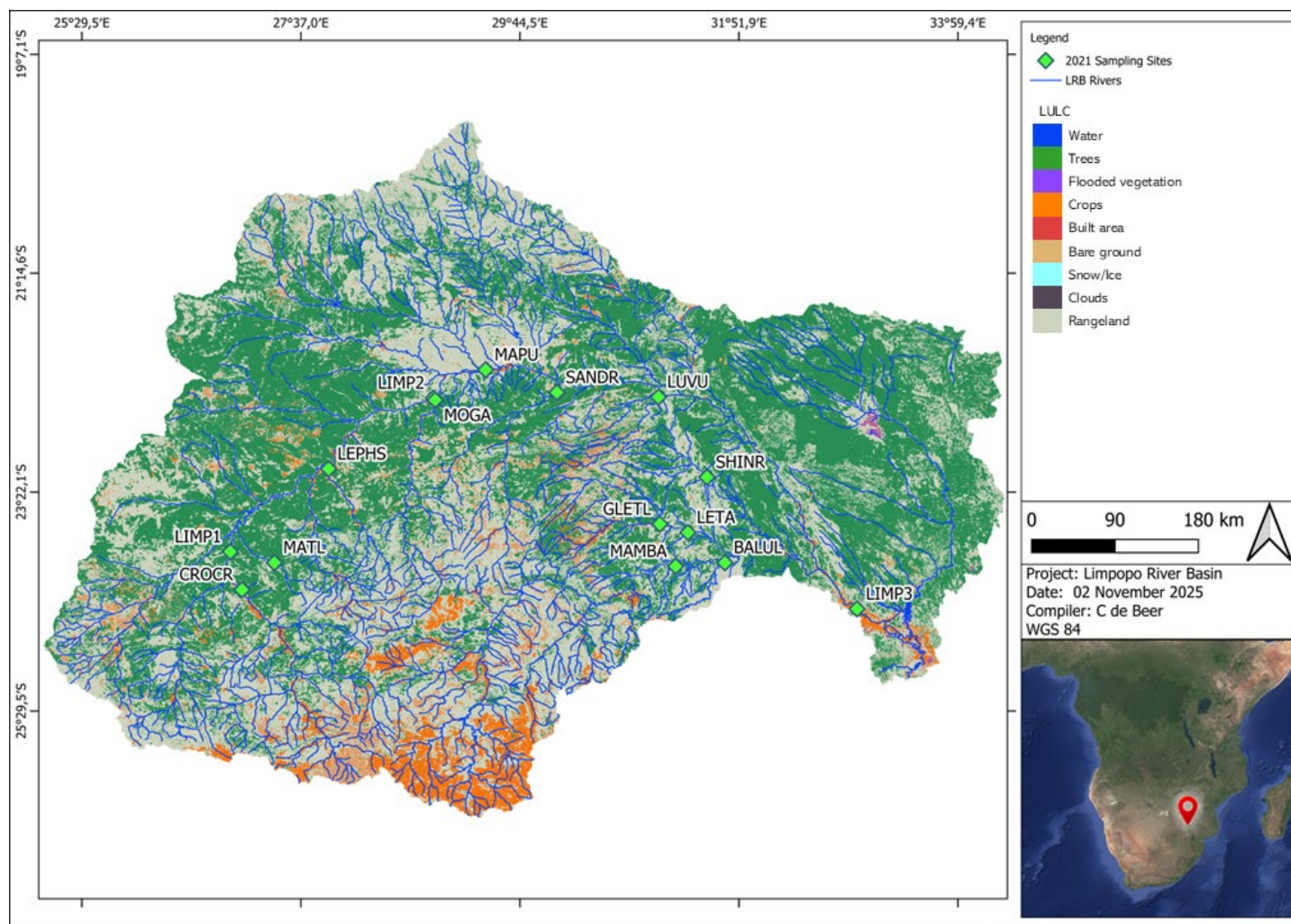


Figure 2-7 The different land cover class coverage (%) and area (km²) of the Limpopo River Basin in 2021. The 2021 survey sites are also indicated.

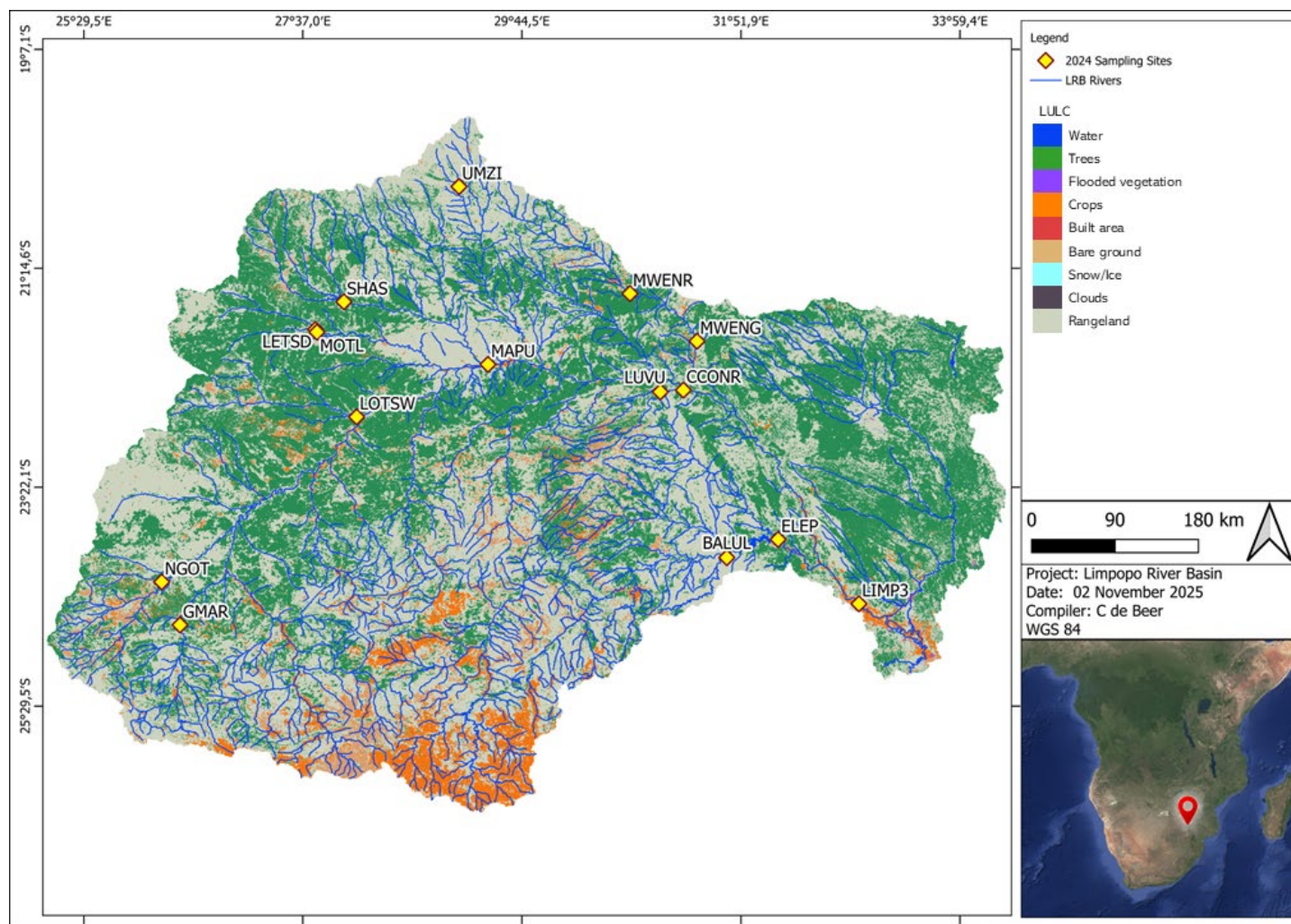


Figure 2-8 The different land cover class coverage (%) and area (km²) of the Limpopo River Basin for 2024. The 2024 survey sites are also indicated.

2.4 Discussion

Globally, the challenges regarding water quality can be seen as one of the biggest concerns of the 21st century (Du Plessis, 2022). This is specifically a challenge in the parts of the shared LRB, where the uneven distribution of economic development in the four countries (South Africa, Botswana, Zimbabwe and Mozambique) causes an imbalance in water usage (Kurugundla *et al.*, 2013). The imbalance of water usage and anthropogenic impacts on water quality, including urbanisation, agricultural activities, mining and forestry can create difficulties in managing the water resources to the benefit of all four countries (Petrie *et al.*, 2015; Kahinda *et al.*, 2016; Riddell *et al.*, 2019; Molekoa *et al.*, 2021). Thus, this discussion will focus on the state of the water quality during 2021 and 2024, as well as the change in water quality for overlapping sites and the possible impacts of changing land-use on the water quality in the LRB.

2.4.1 Water quality for 2021

The measured water quality parameters in comparison with the recommended values for fitness of water use in the LRB and TWQR guideline values for water use and management in South Africa, indicated altered water quality at most of the sites during 2021 (DWAF, 1996; INR, 2013). The *in situ* parameters measured, indicated elevated pH, EC and DO levels at six sites (CROCR, LIMP1, MAPU, SANDR, MAMBA and BALUL), classifying the sites as poor for domestic use and tolerable for irrigation and domestic use according to the pH and EC results respectively. The saturated DO observed at these sites were also high, outside the TWQR, indicating super saturated conditions. The Crocodile River is exposed to sewage effluent, industrial wastewater, agricultural and urban runoff, which can possibly contribute to the poor water quality conditions at CROCR and the downstream site in the Limpopo River at LIMP1 (Du Preez *et al.*, 2018; Phungela *et al.*, 2021). Further, the Mogalakwena River, a tributary of the Limpopo River, upstream of the MAPU site in the Limpopo River, is also impacted by wastewater discharge, mines, and industrial activities in built up areas (Molekoa *et al.*, 2021). According to Molekoa *et al.* (2021), the water quality deteriorated in the Mogalakwena River system from 2016 to 2019. During 2021, site MOGA in the Mogalakwena River indicated elevated EC and saturated DO, with the EC levels that classify the water quality as poor for domestic use and irrigation. Thus, the altered water quality observed at site MAPU can also potentially be attributed to the impacted water quality in the upstream tributaries such as the Mogalakwena River. Sewage effluent is also impacting the Sand River (Seanego & Moyo, 2013; Phungela *et al.*, 2021). The sewage originating from the Polokwane area is impacting the Sand River system with EC and salinity as one of the big contributing factors of water quality in the Sand River. Similar results were observed during 2021 at SANDR (elevated pH and EC) which can possibly be due to the historical impact of

sewage effluent in the Sand River. Furthermore, the historical impacts of mining and effluent discharge in the Olifants River catchment resulted in salt enrichment, which was also observed in 2021 at site MAMBA with elevated pH and EC levels measured during the survey (Marr *et al.*, 2017; Riddell *et al.*, 2019). Site MATL in the Matlabas River exhibited the highest EC concentration. The Matlabas catchment include pristine mires and peatlands where it flows through the Marakele National Park (Bootsma *et al.*, 2019; Dickens *et al.*, 2021). Although the anthropogenic impacts are limited in this area, erosion, instream dams and agricultural activities are still present in the system. Therefore, the elevated EC can potentially be attributed to a combination of natural erosion, agricultural activities and low water levels due to flow interruption by instream impoundments.

It is expected that the DO concentrations would be lower in the rivers where sewage effluent is present due to anaerobic decomposition of organic matter, especially during the night. Contrastingly, super saturated conditions were observed. This can be attributed to higher photosynthetic rates by phytoplankton due to higher light penetration and temperatures during the day when the *in situ* measurements were taken, as well as the higher nutrient concentrations (NO_3 and PO_4) observed at almost all sites (Winder & Somer, 2012). Interestingly, all the upper regions in the LRB exhibited elevated nutrient concentrations with the highest nutrient concentrations recorded in this region as well, classifying most of the sites as unacceptable or tolerable for aquatic use according to the PO_4 and NO_3 concentrations respectively. Similar results were observed in the Crocodile River and Limpopo River during 2012 with nutrient loading being evident (Kurugundla *et al.*, 2013). Further, the high concentrations of NO_3 and PO_4 can possibly be due to agricultural runoff and potentially the higher land erosion in the upper region of the LRB because of land degradation. Additionally, high concentrations of SO_4 and Cl^- were present at site MOGA during 2021. Similar results were observed in the Mogalakwena River in the Mokopane area during the study conducted by Molekoa *et al.* (2021), indicating that the higher SO_4 and Cl^- could potentially originate from surface runoff and the SO_4 more specifically due to agricultural runoff.

The alkalinity levels were also high above the TWQR at almost all of the sites in the LRB. This can also be seen in the Mauchino diagrams where the ionic composition of all the sites was dominated by the total alkalinity, except for MOGA and SANDR, which were dominated by Cl^- . Furthermore, Cl^- , Mg^{2+} , Ca^{2+} and SO_4^{2-} also contributed largely to the ionic composition at most of the sites. The higher total alkalinity, Mg^{2+} and Ca^{2+} support the elevated pH and EC observed in the LRB. The elevated total alkalinity, as well as the higher concentrations of Cl^- , Mg^{2+} , Ca^{2+} and SO_4^{2-} cannot only be attributed by anthropogenic impacts alone, but also the diversity of soils found in LRB, specifically in South Africa, and therefore the natural geology (Dickens *et al.*, 2020).

It is also possible that higher, slightly alkaline pH levels contributed to the cation levels by making it available due to higher pH levels that ionize cations (Mbongwe *et al.*, 2023).

The element concentrations for most of the trace elements (As, Cd, Cr, Cu and Hg) measured for the sites during 2021 were classified as good for aquatic ecosystems. Further, the Zn concentrations were considered good at most of the sites, with slightly elevated concentrations present at six sites. It must also be noted that although there are no specific guidelines for Ni, elevated concentrations were also observed with Ni indicating concentrations higher than most of the elements specifically at sites CROCR, LIMP1 and LUVU. Wastewater and effluent discharge as well as mining and the natural weathering of rock can contribute to the metal concentrations observed in water samples (Molekoa *et al.*, 2021). As previously discussed, it is evident that sewage effluent, agricultural activities, urbanisation and mining are impacting the water quality in the LRB. Additionally, natural erosion, weathering of rocks and soil diversity are also present (Dickens *et al.*, 2020). Therefore, the current condition of the element concentrations during 2021 can be the result of both the anthropogenic impacts and natural geological characteristics of the LRB.

2.4.2 Water quality for 2024

The *in situ* parameters measured during 2024 indicated good pH concentrations for most of the sites, with one site at Letsibogo Dam (LETSD) exhibiting elevated pH levels, classifying the site as poor to use for irrigation according to the fitness for use guideline values (INR, 2013). Additionally, site BALUL in the Olifants River exhibited elevated pH, EC and super saturated DO concentrations, classifying the site as poor for domestic use according to the pH level and tolerable for irrigation and domestic use according to the EC. The higher pH in Letsibogo Dam can possibly be the effect of sediment loading and characteristics of the soil type. Sediment loading occurs due to impoundments that disrupt the sediment flow in natural systems and trapping sediments (Wohl *et al.*, 2010; Hauer *et al.*, 2018). Additionally, the Motloutse River, upstream of Letsibogo Dam is used to supply groundwater for irrigation (Nthokwa *et al.*, 2025). Thus, it is possible that the return flows from irrigation can also contribute to the higher pH observed. The sediment loading and trapping of fine sediments in Letsibogo Dam, along with the accumulative effect of return flows from irrigation can also contribute to the higher EC observed downstream of the dam in the Motloutse River (MOTL). Furthermore, the elevated pH and EC concentrations in the Olifants River (BALUL), can be the result of mining on the Ga-Selai River (tributary of the Olifants River), as well as effluent discharge (Marr *et al.*, 2017; Riddell *et al.*, 2019). Elevated EC concentrations were also observed at the downstream site (ELEP) in the Olifants River. Similar results were observed in the Olifants River during 2021 at sites MAMBA

and BALUL, possibly originating from similar impacts (Marr *et al.*, 2017; Riddell *et al.*, 2019). Overall, slightly elevated EC levels were observed at nine out of the fifteen sites with Groot-Marico potentially being impacted by mainly agricultural runoff and return flows during irrigation (Du Preez *et al.*, 2018). The site in the Shashe River (SHAS), below the Dikgathong Dam, exhibited elevated EC levels, which was also observed in the Motloutse River below Letsibogo Dam. Thus, in this case it is possible that sediment loading and trapping of fine sediments in Dikgathong Dam can also potentially contribute to the higher EC levels downstream at site SHAS (Hauer *et al.*, 2018; Wohl *et al.*, 2010). Furthermore, the higher EC observed at MAPU and LIMP3 in the Limpopo River can be attributed to the accumulation of impacts observed in the tributaries such as the Crocodile, Ngotwane, Mogalakwena, Sand and Olifants rivers (Marr *et al.*, 2017; Du Preez *et al.*, 2018; Riddell *et al.*, 2019; Molekoa *et al.*, 2021).

During the field survey it was noted that the water of the Ngotwane River is mainly fed by effluent discharge originating from the Glen Valley Wastewater Treatment Plant (WWTP) where all the wastewater from Gaborone is treated. This was also described in a report by Martin (2017). The effluent discharged into the Ngotwane River explains the high EC and nutrients (PO_4 and NO_3) concentrations, classifying the system as tolerable, and unacceptable respectively. Further, high PO_4 concentrations were also observed for the rest of the LRB, except for LIMP3 which were good for aquatic ecosystems according to the fitness for use values. The classification of the sites ranged from tolerable at five sites, poor at three sites and unacceptable at five sites. Additionally, the NO_3 concentration at almost all the sites were elevated and classified as tolerable for aquatic ecosystems. Thus, it can be seen that elevated nutrient concentrations (PO_4 and NO_3) were present at most of the sites and therefore indicating the impacts of agricultural activities, urbanisation and industrial or sewage effluent, increasing the nutrient concentrations in the LRB. The nutrient concentrations, specifically PO_4 , indicated similar results during 2021 and 2024 where the upper half of the LRB exhibit higher PO_4 concentrations. Additionally, the high DO saturation observed at four of the sites during 2024 can also potentially be attributed to similar impacts as in 2021, which can potentially be attributed to higher photosynthetic rates by phytoplankton due to higher light penetration and temperatures when the *in situ* measurements were taken. The higher nutrient concentrations (NO_3 and PO_4) observed at almost all sites can also contribute to the saturated DO conditions (Winder & Somer, 2012).

Overall, the alkalinity levels in the LRB were considered high. Elevated alkalinity levels above the TWQR were present at eleven sites, while the remaining four sites also exhibited elevated alkalinity levels, although it indicated to be below the TWQR. The high alkalinity levels were also presented in the Mauchino diagrams, where all the sites were dominated by alkalinity, except for NGOT (Ngotwane River) and MOTL (Motloutse River), which indicated higher Na^+ concentrations.

The higher Na^+ concentrations at NGOT in the Ngotwane River can be the result of sewage effluent feeding the system and the difficulties to remove Na^+ from raw sewage during the treatment process (Aljeddani, 2023). Further, it is also possible that the accumulative impacts of sediment loading and trapping in Letsibogo Dam, irrigation return flows into the Motloutse River, along with semi-arid conditions and groundwater contribution in the catchment could contribute to the higher Na^+ downstream of Letsibogo Dam at site MOTL. Furthermore, a study conducted by Day and King (1995) on the dominance of major ions in the rivers of South Africa indicated four dominant categories. Three of these categories indicated higher concentrations of Mg^{2+} and Ca^{2+} . These categories consisted out of the Dolomite and Pretoria series of the Northern Transvaal, the Karoo and Waterberg sedimentary rocks, igneous rocks of the Basement Complex and the Bushveld Igneous Complex. The third category was not linked to any specific geological formations. Thus, it was expected for the rivers in the LRB to exhibit higher concentrations of Mg^{2+} and Ca^{2+} . This was observed during the study where Mg^{2+} and Ca^{2+} contributed largely to the ionic composition at most of the sites. Similar results were observed during 2021 at the sampled sites in the LRB. Therefore, indicating that the high alkalinity, as well as the high anion and cation concentrations are potentially due to a combination of anthropogenic impacts and the natural geology (i.e. the Marico and Crocodile rivers that are located in mineral rich areas) (Dickens *et al.*, 2020). The higher, slightly alkaline pH levels could also have contributed to the cation levels by making it available due to higher pH levels that ionize cations (Mbongwe *et al.*, 2023).

The element concentrations for most of the trace elements (As, Cd, Cr, Cu and Hg) measured for the sites during 2024 were also classified as good for aquatic ecosystems. Contrastingly, elevated Zn concentrations were observed at all the sites, with thirteen sites exhibiting tolerable concentrations and two sites (GMAR and MWENR) exhibiting unacceptable Zn concentrations. Higher Zn concentrations were also observed at most of the sites during 2021. Therefore, it can potentially be the results of natural erosion, weathering of rocks and soil diversity (Dickens *et al.*, 2020).

2.4.3 Comparison of water quality for the 2021 and 2024 sites in relation to land-use/land-cover

Site MAPU in the Limpopo River indicated a larger increase in all of the selected elements (Cd, Cr, Cu, Hg, Ni, Pb and Zn), as well the pH and $\text{NO}_2 + \text{NO}_3$. The increase in these variables from 2021 to 2024 can potentially be attributed to the historical and present impacts recorded in the upstream tributaries such as the Crocodile and Mogalakwena rivers (Kurugundla *et al.*, 2013; Molekoa *et al.*, 2021). As previously discussed, the Crocodile River is heavily impacted by nutrient loading due to sewage effluent, agricultural runoff and potentially higher land erosion due to land

degradation, whereas the Mogalakwena River is impacted by wastewater discharge, mining and industrial runoff (Kurugundla *et al.*, 2013; Molekoa *et al.*, 2021). Thus, the high increase in the element and nutrient concentrations, as well as the pH can possibly be the result of the accumulative impacts due to land-use activities observed in the upstream tributaries. Overall, the increase in various water quality variables resulted in the degradation of the water quality condition.

Furthermore, site LUVU in the Luvuvhu River also indicated an increase in most of the measured elements (As, Cd, Cu, Ni, Pb and Zn), nutrients and salt (NO_2+NO_3 and SO_4), as well as alkalinity. A recent study conducted by Shibambu *et al.* (2025), indicated similar results where the overall results for the water quality index deteriorated. Significant differences in the water quality of the Luvuvhu catchment was observed, specifically downstream, indicating the impacts of domestic discharge, agricultural runoff and semi-industrial pollution (Shibambu *et al.*, 2025). Therefore, the results recorded during 2021 and 2024, as well as the increase in elements, nutrients and alkalinity observed from 2021 to 2024 is a reflection of these recorded impacts on the water quality in the Luvuvhu catchment.

Site BALUL in the Olifants River also indicated an increase in elements (Cd, Cr, Cu, Hg, Ni, Pb and Zn) from 2021 to 2024. Contrastingly, a decrease in nutrient and salt concentrations (PO_4 , NO_2+NO_3 and SO_4) and alkalinity was observed. As previously discussed, the Olifants River system and its tributaries are impacted by agricultural activities, historical mining and industrial runoff (Marr *et al.*, 2017; Riddell *et al.*, 2019). It is possible that these impacts contributed to the increase in element concentrations in the Olifants River as previous studies have also indicated the accumulation of metals in aquatic organisms in the Olifants River such as *Hydrocynus vittatus* (Gerber *et al.*, 2016). Additionally, the decrease in the PO_4 and SO_4 concentrations can be attributed to the successful implementation of a no-discharge policy by the industrial phosphate plant on the Ga-Selati River, a tributary of the Olifants River (Riddell *et al.*, 2019). The most downstream site (LIMP3) in the Limpopo River indicated the effect of the accumulation of impacts in the LRB, as well as the observed anthropogenic impacts in the tributaries such as the Crocodile, Ngotwane, Mogalakwena, Sand and Olifants rivers (Marr *et al.*, 2017; Du Preez *et al.*, 2018; Riddell *et al.*, 2019; Molekoa *et al.*, 2021;). The increase in elements (Cd, Cr, Cu, Hg, Ni, Pb and Zn) and nutrient concentrations (NO_2+NO_3), as well as the increase in pH from 2021 to 2024 are evident of anthropogenic impacts in the LRB including wastewater discharge, mining, agricultural activities and industrial runoff.

When the LULC classes were assessed, an increase in the areas covered, ranging from highest to lowest, were observed in rangelands, crop fields and built areas from 2021 to 2024. Therefore,

indicating the increase in population and demand for food security. This was also observed in the past decade where 50% out of 20 million people are located in the rural areas and involved in agriculture in the LRB (Petrie *et al.*, 2015; Dickens *et al.*, 2020). Additionally, an increase in urbanisation was also observed in the past decade in the LRB, similar to what was observed from 2021 to 2024 (Petrie *et al.*, 2015; Dickens *et al.*, 2020). Ultimately, this will result in an increase in the demand for water supply and utilisation thereof, which potentially influenced the water quality in the LRB.

Agricultural activities including rangelands and crop fields can impact the water quality through point and non-point sources where agricultural runoff can increase sediment inputs, nutrients and organic waste (Dallas & Day, 2004; Zahoor & Mushtaq, 2023). Thus, the increase in nitrogen concentrations ($\text{NO}_2 + \text{NO}_3$) at most of the sites and the constant high PO_4 concentrations can potentially be the results of an increase in agricultural activities from 2021 to 2024 in the LRB. Additionally, urban runoff and human waste can also increase the nutrients, metals, organic matter and other chemicals (Dallas & Day, 2004). The increase in metal and nutrient concentrations for the overlapping sites from 2021 to 2024, in comparison with the increase in built areas in the LRB, corresponds with the effects of urbanisation on water quality. Therefore, it is possible that the increase in built areas can be the effect of urbanisation and other industries such as mining that ultimately resulted in an increase in metal and nutrient concentrations. In conclusion, the possible effects of agricultural activities and urbanisation such as an increase in metal and nutrient concentrations corresponds with the increase in rangeland, crop fields and built areas from 2021 to 2024 in the LRB.

2.5 Conclusions

The development of the four countries in the shared LRB and subsequently the pressure on water resources were evident during 2021 and 2024. The sampled sites during 2021 and 2024 indicated water quality perturbations at most of the sites. However, the sites sampled during 2024 indicated slightly better quality in comparison with the 2021 sampling sites. The 2021 results indicated elevated pH, EC and DO levels resulting in poor and unacceptable water quality for domestic and irrigation use at six sites, whereas the 2024 results only indicted two sites classified as poor for domestic and irrigation use. Furthermore, the elevated pH observed in the basin was also indicated in the Mauchino diagrams where most of the sites during both sampling years exhibited higher alkalinity, cation and anion concentrations. Additionally, the elevated pH levels observed in the basin potentially contributed to the high cation levels as well, by making cations available through ionisation. The nutrient concentrations (PO_4 and NO_3) were also elevated during both sampling years, specifically in the upper region of the LRB. Although most of the element

concentrations were good for aquatic ecosystems, higher Zn and Cu concentrations, in comparison with the selected elements, were observed throughout the basin during both sampling years. The predominant impacts of agricultural activities, mining, urbanisation and sewage effluent in the LRB are potentially impacting the water quality as indicated by the 2021 results and previous studies conducted in the Crocodile, Mogalakwena, Sand and Olifants rivers. Sewage effluent was also present in the Ngotwane River during 2024, originating from the Glen Valley Wastewater Treatment Plant (WWTP) where all the wastewater from Gaborone is treated. The effects of sewage effluent reflected in the water quality results where elevated EC, cations and nutrients were recorded with the highest out of all the sites recorded in the Ngotwane River. The accumulative effects of these impacts on the tributaries were also observed in the downstream water quality results of the two sites in the Limpopo River where altered water quality was also observed.

Furthermore, higher evaporation rates or the dissolving of minerals and salts from the soils in the Letsibogo and Dikgathlong dams potentially resulted in an increase in EC downstream of the impoundments, specifically in the Motloutse and Shashe rivers. The sites sampled in the Olifants River indicated constant elevated EC levels during both sampling years, potentially due to the historical impact of mining in the Olifants catchment. The impacts of agricultural activities, mining, urbanisation and industrial effluents are undisputable in the LRB as indicated by previous studies, as well as the present. Additionally, the water quality conditions during 2021 and 2024 cannot be attributed to anthropogenic impacts alone, but also potentially the natural weathering of rocks and high soil diversity found in the LRB.

The increase in rangelands, crop fields and built areas from 2021 to 2024, indicated the progression of agricultural activities and urbanisation in the LRB. Although the effects of historical impacts are evident in the water quality, further increases in elements were observed from 2021 to 2024 at all four overlapping sites in the Limpopo (MAPU, LIMP3), Luvuvhu (LUVU) and Olifants (BALUL) rivers. Further increases in nutrients, salts and alkalinity was observed in the Luvuvhu River, potentially indicating the effects of domestic discharge, agricultural activities and semi-industrial pollution. Contrastingly, a decrease in nutrients, salts and alkalinity was observed in the Olifants River, which can be the positive effect of zero discharge from the industrial phosphate plant on the Ga-Selati River in the Olifants catchment. In addition to the increase in elements, the Olifants River has shown an increase in the nutrients and pH, potentially indicating the effect of accumulative impacts, as well as an increase in the LULC activities in the LRB. The effects of agricultural activities, mining and urbanisation on water quality are well known, which can increase element concentrations, nutrients, salts, alkalinity and pH. In conclusion, the increase observed in various water quality variables corresponds with the increase in LULC activities from 2021 to

2024. Therefore, the changes in water quality can potentially be attributed to an increase in agricultural activities, as shown by the increase in rangelands and crop field classes, as well as mining and urbanisation, indicated by the increase in the built areas class.

CHAPTER 3 SEDIMENT QUALITY IN RELATION TO LAND-USE IN THE LIMPOPO RIVER BASIN

3.1 Introduction

Sediment originates through a combination of the natural weathering of rock, erosion, soils and organic substances (Brils, 2008). Sediments serve as a key component contributing to the morphological characteristics of rivers and ultimately affect the diversity and composition of aquatic ecosystems due to its importance for habitat quality (Hauer *et al.*, 2018). Not only does the physical composition of the sediment affect aquatic ecosystems, but it is also a known source of chemical pollutants, acting as a sink for metals (Chon *et al.*, 2012). Additionally, sediment contamination can provide important insights on aquatic ecosystem health due the response-effect relationship between sediment quality and aquatic organisms (Kleynhans, 2007). Thus, the physical and chemical composition of sediments in the environment, influence the diversity and composition of aquatic ecosystems (Erasmus *et al.*, 2020). Therefore, it is important to include sediment quality assessments to manage freshwater ecosystems in a sustainable manner to prevent the further degradation of sediments.

Sediment quality assessments can provide a long-term indication of aquatic ecosystem health, and it can include both the physical and chemical composition of the sediments (Erasmus, 2020). The physical component can include the sediment grain size as well as the organic carbon content, whereas the chemical composition can consist of elements such as metals (Iordache *et al.*, 2022).

The physical component of sediment such as the grain size, clay and organic content contributes largely to the habitat and river morphology in aquatic ecosystems by providing feeding and spawning habitat as well as cover for aquatic organisms (i.e. gravel bar, riffles and cascade or step-pools) (Kleynhans, 2007; Hauer *et al.*, 2018). Therefore, by disrupting the continuity of rivers and flow regimes through impoundments and water abstraction, the channel shape, habitat composition and the sediment transportation can change (Kleynhans, 2007; Hauer *et al.*, 2018). Changes in the sediment features can be flow related, non-flow related or a combination of both (Kleynhans, 2007; Tharme *et al.*, 2008). Overgrazing and vegetation removal or sedimentation (non-flow related) due to anthropogenic impacts along with large floods or water abstraction (flow related) can increase the degradation of the sediment quality (Kleynhans, 2007; Hauer *et al.*, 2018). Furthermore, impoundments trap fine sediments, and is artificially released, resulting in changes in sediment transport (Wohl *et al.*, 2010).

Ultimately, disturbance in sediment transportation will result in an excess or absence of optimal sediment supply. A surplus of fine sediments can cause siltation due to clay intrusion into the interstitial space and cause habitat degradation (Hauer, 2018). Additionally, an increase in fine sediments can also cause an increase in turbidity, which can cause physiological stress to aquatic organisms (Hauer *et al.*, 2018). Fine grained sediments play a large role in the ecological functioning of river systems, but it is also a component in which metals and contaminants are carried in rivers due to the increase of surface area, clay minerals, organic matter and oxides that form fine aggregates (Owens *et al.*, 2005; Yao *et al.*, 2015).

The presence of elements in sediments can be due to the natural geology, or it can be added through anthropogenic impacts (Buscaroli *et al.*, 2021). Furthermore, anthropogenic impacts including river channel management, agricultural activities, wastewater effluent, urbanisation, industrial effluent and hydropower generation can increase the metal and nutrient concentrations in sediments (Chon *et al.*, 2010; Chon *et al.*, 2012; Molekoa *et al.*, 2021). Additionally, fluctuations of elements in sediments can also be affected by temperature, pH and organic matter (Iordache *et al.*, 2022). It is important to note that although some trace elements are essential for the metabolism of aquatic organisms at specific concentrations, non-essential trace elements such as Ag, As, Cd, Cu, Cr, Hg, Ni, Pb and Zn can be toxic and bioaccumulate if it is biologically available (Kolarova & Napiórkowski, 2021). Furthermore, pollutants stored in sediment can be a significant risk to survival, growth and reproduction of aquatic organisms (Kleynhans, 2007).

The dominant ecoregion of the Limpopo River Basin is considered to be a subtropical savannah with high variability in rainfall ranging from a drier western part (200 mm/year) to the lesser dry eastern part (600 mm/year) and the lowland floodplain section in Mozambique that is highly susceptible to flooding due to tropical cyclones (Botai *et al.*, 2020). The lower section of the basin exhibits high sediment loading due to the high rainfall in those areas (Botai *et al.*, 2020). Furthermore, it has also been reported that most of the perennial rivers (i.e. Olifants & Ga-selati rivers) in the Lowveld ecoregion are facing severe pressure due to reduced water flows, high sediment loads, sewage discharge and elevated nutrients and metals (Marr *et al.*, 2017; Rasifudi *et al.*, 2018; Riddell *et al.*, 2019). It was also observed that rivers in lower regions are facing a lot of stress due to major salts originating from agriculture upstream and sediment loads during peak flows (Riddell *et al.*, 2019). It is evident that sediment load is a serious concern in the LRB that affects the aquatic environment. Not only is it a stressor to the aquatic environment, but it also reduces the dam capacity and affects the water quality in the LRB (Dickens *et al.*, 2020). The main sources of sedimentation in rivers include agricultural activities, urbanisation, forestry and sand mining (O'Brien *et al.*, 2021). This makes the sediment a good indicator of catchment management (Dickens *et al.*, 2020).

Sediment is an important component in forming the morphological characteristics of rivers and it contributes largely to habitat quality. It provides a feeding and spawning habitat as well as cover for aquatic organisms. The role of sediment in the ecological functioning of rivers is clear due to the response-effect relationship with aquatic organisms, but it is also a component in which metals and contaminants are carried in rivers. This is due to the increase of surface area in fine sediments, clay minerals, organic matter and oxides that form fine aggregates. Thus, sediment can serve as a potential source of pollution for surface waters. Sediment pollution has already been noted in the lower regions of the LRB. Additionally, it has also been identified as a potential source of pollution in the Marico catchment, Crocodile catchment and Letaba catchment in the LRB. Therefore, the assessment of sediment quality is important to identify the possible effects and contribution of land-use activities on sediment and water quality. The aim of this chapter was to assess the physical (grain size and total organic carbon) and chemical (element concentration) component of sediment quality for the selected sites for both the sampling years 2021 and 2024. Furthermore, the LULC will be assessed for both years and the possible impacts thereof on the sediment quality in the LRB will be discussed.

3.2 Materials and methods

3.2.1 Field sampling

The 2021 field survey included sediment sampling at the 14 sites in the Limpopo River Basin (LRB) during May – July 2021. Subsequently, sediment samples were also taken at the 15 sites that were sampled in the LRB during August – September 2024. The sediment samples were taken in triplicate using a Petite Ponar grab and placed in pre-cleaned 250 mL poly-ethylene containers whereafter it was stored in a freezer for further analysis in the laboratory.

3.2.2 Sediment quality analysis

The sediment samples collected during the 2021 survey were already analysed. Thus, the following analyses methods described were followed for the 2024 sediment samples. First, the sediment samples were oven dried at 60 °C for 72 hours. Next, the particle size was determined according to the method described by Wepener and Vermeulen (2005). The particle size distribution was divided into the following categories: very coarse sand (>2000 µm), coarse sand (500 - 2000 µm), medium sand (212 - 500 µm), fine sand (53 - 212 µm) and mud (<53 µm) (Erasmus *et al.*, 2020).

To determine the total organic carbon (TOC), crucibles were pre-weighed whereafter the dried sediment samples were added and weighed again to determine the mass of the sediment. Next,

the samples were added into an incinerator (L40/11, Nabertherm) and left at 600°C for six hours. Lastly, these samples were left to cool, re-weighed and the TOC of the sediment samples were calculated. The TOC was categorised as high (> 4%), medium (2 - 4%), moderately low (1 – 2%), low (0.05 – 1%) and very low (< 0.05%) (USEPA, 2001; Van Roooyen *et al.*, 2022). The following equation was used to calculate the TOC:

$$\% \text{ Organic Carbon} = \left[\frac{(Mb - Ma)}{Mb} \right] \times 100$$

In the equation Mb = mass of sediment before incineration (g) and Ma = mass of sediment after incineration (g).

The sediment samples were prepared for element analysis by weighing approximately 0.2 g of the dried sediment and adding it into Teflon digestion tubes (Erasmus *et al.*, 2020). Additionally, 7.5 mL HCL (37%, suprapure quality, Merck) and 2.5 mL HNO₃ (65%, Suprapure quality, Merck) were added to the digestion tubes, and the mixtures were digested in a microwave digester (Milestone Ethos Easy 15 Microwave digestion system). Following digestion, the digested samples were transferred to 50 mL volumetric flasks, diluted with 1% HNO₃ and stored in 50 mL falcon tubes. The element concentrations in the sediment samples were determined using quadrupole inductively coupled plasma-mass spectroscopy (ICP-MS) (Agilent 7850 ICP-MS). Quality control was performed using certified reference material (CRM) (NCS DC 73310 Stream Sediment, China National Analysis Centre for Iron and Steel) to validate the analytical procedure of the sediment samples (Table 3-1). The detection limits for the sediments were calculated as three times the standard deviation of the blank measurements (related to a mean sample weight of 204.8 mg respectively).

Table 3-1 Recovery rates (%) of the elements of interest obtained for NCS DC 73310 as well as the Limit of Detection (LOD) and Limit of Quantification (LOQ) in µg/g for the sediment samples.

Element	Sediment		% Recovery
	LOD	LOQ	NCS DC 73310
As	0.00197	0.00592	99.5
Cd	0.01169	0.03507	117.6
Cr	0.03024	0.09072	85.5
Cu	0.23265	0.69794	95.7
Hg	0.00911	0.02733	86.1

Ni	0.01885	0.05656	136.0
Pb	1.72673	5.18018	121.4
Zn	0.41202	1.23607	116.7

3.2.3 Statistical analysis

Grouped column charts were created for the element concentrations at the overlapping sites for 2021 and 2024 using GraphPad Prism 8.4.2 software (GraphPad Software, Inc.). Furthermore, principal component analyses (PCA) were also performed to interpret the temporal and spatial sediment quality distribution. This was done using the Canoco 5 for Windows (v.5.15) statistical package. Parametric data were log-transformed to ensure normality where necessary.

3.3 Results

The results included an overview of the sediment quality during 2021 and 2024. The TOC, sediment grain size and element concentration results were used to determine the condition of the sediment. Lastly the spatial and temporal analysis of the sediment quality sampled at the sites are also included in this section.

3.3.1 Sediment quality during 2021

The sediment quality variables and element concentrations measured in the samples for the 2021 sites can be seen in Table 3-2. The total organic carbon (TOC) varied between the sites ranging from <1% (LIMP2, MAPU, SHINR, LETA and MAMBA), <2% (LIMP1, MATL, MOGA, SANDR and BALUL, <3% (CROCR and LEPHS) and >3% at LUVU. Further, from the sediment grain size analysis results, it can be seen that the sites differed in the composition of sediment grain sizes where most of the sites (LIMP1, LEPHS, LIMP2, MOGA, MAPU, SANDR and SHINR) consisted of a high percentage of coarse sand (500 – 2000 μm) or a combination of coarse sand and medium sand (212 – 500 μm) at MATL, LETA, BALUL and LIMP3. Additionally, LUVU was dominated by very coarse sand (>2000 μm) and CROCR, GLETL and MAMBA consisted mostly out of medium sand.

The element concentrations also varied between the sites with high As concentrations recorded at CROCR (7.52 $\mu\text{g/g}$) and LIMP1 (10.07 $\mu\text{g/g}$). The Cd concentrations remained relatively low with the highest recorded at LUVU (0.43 $\mu\text{g/g}$). The Cr concentrations in comparison with the other elements were the highest at most of the sites, except for MATL and SHINR where the Zn and Ni were the highest, with a concentration of 36.03 $\mu\text{g/g}$ and 107.70 $\mu\text{g/g}$ respectively. Further, the Cu concentrations varied with high concentrations >40 $\mu\text{g/g}$ recorded at MAMBA and BALUL and higher concentrations >50 $\mu\text{g/g}$ at LUVU and SHINR. It can also be observed that the Hg concentrations were low at most of the sites and below the detection limit (<LOD) at seven sites with the highest Hg concentration (0.024 $\mu\text{g/g}$) recorded at GLETL. The Ni and Pb concentrations also varied between sites with the highest Ni concentration (107.70 $\mu\text{g/g}$) recorded at SHINR and Pb concentration (31.32 $\mu\text{g/g}$) at MOGA. Lastly, the Zn concentrations also varied with the highest recorded at MAMBA (125.4 $\mu\text{g/g}$).

Table 3-2 The total organic carbon % (TOC) and element concentrations (µg/g) presented as mean ± standard error and the mean grain size % contribution in the sediment samples during 2021.

Element	CROCR	LIMP1	MATL	LEPHS	LIMP2	MOGA	MAPU	SANDR	LUVU	SHINR	GLETL	LETA	MAMBA	BALUL	LIMP3
TOC	2.06 ± 0.16	1.75 ± 0.71	1.08 ± 0.8	2.38 ± 0.05	0.66 ± 0.22	1.38 ± 0.88	0.98 ± 0.59	1.92 ± 1.3	3.32 ± 2.4	0.90 ± 0.05	No sample	0.73 ± 0.05	0.87 ± 0.16	1.33 ± 0.45	No sample
>2000 µm	22.38	1.44	2.23	29.77	15.07	30.82	21.83	3.65	53.35	18.80	1.33	1.83	1.41	0.28	22.38
500 – 2000 µm	29.40	58.89	46.50	52.90	58.44	51.81	49.33	74.73	26.72	66.93	24.02	45.08	25.05	34.68	29.40
212 – 500 µm	31.75	36.82	46.10	9.94	18.96	14.54	23.46	20.91	15.48	6.47	47.96	44.50	66.04	35.08	31.75
53 – 212 µm	14.51	2.53	4.40	5.55	6.24	2.49	4.94	0.28	3.98	7.41	23.66	7.16	6.75	26.90	14.51
<53 µm	1.59	0.08	0.34	1.57	12.32	0.07	0.04	0.17	0.09	0.27	2.59	0.97	0.19	2.54	1.59
As	7.52 ± 1.01	10.07 ± 2.96	3.85 ± 1.26	3.55 ± 0.67	2.26 ± 0.24	4.26 ± 4.07	No sample	1.50 ± 0.27	3.66 ± 0.51	2.70 ± 0.67	0.69 ± 0.21	2.63 ± 0.71	4.74 ± 0.74	4.21 ± 1.29	No sample
Cd	0.15 ± 0.08	0.13 ± 0.04	0.09 ± 0.004	0.17 ± 0.07	0.17 ± 0.07	0.16 ± 0.08	No sample	0.13 ± 0.06	0.43 ± 0.19	0.15 ± 0.07	0.02 ± 0.005	0.15 ± 0.06	0.17 ± 0.07	0.14 ± 0.05	No sample
Cr	224.30 ± 50.27	204.60 ± 63	30.18 ± 6.03	80.01 ± 31.28	68.58 ± 14.15	362.50 ± 484	No sample	50.53 ± 8.07	129.30 ± 17.83	99.41 ± 16.62	22.58 ± 8.47	120.40 ± 22.54	242.40 ± 85.81	188.60 ± 74.11	No sample
Cu	23.42 ± 9.59	23.22 ± 15.77	4.59 ± 1.88	26.84 ± 11.46	3.93 ± 1.09	27.23 ± 13.65	No sample	19.96 ± 1.03	56.10 ± 11.12	55.22 ± 21.67	8.82 ± 2.7	28.02 ± 1.73	42.91 ± 3.66	41.31 ± 13.98	No sample
Hg	0.014 ± 0.0007	0.014 ± 0.002	0.019 ± 0.005	0.017 ± 0.0005	0.017 ± 0.001	<LOD*	No sample	<LOD*	<LOD*	<LOD*	0.024 ± 0.002	<LOD*	<LOD*	<LOD*	No sample
Ni	66.34 ± 13.81	69.28 ± 34.25	9.99 ± 1.51	42.45 ± 13.63	22.69 ± 0.76	64.06 ± 50.29	No sample	36.90 ± 8.86	85.22 ± 14.13	107.70 ± 29.94	8.47 ± 2.5	46.61 ± 5.0	97.66 ± 25.72	84.68 ± 27.92	No sample
Pb	27.19 ± 1.85	21.34 ± 7.17	11.08 ± 3.1	25.29 ± 10.24	8.95 ± 1.54	31.32 ± 27.66	No sample	6.78 ± 2.39	22.68 ± 4.89	9.20 ± 3.31	3.0 ± 0.54	12.22 ± 1.47	10.89 ± 1.07	15.51 ± 9.8	No sample
Zn	60.01 ± 3.17	44.07 ± 18.51	36.03 ± 10.06	50.77 ± 16.86	32.51 ± 2.32	56.83 ± 29.23	No sample	39.23 ± 10.13	87.44 ± 13.68	55.6 ± 22.8	19.42 ± 7.65	42.34 ± 1.18	125.4 ± 21.74	80.79 ± 20.07	No sample

<LOD* - Below Limit of Detection.

3.3.1.1 Spatial distribution of sediment quality variables during 2021

This PCA biplot describes 65.87% of the variation in the data, where 37.2% is displayed on the first axis and 28.67% is displayed on the second axis (Figure 3-1). Sites LEPHS, MOGA, LUVU and CROCR were characterised by higher element concentrations (Cd and Pb), organic content and very coarse sand (>2000 μm), whereas MATL and GLETL were associated with higher concentrations of Hg and mud (<53 μm). Furthermore, SHINR was characterised by coarse sand (500 – 2000 μm) and BALUL by medium sand (212 – 500 μm). Lastly, BALUL, MAMBA and LIMP1 indicated to have higher concentrations of Cu.

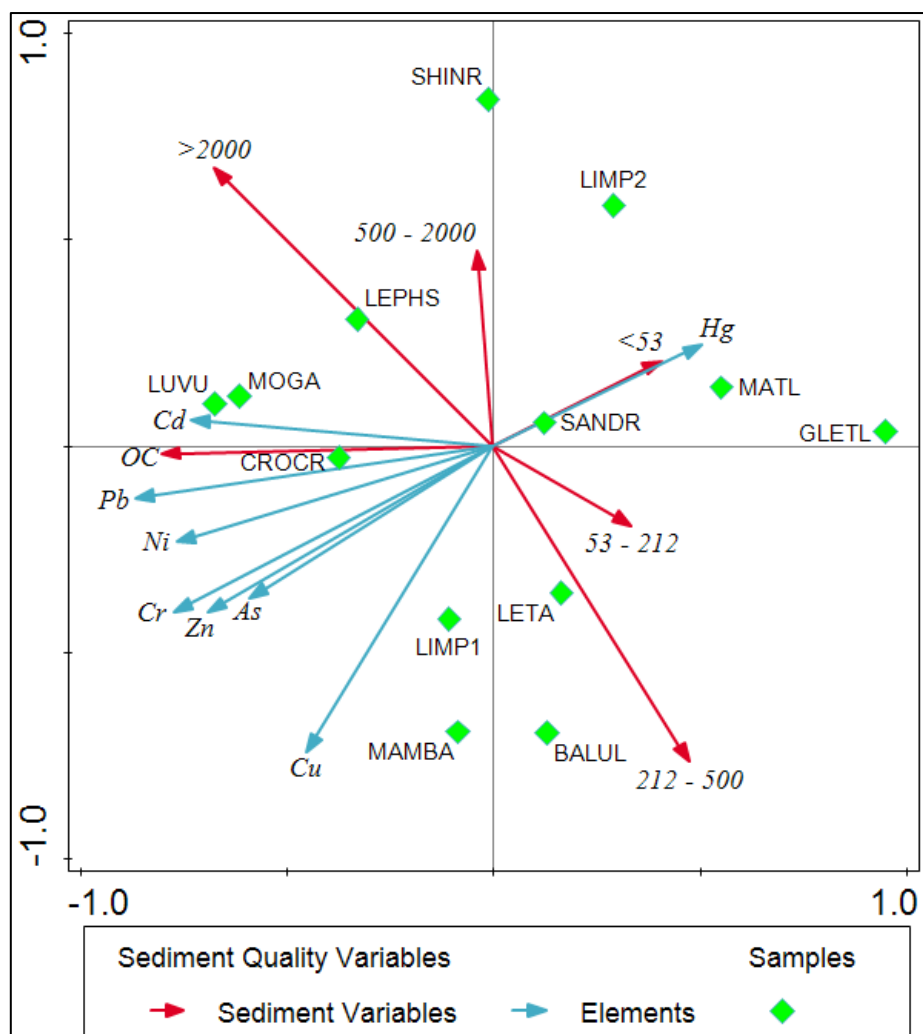


Figure 3-1 A PCA biplot indicating the different % of the grain sizes and organic content (OC) as well as the element concentrations measured in the sediment samples during 2021 in the Limpopo River Basin. This PCA biplot describes 65.87% of the variation in the data, where 37.2% is displayed on the first axis and 28.67% is displayed on the second axis.

3.3.2 Sediment quality during 2024

The sediment quality variables and element concentrations measured in the samples for the 2024 sites can be seen in Table 3-3. The total organic carbon (TOC) varied between the sites ranging from <1% (MAPU and ELEP), <2% (NGOT, MOTL, SHAS, MWENG and BALUL), <3% (MWENR, LUVU and LIMP3), <4% (GMAR and CCONR) and >4% (LOTSW, LETSD and UMZI). From the sediment grain size analysis results it can be seen that the sites differed in the composition of sediment grain sizes where most of the sites (LOTSW, MOTL, LETSD, SHAS, UMZI, MAPU, MWENR, MWENG, ELEP and LIMP) consisted of a higher percentage of coarse sand (500 – 2000 µm) or a combination of very coarse sand (>2000 µm), coarse sand and medium sand (212 – 500 µm) at GMAR. Additionally, LUVU and BALUL were dominated by medium sand whereas NGOT and CCONR consisted mostly out of mud (<53 µm).

The element concentrations varied between the sites with high As concentrations recorded at UMZI (7.52 µg/g). The Cd concentrations remained relatively low with the highest recorded at ELEP (0.15 µg/g). The Cr concentrations in comparison with the other elements were higher than most of the other elements with the highest concentrations out of all the elements at GMAR, MWENR, MWENG, CCONR and ELEP. Further, the Cu concentrations varied with high concentrations >30 µg/g recorded at GMAR and LOTSW and higher concentrations >40 µg/g at LETSD and UMZI. It can also be seen that the Hg concentrations were low at all of the sites with the highest Hg concentration (0.03 µg/g) recorded at UMZI. The Ni and Pb concentrations also varied between sites with the highest Ni concentration (43.81 µg/g) recorded at UMZI as well as the Pb concentration (25.18 µg/g) at UMZI. Lastly, the Zn concentrations were the highest at most of the sites (NGOT, LOTSW, LETSD, SHAS, UMZI, MAPU, LUVU, BALUL and LIMP3) out of all the elements, with the highest concentrations (68.76 µg/g) at UMZI.

Table 3-3 The total organic carbon % (TOC) and element concentrations (µg/g) presented as mean ± standard error and the mean grain size % contribution in the sediment samples during 2024.

Element	GMAR	NGOT	LOTSW	MOTL	LETSD	SHAS	UMZI	MAPU	MWENR	MWENG	LUVU	CCONR	BALUL	ELEP	LIMP3
TOC	3.19 ± 1.76	1.32 ± 0.17	6.9 ± 1.7	1.56 ± 0.86	5.8 ± 2.08	1.19 ± 0.36	5.03 ± 2.87	0.6 ± 0.17	2.83 ± 1.41	1.28 ± 0.77	2.06 ± 1.17	3.13 ± 0.18	1.88 ± 0.3	0.39 ± 0.02	2.52 ± 1.44
>2000 µm	21.08 ± 9.43	18.86 ± 11.62	14.17 ± 7.67	25.39 ± 0.55	11.38 ± 3.88	5.22 ± 1.03	11.44 ± 7.16	9.03 ± 4.8	26.76 ± 6.52	26.98 ± 16.86	0.59 ± 0.28	0.67 ± 0.15	0.38 ± 0.33	2.46 ± 1.47	4.36 ± 2.33
500 – 2000 µm	28.33 ± 4.11	18.34 ± 8.74	51.33 ± 0.51	49.16 ± 4.97	31.10 ± 0.9	59.83 ± 4.81	35.73 ± 6.61	62.07 ± 1.93	48.98 ± 2.14	30.86 ± 2.29	32.01 ± 4.51	2.17 ± 0.39	26.63 ± 7.55	69.82 ± 2.34	51.57 ± 11.08
212 – 500 µm	29.68 ± 5.63	16.85 ± 5.83	22.07 ± 5.65	11.78 ± 1.49	22.73 ± 0.89	26.18 ± 2.6	20.88 ± 0.83	23.31 ± 5.25	20.66 ± 3.87	27.66 ± 8.14	60.93 ± 1.73	7.1 ± 0.73	56.29 ± 6.0	26.57 ± 2.86	34.34 ± 11.51
53 – 212 µm	17.29 ± 6.37	42.45 ± 21.07	9.21 ± 1.95	9.78 ± 2.5	26.55 ± 1.77	8.25 ± 4.01	17.48 ± 7.3	5.25 ± 0.81	2.86 ± 0.66	12.31 ± 6.42	5.54 ± 2.48	86.18 ± 1.09	16.36 ± 1.83	0.95 ± 0.09	9.28 ± 3.2
<53 µm	3.61 ± 2.14	3.50 ± 2.4	3.21 ± 0.55	3.89 ± 1.4	8.24 ± 1.78	0.52 ± 0.33	14.46 ± 6.96	0.34 ± 0.13	0.74 ± 0.25	2.20 ± 1.83	0.94 ± 0.38	3.88 ± 1.3	0.34 ± 0.7	0.20 ± 0.03	0.45 ± 0.22
As	1.39 ± 0.09	0.87 ± 0.18	1.52 ± 0.33	1.05 ± 0.5	2.14 ± 0.63	0.48 ± 0.01	10.16 ± 3.86	0.55 ± 0.06	0.51 ± 0.07	0.81 ± 0.27	0.41 ± 0.02	0.69 ± 0.1	1.04 ± 0.07	1.09 ± 0.24	0.83 ± 0.13
Cd	0.07 ± 0.01	0.07 ± 0.003	0.10 ± 0.02	0.06 ± 0.01	0.09 ± 0.01	0.09 ± 0.03	0.08 ± 0.04	0.05 ± 0.005	0.06 ± 0.009	0.07 ± 0.01	0.11 ± 0.03	0.07 ± 0.01	0.07 ± 0.01	0.15 ± 0.06	0.06 ± 0.02
Cr	122.32 ± 25.36	37.92 ± 4.07	57.53 ± 10.54	15.86 ± 1.94	32.51 ± 8.5	12.99 ± 0.83	66.36 ± 11.39	10.65 ± 0.99	21.06 ± 1.54	28.17 ± 4.85	14.83 ± 0.44	40.50 ± 4.16	44.24 ± 3.75	29.24 ± 6.26	19.79 ± 1.07
Cu	38.94 ± 1.93	17.13 ± 3.25	37.56 ± 5.99	11.76 ± 2.36	43.97 ± 6.4	8.03 ± 0.79	47.91 ± 7.32	10.94 ± 0.74	17.41 ± 6.3	14.45 ± 2.65	11.74 ± 1.37	22.06 ± 3.32	18.98 ± 3.29	19.96 ± 4.3	9.49 ± 1.32
Hg	0.02 ± 0.001	0.02 ± 0.0002	0.02 ± 0.0002	0.02 ± 0.0001	0.02 ± 0.002	0.02 ± 0.0001	0.03 ± 0.01	0.02 ± 0.0002	0.02 ± 0.0009	0.02 ± 0.0002	0.02 ± 0.0002	0.02 ± 0.0001	0.02 ± 0.0002	0.02 ± 0.0001	0.02 ± 0.002
Ni	29.48 ± 4.23	10.99 ± 1.33	32.34 ± 7.2	11.39 ± 2.97	26.31 ± 5.89	11.43 ± 0.73	43.81 ± 8.33	9.24 ± 0.24	20.21 ± 5.33	21.74 ± 4.37	17.61 ± 4.67	31.87 ± 3.32	28.68 ± 1.59	15.55 ± 1.88	15.47 ± 0.58
Pb	13.61 ± 3.49	8.71 ± 2.32	18.86 ± 3.58	8.84 ± 3.34	18.70 ± 3.22	3.79 ± 0.88	25.18 ± 5.53	5.36 ± 0.63	9.16 ± 1.66	9.39 ± 2.03	4.48 ± 0.78	8.49 ± 1.14	4.91 ± 0.52	20.74 ± 7.1	5.56 ± 1.79
Zn	64.33 ± 11.55	57.74 ± 9.04	63.04 ± 20.43	18.48 ± 2.37	50.82 ± 13.91	43.63 ± 9.04	68.76 ± 23.15	18.54 ± 1.62	20.89 ± 3.94	26.31 ± 2.31	33.35 ± 7.93	28.93 ± 0.64	51.60 ± 5.18	21.24 ± 2.69	34.33 ± 12.11

3.3.2.1 Spatial distribution of sediment quality variables during 2024

This PCA biplot describes 71% of the variation in the data, where 42.72% is displayed on the first axis and 28.26% is displayed on the second axis (Figure 3-2). Sites LUVU, ELEP, LIMP3 and SHAS were characterised by medium sand (212 – 500 μm) and higher concentrations of Hg and Cd, whereas BALUL was characterised by higher Zn and Ni concentrations and CCONR by organic content, As, Cr, Cu and fine sand (53 – 212 μm). Furthermore, LETSD, UMZI, GMAR and NGOT indicated higher mud (<53 μm) content and LOTSW, MWENG, MOTL and MWENR higher Pb and very coarse sand (>2000 μm).

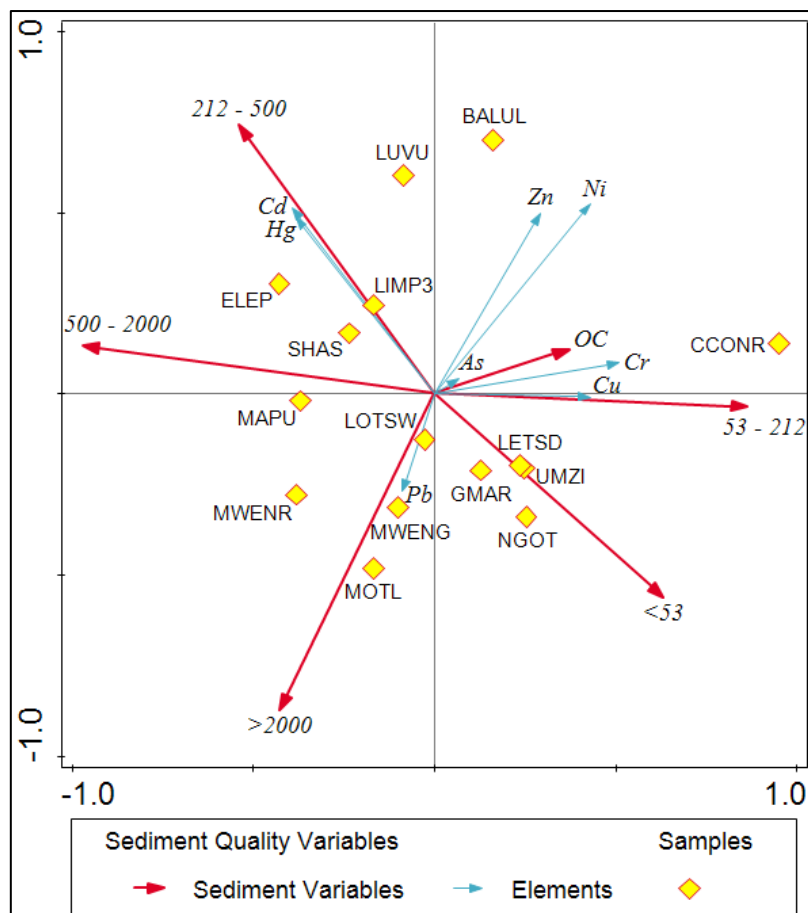


Figure 3-2 A PCA biplot indicating the different % of the grain sizes and organic content (OC) as well as the element concentrations measured in the sediment samples during 2024 in the Limpopo River Basin. This PCA biplot describes 71% of the variation in the data, where 42.72% is displayed on the first axis and 28.26% is displayed on the second axis.

3.3.3 Spatial and temporal analysis of sediment quality for the 2021 and 2024 overlapping sites

3.3.3.1 Sediments quality variables

The 2021 survey aimed to assess the mainstem of the LRB, whereas the 2024 survey aimed to assesses the tributaries of the LRB. Thus, only two sediment sites were sampled during both years, which were considered for the spatial and temporal analysis. The PCA biplot describes 93.35% of the variation in the data, where 62.44% is displayed on the first axis and 30.92% is displayed on the second axis (Figure 3-3). The PCA biplot indicated that both overlapping sites (BALUL and LUVU) were characterised by higher concentrations of organic content and all the elements examined during 2021, except for Hg. Contrastingly, both overlapping sites (BALUL and LUVU) indicated higher Hg concentrations during 2024. Additionally, LUVU was characterised by a higher composition of very coarse sand (>2000) and BALUL by mud (<53 μm), fine sand (53 – 212 μm) and coarse sand (500 – 2000 μm) during 2021. However, both sites grouped together during 2024, mainly due to lower metal concentrations, and were characterised by medium sand.

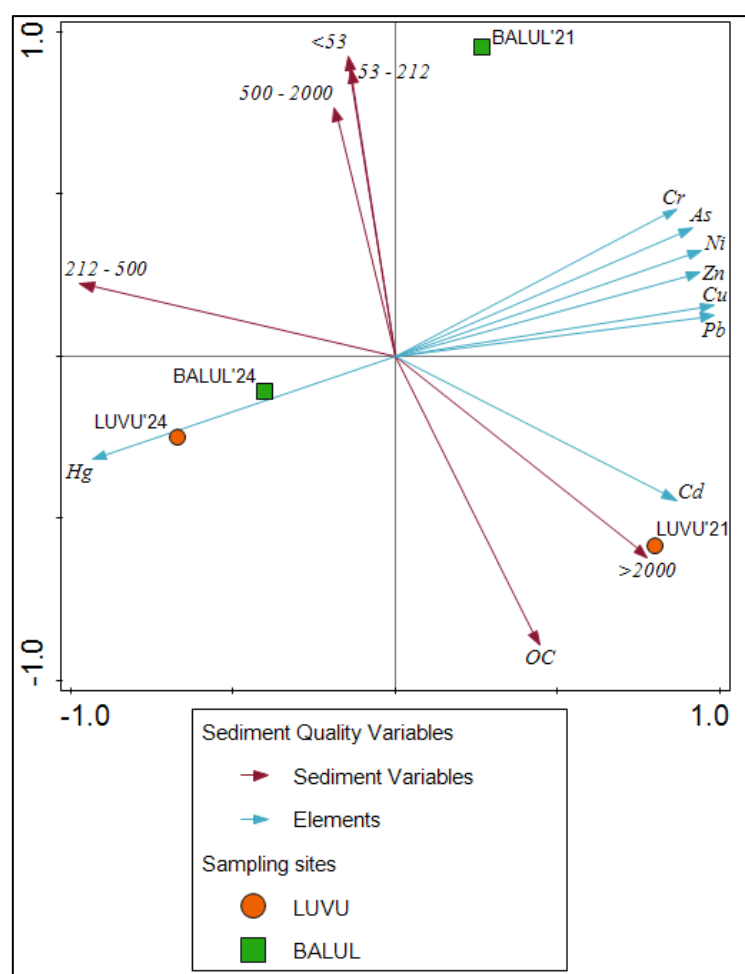


Figure 3-3 A PCA biplot indicating the different % of the grain sizes, organic content (OC) and trace element concentrations measured in the sediment samples at the 2021 and 2024 overlapping sites in the Limpopo River Basin. This PCA biplot described 93.35% of the variation in the data, where 62.44% is displayed on the first axis and 30.92% is displayed on the second axis.

3.3.3.2 Elements

The difference in element concentrations in the sediment samples for the overlapping sites between 2021 and 2024 are presented in Figure 3-4. From the charts both overlapping sites (LUVU and BALUL) indicated notable higher concentrations of As, Cr, Cu, Ni, Pb and Zn during 2021. Thus, indicating a decrease in element concentrations in the sediment from 2021 to 2024. Although the Cd and Hg concentrations were low (<0.2), a decrease in Cd concentrations was observed and a slight increase in Hg concentrations at both sites from 2021 to 2024 (Table 3-2

and Table 3-3). Similar results were indicated in Figure 3-3, where a decrease in most of the sediment element concentrations were observed, except for Hg.

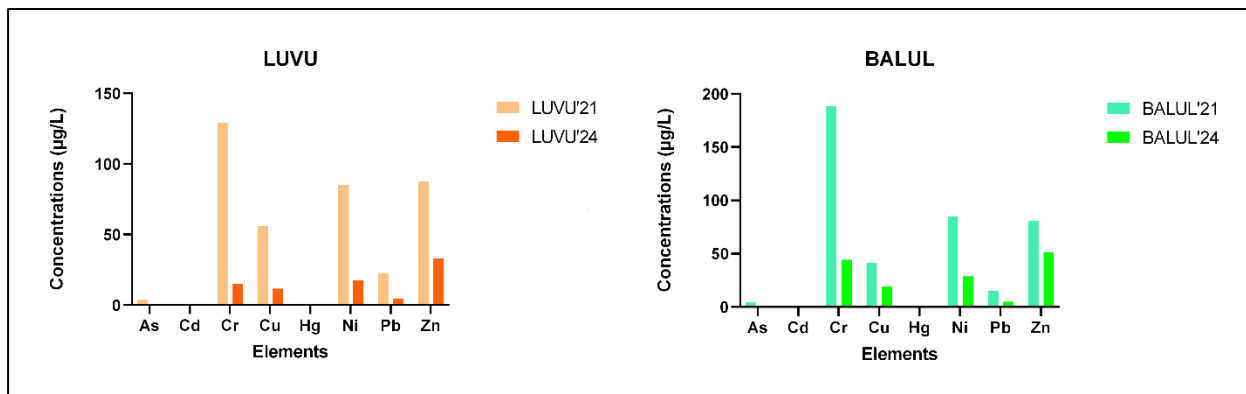


Figure 3-4 Comparison of the sediment element concentrations (µg/g) at the overlapping sites (LUVU and BALUL) in the Limpopo River Basin between 2021 and 2024.

3.4 Discussion

Sediments occur naturally through erosion, soils, organic substances and the weathering of rocks (Brils, 2008). The physical characteristics of sediment can affect aquatic ecosystems, and it can act as sink for chemical pollutants and metals (Chon *et al.*, 2012; Erasmus, 2020). Changes in sediment quality can occur due to flow related and non-flow related impacts. The LRB exhibits a high diversity of soils and high variability in rainfall (Botai *et al.*, 2020; Dickens *et al.*, 2020). Additionally, the lower section of the LRB experience higher sediment loading due to higher rainfall (Botai *et al.*, 2020). Furthermore, the sediment quality of rivers in the lowveld ecoregion is impacted by sewage discharge, sediment loading and elevated elements and nutrients (Marr *et al.*, 2017; Rasifudi *et al.*, 2018; Riddell *et al.*, 2019). Sedimentation also occurs in the LRB, where agricultural activities, urbanisation, forestry and sand mining serve as the predominant anthropogenic contributors (O'Brien *et al.*, 2021). Furthermore, sediment pollution has already been noted in the lower region and has also been identified as a potential source of pollution in the Marico catchment, Crocodile catchment and Letaba catchment in the upper LRB (Dickens *et al.*, 2020). The following discussion will include the sediment quality during 2021 and 2024, as well as the change in sediment quality for the overlapping sites from 2021 to 2024.

3.4.1 Sediment quality during 2021

The sediment quality parameters indicated variation in the percentage TOC, sediment grain size composition, and element concentrations throughout the LRB during 2021. There are currently no sediment quality guidelines available for the LRB. However, higher TOC was recorded in the sediment samples for the Crocodile, Lephalale, Mogalakwena, Sand, Olifants, and Luvuvhu rivers, as well as the most upstream site in the Limpopo River (LIMP1). The sites that exhibited high TOC were distributed throughout the basin with no specific order (i.e. from upstream to downstream). Additionally, higher TOC can increase the element concentrations due to the bigger surface area for elements to bind to, as well as the affinity of pollutants to bind to organic material (Owens *et al.*, 2005; Yao *et al.*, 2015; lordache *et al.*, 2022). The elevated TOC measured in the sediment of the Crocodile River (CROCR) and Limpopo River (LIMP1), downstream of CROCR, can be the result of agricultural runoff and sewage effluent in the Crocodile River (Du Preez *et al.*, 2018; Phungela *et al.*, 2021). Furthermore, the Lephalala River that flows through rural settlements and agricultural lands has shown riverbank modification, flow alterations and an increase in turbidity (Sibiya *et al.*, 2025). Therefore, it is possible that effluents originating from agricultural fields and rural communities can contribute to the higher TOC observed in the Lephalala River. The Mogalakwena and Sand rivers have similar anthropogenic impacts as the Crocodile River, where sewage effluent is a big concern, potentially contributing to the TOC

observed in the Mogalakwena and Sand rivers (Seanego & Moyo, 2013; Du Preez *et al.*, 2018; Phungela *et al.*, 2021). Lastly, both the Olifants and Luvuvhu rivers are also impacted by agricultural runoff, and effluents originating from either mining or industrial activities, which can cause an increase in the TOC (Riddell *et al.*, 2018; Shibambu *et al.*, 2025).

The sediment grain size analysis indicated that most of the sites were dominated by coarse sand, or a combination of coarse and medium sand, which can potentially contribute to similar geological characteristics for most of the sampled sites during 2021. Furthermore, the Luvuvhu River consisted of a high percentage of very coarse sand, whereas the Crocodile, Letaba and Olifants (MAMBA) rivers consisted of medium sand.

The As concentrations was the highest in the sediment of the Crocodile River and the downstream site in the Limpopo River (LIMP1). The high As concentrations can be a result of sewage effluent, where sewage can contain higher concentrations of As (De Aguilar *et al.*, 2025). Additionally, the higher As concentration in the Crocodile and Limpopo rivers can also be due to the gold mining in the upper reaches of the Crocodile River, where previous studies indicated extremely high As, Zn, Ni, Zn and U concentrations in the sediments close to the mine (Windisch *et al.*, 2022). The sediment of the Matlabas River exhibited some of the highest Zn and Ni concentrations during the study. Although erosion, instream dams and agricultural activities are present in the system, the overall anthropogenic impacts are limited (Bootsma *et al.*, 2019; Dickens *et al.*, 2021). Thus, the element concentrations can be due to the natural geology. The highest Cu concentrations were recorded in the sediment of the Luvuvhu and Shingwedzi rivers. Additionally, the Shingwedzi River sediment indicated higher concentrations of Zn and Ni. The elevated Cu concentration in the sediment of the Luvuvhu river can potentially be the impact of agricultural runoff, domestic discharge and semi-industrial pollution in the catchment (Dickens *et al.*, 2020; Dickens *et al.*, 2021; Shibambu *et al.*, 2025). However, the anthropogenic impacts in the Shingwedzi River are limited, with minimal subsistence farming and informal settlement present, indicating that the high Cu concentrations can be due to the natural geology (Dickens *et al.*, 2020; Dickens *et al.*, 2021; Shibambu *et al.*, 2025). Furthermore, the Mogalakwena River indicated overall higher element concentrations, specifically Cr and Pb, which can be the result of mines, sewage effluent and industrial runoff polluting the system (Molekoa *et al.*, 2021). Both sites in the Olifants indicated high element concentrations in the sediment, specifically Cu and Zn, which can be due to the historical impact of metals in the Olifants River (Riddell *et al.*, 2019). Additionally, the Cr concentrations were notably higher at most of the sites in the LRB. Lastly, the higher element concentration observed in the sediment samples during 2021 also indicated the ability of sediment to act as a sink for elements and other pollutants (Chon *et al.*, 2012).

3.4.2 Sediment quality during 2024

The TOC recorded in the sediment samples during 2024 were overall higher in the LRB than 2021. This includes the Groot Marico, Lotsane, Umzingwane and Limpopo (CCONR) rivers, as well as Letsibogo Dam, which exhibited high percentages of TOC. The anthropogenic impacts in the Groot-Marico system are limited with agricultural activities and safari lodges being the main the impact (Dickens *et al.*, 2020). Further, limited studies including impacts for the Lotsane River are present, with small scale gold mining in the catchment being the main concern (Mudiwa *et al.*, 2022). Thus, the higher TOC observed in the sediment of these systems can potentially be of natural origin and not only anthropogenic activities. Furthermore, the Umzingwane River is impacted to a larger extent by illegal gold mining, that resulted in organic and inorganic pollution (Muringaniza *et al.*, 2022). The organic pollution potentially contributed to the higher TOC percentage observed during 2024 (Muringaniza *et al.*, 2022). In addition to the anthropogenic activities recorded in the LRB and tributaries of the Limpopo River, the site sampled at Crooks Corner in the Limpopo River was also inhabited by many hippos and crocodiles at the time of the survey, which could also potentially contribute to the elevated TOC in the sediment. Lastly, the elevated TOC observed in Letsibogo Dam can be due to the capabilities of a dam to trap fine sediments and organic matter, as well as the agricultural activities and irrigation return flows upstream of the dam in the Motloutse River (Nthokwa *et al.*, 2025).

The sediment grain size analysis indicated similar results as 2021, where most of the sites exhibited a higher percentage of coarse sand, and secondly a combination of very coarse, coarse and medium sand. Furthermore, the Luvuvhu and Olifants rivers had a higher percentage of medium sand, whereas the Ngotwane and Limpopo rivers (CCONR) had a higher percentage of fine sand. Fine sand can increase the metal concentrations, due to a bigger surface area where elements and organic matter can bind to form aggregates (Owens *et al.*, 2005; Yao *et al.*, 2015). This was also observed in the Limpopo River at Crooks Corner where the highest fine sand was observed as well as high concentrations of TOC, As, Cr, Cu, Ni and Zn.

The element concentrations measured in the sediment of the sites sampled during 2024 were lower than the sites sampled during 2021 for most of the elements. The most downstream site in the Olifants River exhibited the highest Cd concentrations in the sediment. This can be due to the historical impacts of mining and effluent discharge in the catchment (Marr *et al.*, 2017; Riddell *et al.*, 2019). Additionally, the site was also situated below Masingir Dam, which can also possibly affect the element concentrations by trapping fine sediments with higher element concentrations and releasing it when the physico-chemical parameters (i.e. pH) of the dam water changes. Four sites had higher Cu concentrations than the other sites, with the highest recorded in the sediment

of the Umzingwane River. Additionally, the Umzingwane River sediment also had the highest As, Ni, Pb and Zn concentrations. Previous studies indicated elevated Cu, Fe, pH, organic matter, dissolved solids and turbidity in the Umzingwane River and the further increase of these variables closer to the gold mines (Muringaniza *et al.*, 2022). Thus, it is possible that the gold mining also resulted in the increase of additional elements over time. Lastly, the Cr concentrations were overall higher than most of the elements at all of the sites. Similar results were observed during 2021. This indicates that high Cr concentrations throughout the LRB can also potentially be attributed to the geology and not only anthropogenic impacts, because different impacts will potentially result in variation of element concentrations, rather than an increase in just Cr concentrations.

3.4.3 Comparison of sediment quality for the 2021 and 2024 overlapping sites in relation to land-use/land-cover

Two sites sampled during 2021 overlapped with sites sampled during 2024. One site in the Luvuvhu River (LUVU) and the second site in the Olifants River (BALUL). The comparison between the two sites indicated the movement of sediment in the basin where LUVU was characterised by a higher composition of very coarse sand and BALUL by a combination of mud, fine sand and coarse sand during 2021, whereas both sites were characterised by medium sand during 2024. Furthermore, higher TOC and element concentrations for most of the elements, except Hg, were present in the sediment during 2021. Thus, most of the element concentrations and TOC decreased in the sediment from 2021 to 2024, potentially indicating the movement of finer sediments and aggregates due to higher rainfall in the LRB or the releasing of elements back into the water column due to changes in environmental conditions.

3.5 Conclusion

The sediment quality indicated variation in the percentage TOC, sediment grain size composition and element concentrations throughout the LRB during both the 2021 and 2024 sampling years. Although there are no sediment quality guidelines available for the LRB, higher TOC was observed throughout the basin, during both sampling years. The TOC recorded in the sediment samples during 2024 were overall higher than in 2021. Furthermore, the sites that exhibited high TOC, were distributed throughout the basin with no specific order (i.e. from upstream to downstream). The elevated TOC observed during both years can mainly be the result of agricultural activities. Additionally, sewage effluent in some river systems such as the Crocodile, Mogalakwena and Sand rivers also contributed to higher TOC. Furthermore, mining and urbanisation also contributed to higher TOC in the sediment of the sites sampled in the Olifants, Luvuvhu, Lotsane and Umzingwane rivers. Illegal gold mining in the Lotsane and Umzingwane

rivers are of great concern as it also contributes to organic and inorganic pollution. Letsibogo Dam also indicated higher TOC during 2024, which can be due to the capabilities of a dam to trap fine sediments and organic matter, and not only the effect of agricultural activities upstream in the Motloutse River.

The sediment grain size analysis indicated similar results during both sampling years where most of the sites were dominated by coarse sand. Additionally, the sediment for some sites also consisted out of a combination of coarse and medium sand during 2021 and a combination of very coarse, coarse and medium sand during 2024. Contrastingly, the Ngotwane and Limpopo (CCONR) rivers had a higher percentage of fine sand. Fine sand can increase the metal concentrations, due to a bigger surface area where elements and organic matter can bind to form aggregates. This was observed in the Limpopo River at Crooks Corner during 2024 where the highest fine sand was observed as well as high concentrations of TOC, As, Cr, Cu, Ni and Zn. The element concentrations were overall higher during 2021 than in 2024. Both sampling years indicated higher element concentrations for specific elements at different sites. The As concentration was the highest in the sediment of the Crocodile River, and the downstream site in the Limpopo River during 2021. The higher As can potentially be the effect of sewage effluent in the Crocodile River, as well as the gold mining in the upper reaches of the Crocodile River. Furthermore, the Luvuhu River exhibited a higher Cu during 2021, which can be the effect of agricultural activities, domestic discharge and industrial runoff. The Mogalakwena River is also heavily impacted by sewage effluent, industrial runoff and mines, which can be seen in the higher Cr and Pb concentrations observed in the sediment. During 2024, the Umzingwane River exhibited the highest concentrations of As, Ni, Pb in comparison with the other sampled sites. This can mainly be due to the gold mining in river. The Olifants river indicated elevated Cu and Zn during 2021 and the highest Cd concentration during 2024, indicating the impact of historical mining and agriculture in the catchment. Some rivers with lesser anthropogenic impacts also indicated elevated element concentrations, such as the Matlabas River that indicated elevated Zn and Ni concentrations, and the Shingwedzi River that exhibited a higher Cu concentration. Thus, it is possible that the elevated element concentrations are of natural geogenic origin and not specifically anthropogenic impacts alone. Furthermore, it was also observed that the Cr concentrations were overall higher than most of the elements at all of the sites for both sampling years.

Lastly, the overlapping sites indicated the movement of sediment in the LRB. The Luvuvhu River was characterised by a higher composition of very coarse sand and BALUL by a combination of mud, fine sand and coarse sand during 2021, whereas both sites were characterised by medium sand during 2024. Furthermore, higher TOC and element concentrations for most of the elements,

except Hg, were present in the sediment during 2021, indicating a decrease in most of the elements and TOC from 2021 to 2024.

CHAPTER 4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The Limpopo River Basin, shared by Botswana, Zimbabwe, South Africa and Mozambique is of high value for social, economic and ecological purposes. The limited water resources in the basin, in conjunction with the development of the four countries, are constantly increasing the pressure on the LRB to supply the water demand in quantity and quality. The effects of a rising economy and increasing human populations are evident. Anthropogenic impacts such as mining, agricultural activities, urbanisation, industrial effluent and sewage effluent are the main drivers contributing to the deteriorating water quality and sediment quality in the LRB. Therefore, the aim was to determine the change of water- and sediment quality within the LRB from 2021 to 2024 and link potential changes with possible land-use activities. This was achieved by assessing the change in water- and sediment quality from 2021 to 2024, as well as the land-use activities that could potentially contribute to the changes observed in the LRB.

Water quality perturbations were observed at almost all of the sites sampled during 2021 and 2024. According to the fitness for use values for the LRB, elevated pH, EC and DO levels were observed throughout the basin with six sites being classified as poor and unacceptable during 2021, and two sites being classified as poor during 2024 for domestic and irrigation use. The elevated pH was also indicated in the Mauchino diagrams where most of the sites exhibited higher alkalinity, cation and anion concentrations. Furthermore, elevated nutrient concentrations (PO_4 and NO_3) were observed in the LRB, specifically in the upper region, indicating the effects of mining and agricultural activities. The fitness for use values indicated that most of the selected element concentrations were good for aquatic ecosystems. However, it is worth noting that higher zinc (Zn) and copper (Cu) concentrations, in comparison with the selected elements, were observed throughout the basin during both sampling years. Anthropogenic impacts and more specifically, agriculture, mining, urbanisation and sewage effluent were evident in river systems during 2021. This was observed throughout the basin, including rivers such as the Crocodile, Mogalakwena, Sand and Olifants rivers. The Ngotwane River also indicated the predominant effects of sewage effluent where elevated EC, cations and nutrients were recorded, with the highest out of all the sites recorded in the Ngotwane River. The accumulative effects of these impacts on the tributaries were also observed in two downstream sites in the Limpopo River where altered water quality was also observed. Furthermore, an increase in EC was observed

downstream of Letsibogo and Dikgathlong dams, potentially indicating the effect of higher evaporation rates and the dissolving of minerals and salts in impoundments. Overall, the water quality results indicated water quality perturbations to some degree for at least one parameter at all of the sites during both sampling years.

There are currently no sediment quality guidelines for the LRB. However, the percentage total organic carbon (TOC) was elevated in the sediment at most of the sites during both sampling years, with the 2024 sites exhibiting overall higher TOC than the 2021 sites. The higher TOC can potentially be the result of agricultural activities and land degradation that is causing an increase in erosion, as well as sewage effluent in some river systems (Crocodile, Mogalakwena and Sand), ultimately contributing to the higher TOC observed in the sediment. Additionally, mining and urbanisation also contributed to higher TOC in the sediment of the Olifants, Luvuvhu, Lotsane and Umzingwane rivers. The impacts of instream impoundments on sediment quality are also present in Letsibogo Dam, where higher TOC was present due to the potential trapping of fine sediments and organic matter. Furthermore, the sediment grain size analysis indicated that most of the sites during 2021 and 2024 were dominated by coarse sand and secondly, a combination of coarse and medium sand during 2021 and a combination of very coarse, coarse and medium sand during 2024. The Ngotwane and Limpopo (CCONR) rivers had a higher percentage of fine sand. The Limpopo River at Crooks Corner during 2024 exhibited the highest fine sand, as well as high concentrations of TOC, arsenic (As), chromium (Cr), Cu, nickel (Ni) and Zn. Higher element concentrations and TOC can be due to the characteristics of fine sand with increased surface area, where elements and organic matter can bind to form aggregates. Additionally, it was also observed that the selected element concentrations in the sediment were overall higher during 2021 than in 2024. Some sites also indicated higher concentrations for specific elements. During 2021, the Crocodile River and the downstream site in the Limpopo River had the highest concentrations of As, whereas the Luvuvhu River exhibited higher Cu, and the Mogalakwena River had higher Cr and Pb. During 2024, the Umzingwane River exhibited the highest As, Ni and Pb concentrations. Interestingly, both rivers (Crocodile and Umzingwane) that are impacted by some degree of gold mining, exhibited elevated As concentrations. The sediment of the Olifants River had the highest Cu and Zn concentrations during 2021 and the highest Cd concentration during 2024, reflecting the historical impacts of mining and agriculture in the sediment quality of the system. Lastly, it was also observed that the Cr concentrations were overall higher than most of the elements at all of the sites for both sampling years, potentially due to the natural geology and not only anthropogenic impacts.

The land-use/ land-cover (LULC) assessment indicated an increase in rangelands, crop fields and built areas from 2021 to 2024. The increase in LULC is the direct effect of an increase in

human population, hence the progression of agricultural activities and urbanisation in the LRB. As a result, the water quality analysis indicated increases in selected elements from 2021 to 2024, at all four overlapping sites in the Limpopo (MAPU, LIMP3), Luvuvhu (LUVU) and Olifants (BALUL) rivers. Additionally, the Luvuvhu River indicated an increase in nutrients, salts and alkalinity, potentially indicating the effects of domestic discharge, agricultural activities and semi-industrial pollution in the system. Contrastingly, a decrease in nutrients, salts and alkalinity was observed in the Olifants River, which can be the positive effect of zero discharge from the industrial phosphate plant on the Ga-Selati River in the Olifants catchment. However, the Olifants River has shown an increase in the nutrients, potentially indicating the effect of an increase in the LULC activities such as agriculture. The increase observed in various water quality variables corresponds with the increase in LULC activities from 2021 to 2024. Therefore, the changes in water quality can potentially be attributed to an increase in agricultural activities, as shown by the increase in rangelands and crop field classes, as well as mining and urbanisation, indicated by the increase in the built areas class. Furthermore, the overlapping sediment quality sites also indicated changes from 2021 to 2024. The Luvuvhu River was characterised by a higher composition of very coarse sand and BALUL by a combination of mud, fine sand and coarse sand during 2021. This composition changed and both sites were characterised by medium sand during 2024. Additionally, higher TOC and element concentrations for most of the elements, except Hg, were present in the sediment during 2021 and decreased from 2021 to 2024.

The element concentrations were higher in the sediment and lower in the water during 2021, whereas the element concentrations were higher in the water and lower in the sediment during 2024. Therefore, the change in sediment composition, and lower element and TOC concentrations observed in the sediment during 2024 can potentially be due to higher rainfall, causing the movement of sediment and the release of elements into the water. This is also supported by the higher element and nutrient concentrations observed in the water samples during 2024. Ultimately, the impacts of existing anthropogenic activities are evident and further water quality deterioration was observed from 2021 to 2024. Thus, indicating the impacts of an increase in LULC.

In conclusion, this study provided an overview of the water- and sediment quality within the LRB as well as the potential impact of land-use activities on water- and sediment quality. It was evident that agriculture, mining, urbanisation, sewage effluent and industrial runoff contributed to the deteriorated condition of the water- and sediment quality, as well as the further deterioration in water quality from 2021 to 2024 in the LRB. Ultimately, the data provided by this study can contribute to the environmental flow determination, monitoring and managing of the LRB through IWRM to improve the water resource management in the transboundary basin.

4.2 Recommendations

The present study produced meaningful findings, but there will always remain scope for improvement and future research. Therefore, the following recommendations are proposed for future research:

- During the present study the sites were not sampled seasonally. Therefore, water- and sediment quality results that are provided for each year (2021 and 2024), were determined from single surveys. Thus, it is recommended to sample the sites twice a year during a high flow and low flow season. This will remove seasonal variation and produce a more accurate overview of the water- and sediment quality in the LRB.
- Limited overlapping sites were included in the study. Thus, it is recommended for future studies to include more overlapping sites to improve the assessment of changes in water- and sediment quality over time due to changes in LULC. By monitoring the same sites will remove the variability of natural factors such as geology and climate or different anthropogenic impacts.
- Historical water- and sediment quality sites were not included in this study. Therefore, it is recommended to include historical data to improve the understanding, as well as the comparison of the present water- and sediment quality condition.
- The sampling sites were not categorised according to ecological regions, quaternary catchments or sub-catchments. Different ecological regions, quaternary catchments or sub-catchments can exhibit different geological characteristics. This can affect the water- and sediment quality by exhibiting different element concentrations and other natural characteristics. Therefore, in order to improve the understanding and impact of LULC on the water- and sediment quality, it is recommended to divide the sampling sites into different regions.
- The assessment of water- and sediment quality in isolation is efficient, but to improve the understanding of the impact thereof on the aquatic environment it is recommended to include the assessment of water- and sediment quality in conjunction with a biological indicator such as diatoms. By including the monitoring of aquatic communities, as well as the diversity and abundances of the organisms, will help indicate the changes in water- and sediment quality and the impact of anthropogenic activities.

- Lastly, it also recommended to use historical data, as well as ecological sensitivities to create water- and sediment quality guidelines for the LRB. The development of guidelines will improve and standardise the assessment of water and sediment quality for the LRB.

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