EFFECTS OF SEDIMENTATION ON WATER QUALITY IN THE METOLONG RESERVOIR, MASERU, LESOTHO

BY

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DECLARATION

The work contained in this dissertation was carried out and completed by MATS'ELISO CELESTINA MAKHAKHE (200300990) at the Water Institute, National University of Lesotho. I hereby declare that this study constitutes my original work and has never been submitted for the award of a degree or diploma to any University. To the best of my knowledge this dissertation contains no material written by another person except where due reference is made in the dissertation itself.

Signature……………………………………………………..….Date……………………………

As the candidate's supervisor, I certify the above statement to be correct to my knowledge and have recommended this dissertation for submission.

SupervisorDr. Tebesi Raliengoane**……………………………………Date…………………………………………..**

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LIST OF SYMBOLS AND ABBREVIATIONS

°	Degrees
=	Equal
>	Greater than
<	Less than
′	Minutes
/	Per
%	Per cent
″	Seconds
BOD	Biological Oxygen Demand
Cd	Cadmium
cm	Centimeter
COD	Chemical Oxygen Demand
CoW	Lesotho Commissioner of Water
Cr	Chromium
CSV	Comma–Separated Values
Cu	Copper
DEM	Digital Elevation Map
DO	Dissolved Oxygen
E	East
EC	Electrical Conductivity
et al. (et alis)	And others
etc.	Et cetera
Fe	Iron
Fig.	Figure
G	Gram
GBDT	Gradient Boosting Decision Trees
GEE	Google Earth Engine
GIS	Geographic Information System
H	Height
ha	Hectares
IWRM	Integrated Water Resources Management
K	Kilo
KWO	Kansas Water Office
L	Litre
LESIS	Lesotho Soil Information Systems
LHDA	Lesotho Highlands Development Authority
LMS	Lesotho Meteorological Services
LSTM	Long Short–Term Memory
M	Meter
masl	Meters above sea level
mcm	Million Cubic Meter
mm	Millimeters
MNDWI	Modified Normalized Difference Water Index
mS/m	MilliSiemens per Meter
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
Ni	Nickel

NTU	Nephelometric turbidity units
ORASECOM	Orange Senqu River Commission
Pb	Lead
ppm	Parts Per Million
QGIS	Quantum GIS
RUSLE	Revised Universal Soil Loss Equation
S	South
SADC	Southern African Development Community
SAE	Surface Area Elevation
SWAT	Soil and Water Assessment Tool
Tab.	Table
TDS	Total dissolved solids
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
UTM	Universal Transverse Mercator
V	Volume
WASCO	Lesotho Water and Sewerage Company
WGS	World Geodetic System
WHO	World Health Organization
WRC	Water Research Commission
Zn	Zinc

ABSTRACT

Reservoir sedimentation is a significant environmental challenge affecting the sustainability of water resources, particularly in Lesotho, where soil erosion and land degradation are prevalent due to intensive land–use activities and fragile ecosystems. Metolong Reservoir is a critical water supply for approximately two–thirds of Lesotho's population, challenged with rapid sedimentation which lowers the water quality and threatens the long–term viability of the reservoir, yet no known studies have been done to correlate sedimentation and water quality in the area. This study investigated how sedimentation affects water quality in the Metolong Reservoir by quantifying sediment accumulation in the Metolong Reservoir from 2020 to 2022 and analyzing the impact of sedimentation on key water quality parameters. The study employed historical bathymetric and water quality data (2020–2022), complemented by GIS–based spatial analysis and R statistical modeling to assess the spatial and temporal relationships between sediment deposition and changes in water quality parameters, following the causal–comparative research design. Water quality parameters analyzed were aluminum, Electrical Conductivity (EC), iron, manganese, nitrates, nitrites, phosphates, sulphates, TDS and turbidity. Bathymetric analysis revealed a total sediment accumulation of approximately 1,705,583 m^3 (2.68% of reservoir capacity) between 2020 and 2022, concentrated primarily near the reservoir’s middle and towards the dam, resulting in an annual storage loss of 1.34%.Linear regression analysis revealed turbidity as the most significant at ($p<0.05$).The study also identified turbidity and nitrates as key water quality parameters significantly influenced by sedimentation, with turbidity showing the strongest correlation ($r = 0.60$) and nitrates showing a moderate correlation ($r = 0.2$) with sediment volume suggesting possible links with upstream land use and nutrient runoff. There was an increase in nutrients and heavy metals concentration from 2020–2022, indicating a need for intervention, though most water quality parameters were still within WHO and South African water quality standards. The findings confirm that sedimentation negatively affects water quality, underscoring the need for integrated catchment management strategies, including sediment control, land–use planning, and systematic water quality monitoring to safeguard reservoir operations and public health.

Key Words

Erosion, pollution, reservoir, sedimentation, water quality

CHAPTER ONE

INTRODUCTION

1.1 Background

Reservoir sedimentation is generally caused by soil erosion. It is exacerbated by both natural and anthropogenic activities such as deforestation, overgrazing, and poor agricultural practices that lead to increased sediment load in rivers (Rodriguez *et al.*, 2023). It has major implications for storage capacity, reservoir lifetime and water quality (Patro *et al*., 2022). According to Perera *et al*. (2023) the global reservoir storage is estimated to decline from 6316 to 4665 billion m^3 causing a 26% storage loss by 2050. Reservoir sedimentation leads to loss of approximately 0.5–1% of global storage volume annually impacting hydropower, drinking water supplies and irrigation (Mouris *et al*., 2023). Globally, an additional 10% of reservoir storage loss will likely occur from 2022 (16%) to 2050 (26%), with averaged annual losses of 0.36% of initial global storage capacity (Perera *et al*., 2023).

Reservoir sedimentation is also a challenge in the African continent, especially in regions with high rainfall variability and land use due to the reliance on reservoirs for water supply and hydropower (Perera *et al*., 2023). The cumulative loss of storage in Africa is estimated to reach 17 and 24% by 2030 and 2050 respectively (Perera *et al*., 2023). According to SADC (2015) reservoir sedimentation impacts water storage capacity, water quality as well as the lifespan of reservoirs in the region.

Lesotho is no exception to the reservoir sedimentation and is estimated to show 8, 11, and 18% storage loss by 2022, 2030, and 2050 respectively (Perera *et al*., 2023). The ‘Muela reservoir in Lesotho has experienced an average annual loss in storage capacity of 15,400 m^3 (approximately 0.26%) from 1985 to 2015 due to sedimentation. Additionally, some reports estimated an average loss of 21,000 m^3 storage (Perera *et al*., 2023), reflecting variability in sediment inflows and deposition patterns and differences in measurement methods, time periods, or data sources. However, there is an initiative to remove the sediment from the reservoir (LHDA, 2018). According to LHDA (2020) the bathymetric surveys conducted in the Metolong Reservoir in 2020 indicated a reduced storage capacity due to reservoir sedimentation.

As a result, sedimentation harbors nutrients which result in eutrophication and declining water quality. This increases the cost of drinking water treatment and can also result in odor and taste problems (Patro *et al*., 2022). Sedimentation affects the physical, chemical and biological properties of water bodies, thus affecting the amount of oxygen available to aquatic organisms and bringing health hazards to the people as well.

It is crucial thereof to study the relationship between sedimentation levels and reservoir water quality to establish the associated effects on the Metolong reservoir. This reservoir is an important supplier of domestic and industrial water in Lesotho, supplying two–thirds (2/3) of the country’s population in five areas namely, Maseru the capital town, nearby towns such as Teyateyaneng (TY), Morija, Mazenod and Roma (World Bank Group, 2015).

1.2 Problem Statement

Although the Metolong Reservoir has a critical role in supplying water to two–thirds (2/3) of Lesotho's population for domestic and industrial use (Lowry, 2015), it is threatened by increasing sedimentation levels due to human actions; particularly agriculture leading to reduced storage capacity (ReNoka, 2022; LHDA, 2020) as shown in Figure 1 and potential declines in water quality as shown in Figure 2 which can have adverse health, environmental and economic impacts.

According to my knowledge, no documented research has been done to understand the relationship between sedimentation and the water quality of the reservoir in the study area.

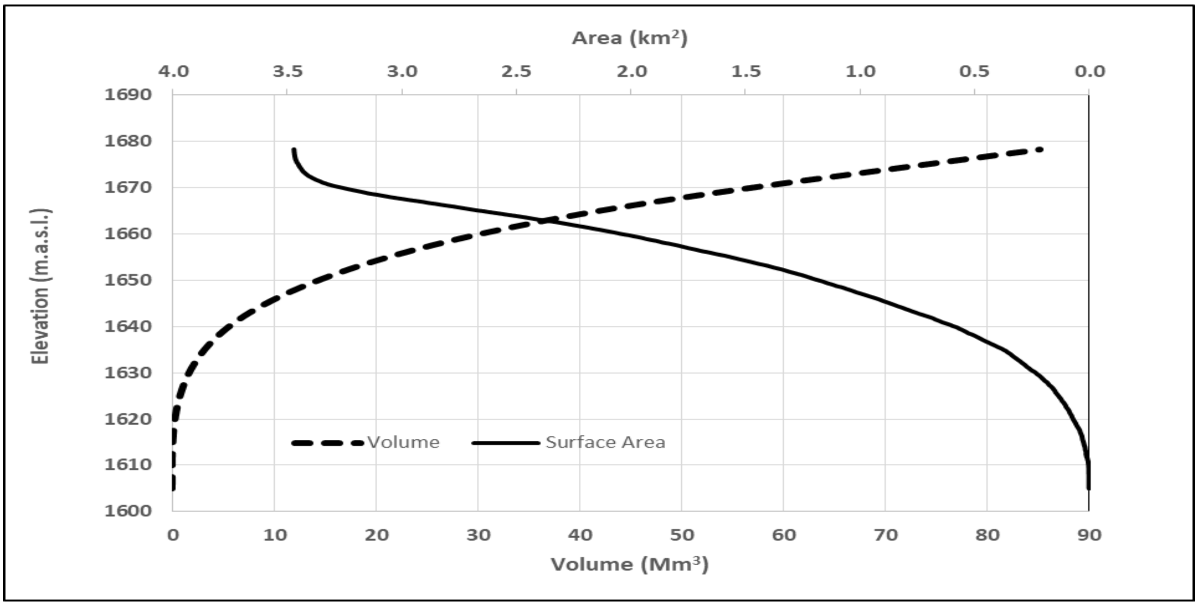


Figure 1: Surface Area Elevation curve of the Metolong Reservoir (LHDA, 2020).

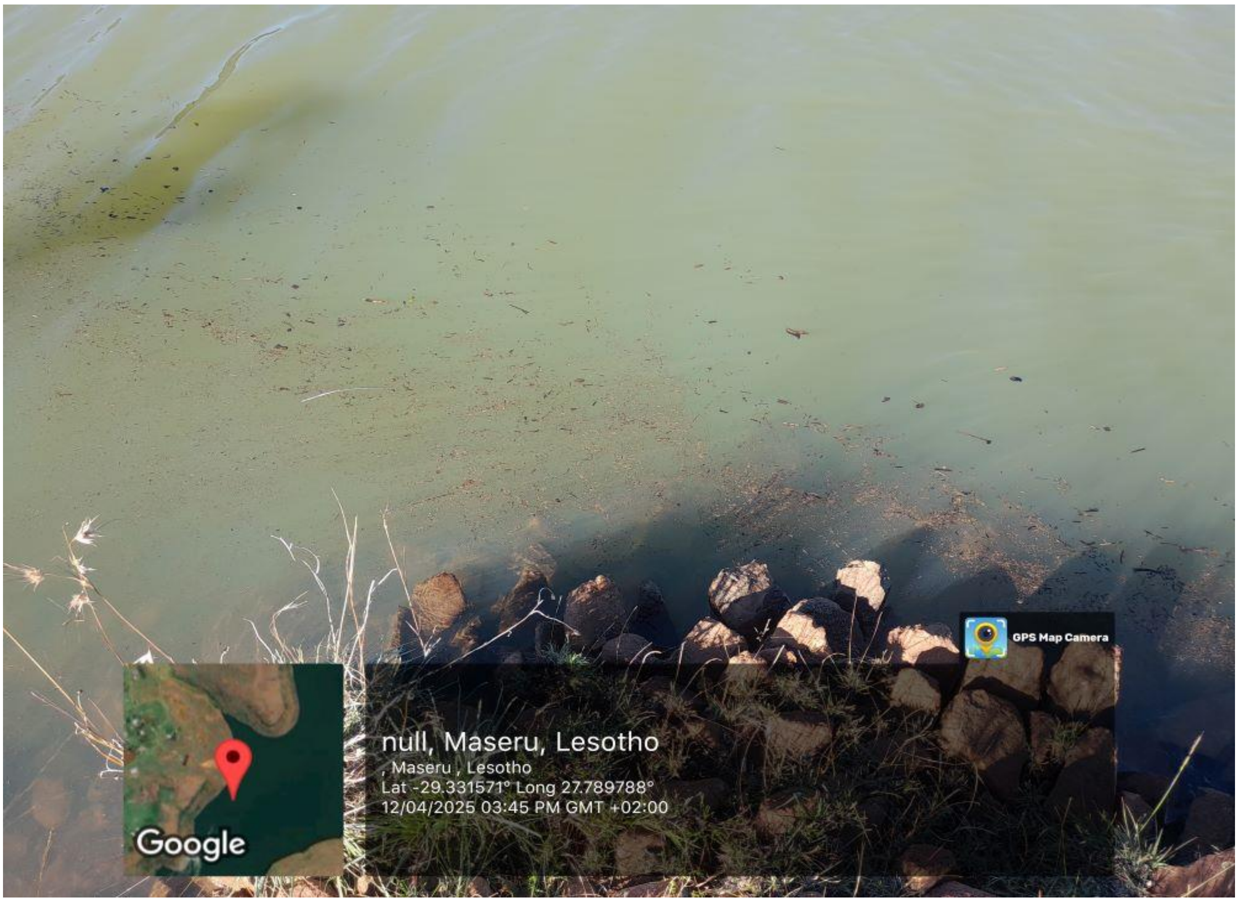


Figure 2: Sediment induced pollution at the Metolong Reservoir

1.3 Drivers to the Problem

Different land uses such as conventional agricultural activities in the catchment contribute to increase in nutrient and sediment supply to adjacent waters, resulting in reduced water quality and increased sedimentation levels (Palinkas *et al.*, 2022).

Climate change exacerbates sedimentation rates by intensifying rainfall variability and erosion processes (Mouris *et al*., 2023).

1.4 Research Questions

1.4.1 Main research question

What are the effects of sedimentation on water quality in the Metolong Reservoir?

1.4.2 Specific research questions

1.4.2.1 What are the sedimentation levels in the Metolong Reservoir?

1.4.2.2 Which parameters of water quality are affected by sedimentation and how are they affected?

1.4.2.3 How do the sediment levels affect water quality at different sampling depths?

1.5 Research hypotheses

1.5.1 Null hypothesis (H_0)

Sedimentation does not have a significant effect on water quality in the Metolong Reservoir.

1.5.2 Research hypotheses (H_1)

Sedimentation negatively affects water quality in the Metolong Reservoir.

1.6 Research Objectives

1.6.1 Main objective

This study aims to investigate the effects of sedimentation on water quality in the Metolong Reservoir.

1.6.2 Specific objectives

1.6.2.1 To assess the sedimentation levels in the Metolong Reservoir.

1.6.2.2 To establish the relationship between sedimentation and the selected water quality parameters.

1.6.2.3 To establish how the sediment levels affect water quality at different sampling levels.

1.7 Significance of Study

This research might help to understand the effects of sedimentation on water quality in the Metolong Reservoir enabling stakeholders to develop informed strategies and policies to mitigate sedimentation. The research might also guide the Lesotho Water and Sewerage Company (WASCO) to effectively plan and budget for water treatment and management. It might also inform the Department of Environment (DOE) and other stakeholders of the contribution of the reservoir to the pollution of the surrounding environment and device appropriate policies and awareness measures for the downstream communities, highlighting the importance of Integrated Water Resources Management (IWRM) in managing water resources.

1.8 Outline of the Thesis

The arrangement of this research is made up of six chapters that are structured as outlined in the following sentences. Chapter One presents the background of the study, causes and drivers along with implications of the sedimentation problem in reservoirs. The chapter also presents an overview of reservoir sedimentation globally, regionally as well as locally and in the study area. It outlines the study objectives, research questions and the significance of the study to IWRM. Chapter Two focuses on the literature review on key concepts and studies pertaining to sedimentation and water quality while Chapter Three discusses the methods and procedures used in this research, which include a comprehensive overview of the study area, research design, approaches to data collection, processing and analysis. Chapter Four presents results and findings while Chapter Five discusses those findings and results, then Chapter Six which is conclusion and recommendations.

CHAPTER TWO

LITERATURE REVIEW

Dams and reservoirs contribute significantly to human development. They are mostly constructed on rivers and streams for different purposes. However, sediments accumulate in reservoirs from catchments, reducing their lifespan and posing other challenges (Tikenera *et al.*, 2025; Kuma *et al.*, 2024). Bednar and Marton (2022) argue that sedimentation occurs naturally in all water bodies. However, it is more pronounced in reservoirs because they function as settling basins, causing sediment deposition as a result of low or no velocity of water in the reservoir, and thereby reducing the storage capacity. Activities such as urbanization and agriculture frequently accelerate this process, resulting in higher sediments entering the water bodies (KWO, 2008).

2.1 Assessment of Sediment Levels in the Reservoir

Sediment yield is a critical indicator for assessing the effects of sedimentation on a reservoir (Iqlash *et al.*, 2024). Rangaiah *et al.* (2016a) also recommend regular assessment of reservoir capacity and sediment buildup as an essential tool for preserving and extending the lifespan of the reservoir. However, Iqlash *et al.* (2024) also anticipate that intense rainfall events in the catchment regions increase the flow of sediment and nutrients into the reservoir. Additionally, Gwari and Ugoala (2009a) stated that the rate at which sedimentation accumulates in reservoirs should be proportional to the erosion of the surrounding catchment. According to Singh *et al.* (2021), direct hydrographic survey and the indirect inflow–outflow sediment methods are two main primary approaches used to estimate reservoir sedimentation.

Feng *et al.* (2025) utilized the Soil and Water Assessment Tool (SWAT) to estimate erosion and sedimentation rates of the Sutami Reservoir in Indonesia. The study used secondary data, such as a Digital Elevation Model (DEM) map, land use map, soil classification map, and climatological parameters, namely wind speed, temperature, humidity, solar radiation and recorded rainfall. The study concluded that the SWAT model is ideal and accurate for predicting erosion and sediment, giving similar results to those calculated using the Universal Soil Loss Equation (USLE).

Kuma *et al.* (2024) simulated sediment yield and mapped sub–basins with high sediment yield as sediment hotspots using SWAT in the Gibe One Reservoir in

Ethiopia. In the study, river flow and sediment data were calibrated and validated. The findings indicated that the average annual sediment produced by the catchment between 2003 and 2016 was 62.5 tons per hectare per year. The study further revealed that after thirteen (13) years of operation, the reservoir capacity reduced by 5.7 % due to sediment deposits. However, the study likely underestimated the output sediment since there was no time series data for the study catchments, but instead, the sediment rating curve was used.

Mehta and Verma (2024) assessed sedimentation of the Kadana Reservoir in India using satellite data and records of water levels from 2000 to 2020 using QGIS and Google Earth Engine (GEE). The findings of the study showed that loss of live storage since impoundment due to sedimentation was 38.52 and 22.79% after the year 2000. However, the study assumed that the reservoir has uniform sedimentation patterns, which is not the case in reality.

Rashid (2023) used GIS and remote sensing to assess sediment quantities in the Dukan Reservoir in Iraq. The study used satellite data to evaluate the area of water coverage, using the Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI) to improve the visibility of water surfaces in the satellite images. The results of the research were an annual sedimentation of 13.78 MCM and 14.95 MCM for NDWI and MNDWI, respectively, which are relatively close values, emphasizing the accuracy of the methods used.

Punit *et al.* (2020) estimated sediment yield in the Jayakwadi dam in the Aurangabad district in Maharashtra, India. They used computations from Khosla's, Joglekar, Varshny and Froehlich equations to estimate sediment yield for 10 years and compared them to those found from bathymetric surveys. Sediment yield indicated an average of 0.79824, 2.111986 and 4.338161 ha per 100 square kilometer per year for the Khosla's, the Joglekar and the Varshny equation respectively compared to the Froehlich formula (2.6175 % loss/year). They concluded that the Joglekar equation gave approximate results.

Tesfaye *et al.* (2020) conducted a study on small reservoirs in the Sub–Saharan Africa using remote sensing data combined with field observations to estimate sediment deposition rates. They employed a mixed–methods methodology, combining bathymetric changes detected from satellite imagery and field sediment data from 12 reservoirs over 10 years. Their findings revealed rapid sediment accumulation at a deposition rate of 1–6 cm per year in areas that are highly affected by intensive upstream land use.

Sawadogo and Basson (2018) studied sediment yield and reservoir sedimentation modelling of the Polihali Reservoir, in Lesotho. In their study they used a quasi–three–dimensional hydrological modelling (daily rainfall–runoff–sediment transport) to predict the sediment yield and the findings projected 900 tons per square kilometer, which matched with the observed sediment transport data on the river showing accuracy and reliability of the method. The model showed that after 100 years of operation, the reservoir storage capacity will be reduced to 90%.

Rangaiah *et al.* (2016b) identified the best theoretical approaches to predict the sedimentation rate of Thandava, Konam, and Raiwada Reservoirs in India by comparing with hydrographic survey results. The methods used included, Grade's, Khosla's, and Joglekar's methods. The findings indicated that the sediment yield rate calculated using Khosla's method is similar to the rate determined from the hydrographic survey data for Thandava and Konam Reservoirs. In the case of Raiwada Reservoir, Joglekar's method produced a sediment rate aligned with the figure obtained from the hydrographic survey data. They concluded that Khosla's method was the best theoretical approach.

According to Dalu *et al.* (2013), in their study to model sedimentation rates of the Malilangwe Reservoir in Zimbabwe using the Wallingford (2004) equations with the aid of NDVI (remote sensing), the sedimentation rate of the reservoir was approximately 120.1 tons per square kilometer per year with a mean annual sediment concentration of 2,400 ppm.

2.2 Effects of Sedimentation on Water Quality Parameters

Sedimentation reduces the water quality of the reservoir by accumulating nutrients, trace metals, pathogens, organic chemicals and other compounds, impacting aquatic ecosystems and potentially leading to increased maintenance expenses (Jha *et al.*, 2024; Michalek and Cupak, 2022). The buildup of sediment in reservoirs presents a significant challenge that affects the water quality, impacting the different uses of reservoirs and of primary concern is to maintain the safety of drinking water supplies (Rashid, 2023; KWO, 2008). According to Li *et al.* (2024), sediments serve as an accumulating area for heavy metals that pose risks to aquatic habitats and other life forms through the food chain.

Chabokpour (2025) examined sediment transport and its relationship to water quality parameters and hydrological characteristics in the Sufi Chay River in Iran, utilizing long–term data and a combination of traditional statistical methods. The author found a strong correlation between sediment discharge and water quality parameters such as flow rate, TDS and EC. In addition, a study by Heidarzadeh and Nejad (2017) on modeling the impact of sedimentation on TDS using the CE–QUAL–W2 software in the Shahriyar Reservoir in Iran indicated that sedimentation increased TDS levels in the outflow during normal, wet, and dry periods.

Benicio *et al.* (2025) employed the biological *Allium cepa* test to assess the cytotoxic and genotoxic effects of water and sediments from the Cana Brava Reservoir, in Brazil. They concluded that the concentrations of heavy metals such as chromium, nickel, cadmium, lead, sodium, zinc, copper, iron, manganese, calcium, magnesium, potassium and aluminum, EC, TDS and elevated concentrations of nitrogen and phosphorus indicated possible pollution in the reservoir due to high concentrations of nutrients and organic matter coming from management activities happening upstream.

A study by Geng *et al.* (2024) investigated the influence of water–sediment factors on water quality in Dongting Lake, China and indicated significant trends in total nitrogen and phosphorus. The study highlighted the importance of managing water–sediment interactions based on hydrological characteristics.

Akash *et al.* (2024) assessed water quality degradation due to anthropogenic activities in the Burhi Gandak River, Bihar, India. Water samples showed significant seasonal, spatial and temporal variations, with high degradation in industrial areas, emphasizing the complexity of the relationship between sedimentation, pollution, and water quality.

Yanglan *et al.* (2024) used water quality data from 20 monitoring stations (2017–2023) in the Min River Basin, China and analyzed it using LSTM and GBDT–LSTM models. The results revealed poor water quality in areas with sediment accumulation from upstream.

A study was conducted in the Anzali Lagoon, Iran, to examine the impact of sediment on the population of *Macrobrachium nipponense* (Aminisarteshnizi, 2024). The results indicated a relationship between prawn population and sediment type, with clay sediments associated with lower prawn numbers.

Woldeab *et al.* (2023) examined the changes in water quality parameters at different depths of the Gilgel Gibe I reservoir in Ethiopia. Turbidity, EC, biochemical oxygen demand (BOD_5), and nitrates showed a positive correlation, whereas temperature, dissolved oxygen (DO), and pH showed a negative correlation with depth. They noted that pollution load accumulated mostly at the bottom of the reservoir, changing water quality across different depths. They concluded that this is associated with runoff and the decomposition of organic matter.

According to Michalek and Cupak (2022), in their study to determine heavy metals pollution in reservoir sediments, water samples were collected at 0.2 m depth below water level from different reservoir sampling points. They found high concentrations of nickel exceeding permissible limits in some sampling points. They also found that pH decreased with increasing water depth.

Ugwele *et al.* (2021) studied the effects of farming activities on the water quality of the Obinna River watershed in Nigeria. Water and sediment samples were collected during farming and non–farming seasons to analyze turbidity, nitrates, phosphates, and heavy metals. The findings revealed that dissolved solids, nitrogen, turbidity, phosphates and ammonia exceeded WHO limits and showed high levels of heavy metals.

Kithiia (2012) studied the effects and implications of sediment loads on water quality in the Nairobi River basins in Kenya between 1998 and 2005. The study revealed a close relationship between certain water characteristics such as TDS, conductivity, turbidity and color, and concluded that sediment loads significantly contributed to pollution and reduction of water quality in the Nairobi River basin.

Water (2021) assessed dynamics in the water and sediment columns of the Alqueva reservoir in Berja, Portugal. Water sampling points were selected at different depths. The nutrients and organic matter were found to be in excess in the water, with high phosphorus concentrations. It was concluded that meteorological conditions and land–use activities increased sedimentation, reservoir eutrophication, and declined water quality.

Ziemińska–Stolarsk *et al.* (2020) examined the concentration of compounds and heavy metals at the bottom of Sulejów Reservoir in Poland. Sediments' samples were collected at different depths for analysis of total phosphorus, total Kjeldahl nitrogen, total organic carbon, ratio of total organic carbon to nitrogen (C: N), organic matter content, cadmium, chromium, and lead. Lower concentrations of organic matter were found at shallow parts, whereas concentration was highest at deeper parts. Heavy metals were also found to be concentrated at the bottom sediment. The findings highlighted that accumulation of compounds in water was a result of discharge–dependent sedimentation and their distribution, which is influenced by agricultural activities and that the concentrations of heavy metals represented those in the natural content of soils.

Tundu *et al.* (2017) assessed sedimentation and its impacts on water quality in the Mazowe Catchment, Zimbabwe, using the Revised Universal Soil Loss Equation (RUSLE) model, ground observations, and GIS–based remote sensing data to estimate soil erosion and sediment loss within the catchment. The results indicated significant sediment accumulation and strong correlations between sediment yield, turbidity and TDS. They concluded that sedimentation deteriorated the water quality.

Estigoni *et al.* (2017) assessed sedimentation through bathymetric surveys and core samples from 2004 to 2014 in Furnas Hydroelectric Power Plant, Brazil. The authors reported significant silting with nitrogen remaining largely in water during the dry season. The study suggested that sedimentation might enhance downstream water quality by absorbing nutrients into the sediment particles.

Ndungu *et al.* (2013) investigated water quality status and pollution sources in Lake Naivasha, Kenya using principal component analysis (PCA) and cluster analysis (CA). They found that turbidity correlated directly with nutrients and iron, indicating the influence of agricultural and domestic pollution sources. They concluded that sediments can bind with heavy metals and phosphorus, leading to water quality deterioration.

Gwari and Ugoala (2009b) studied sedimentation in water bodies in Nigeria. They used historical flow and sediment transport data. They stated that turbidity levels, total phosphorus, total nitrogen, total organic carbon, iron, zinc, lead, and various toxic substances entering estuaries from their watersheds, yield high correlation against high sedimentation rates.

2.3 Gap Analysis

To this date, there is scarcity of documented research focusing on reservoir sedimentation and water quality in the Metolong Reservoir, as studies have not been conducted in conjunction. For big dams and reservoirs in Lesotho, the integrated study of reservoir sedimentation and water quality is known to have been conducted only on the Maqalika Reservoir by Masupha (2005). According to my knowledge, no documented studies have been done to establish how the two variables affect each other in the study area yet the region is threatened by sedimentation because of its high erosion risk. For the Metolong study area, two studies have been conducted on the sedimentation in 2020 and 2022 (LHDA, 2020, 2022) focusing primarily on sediment accumulation elevations. On the other hand, temporal and spatial water quality studies were done by WASCO. While the bathymetric studies inform reservoir storage loss, they do not capture changes in water chemistry; conversely, the WASCO approach tracks water quality trends but does not account for the role of sediment loads. It is therefore essential to study the correlation between sedimentation and water quality to establish how sedimentation processes influence water quality dynamics.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Description of the Study Area

This section describes the geographical location, characteristics of the reservoir and activities around the study area.

3.1.1 Geographical location characteristics

The Metolong Reservoir, situated in the western lowlands of Lesotho within the Middle Mohokare sub–catchment with an area of 651.305 km² (GoL, 2018), approximately 35 km east of the capital, Maseru (Figure 3), is the country's first roller–compacted concrete dam (WRC, 2014; ORASECOM, 2013). Geographically, it is situated on a latitude of 29°20′9″ S and a longitude 27°46′36″ E, at an elevation of 1,633 meters. The reservoir covers approximately 2.6 km² and is primarily fed by the South Phuthiatsana River, a major tributary of the Caledon River.

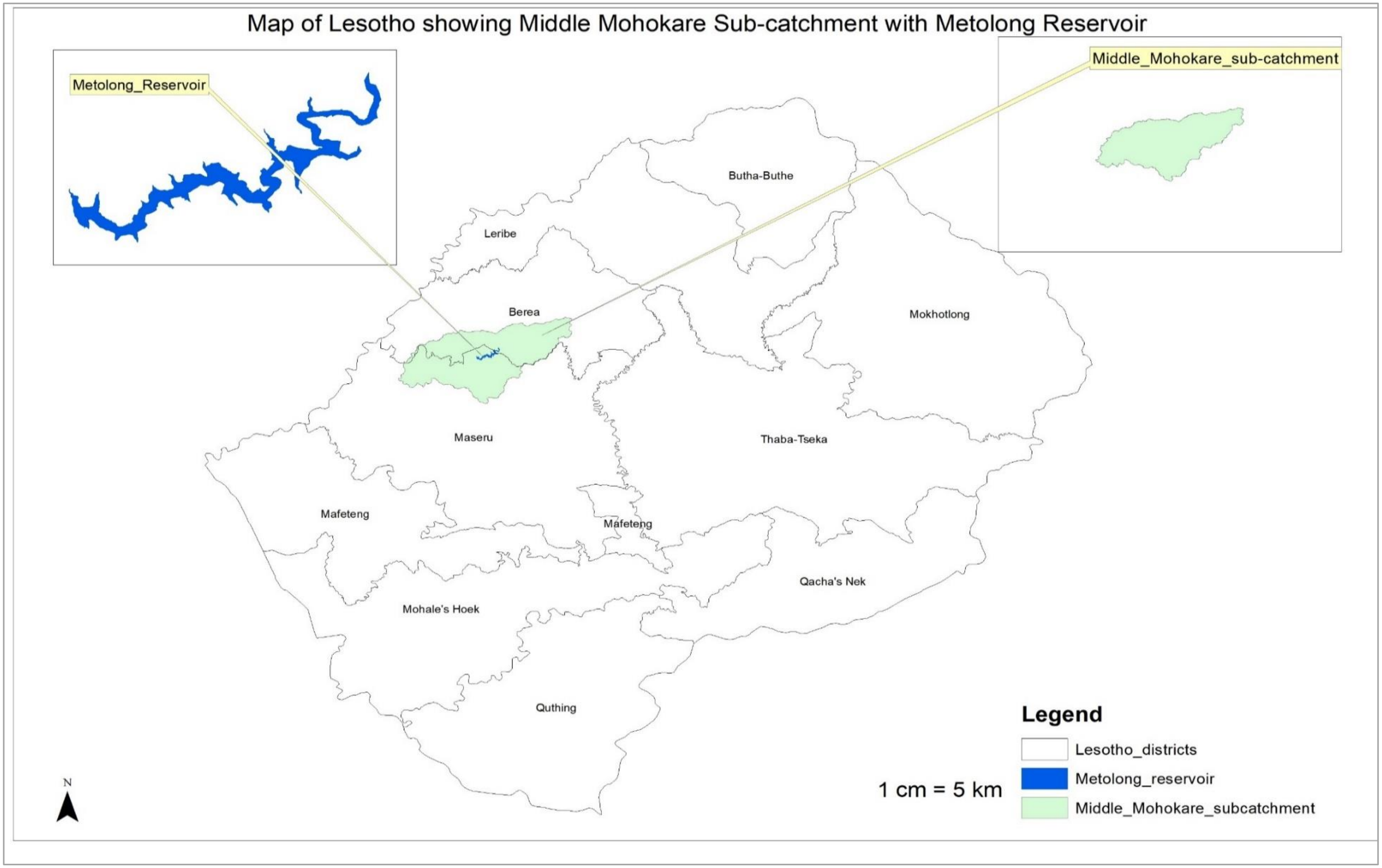


Figure 3: Middle Mohokare sub–catchment with Metolong Reservoir: UTM Zone 35S, WGS84

3.1.2 Main features of the Metolong Reservoir

Table 1: Key Characteristics of the Metolong Reservoir (WRC, 2014)

Construction Completion Year and Start of Operation	2015
Type of Dam/Wall	Roller–compacted concrete
Reservoir Height	83 m
Crest Length	280 m
Reservoir Capacity	63.7 million cubic meters (m^3)
Downstream Face of Slope	0.8:1 (H: V)
Pump Station Rate	75Ml/day (1.2 cubic meter per second)
Purpose	Domestic and industrial

3.1.3 Land uses and land cover in the Middle Mohokare sub–catchment

The upstream catchment area is characterized by rangelands, croplands, settlements, forests, other anthropogenic land management activities, including sand mining, quarrying, cultivated agriculture etc. as shown in Figure 4 and 5.

Figure 4*:* Image showing land uses around the reservoir (Google Earth Pro, 2024)

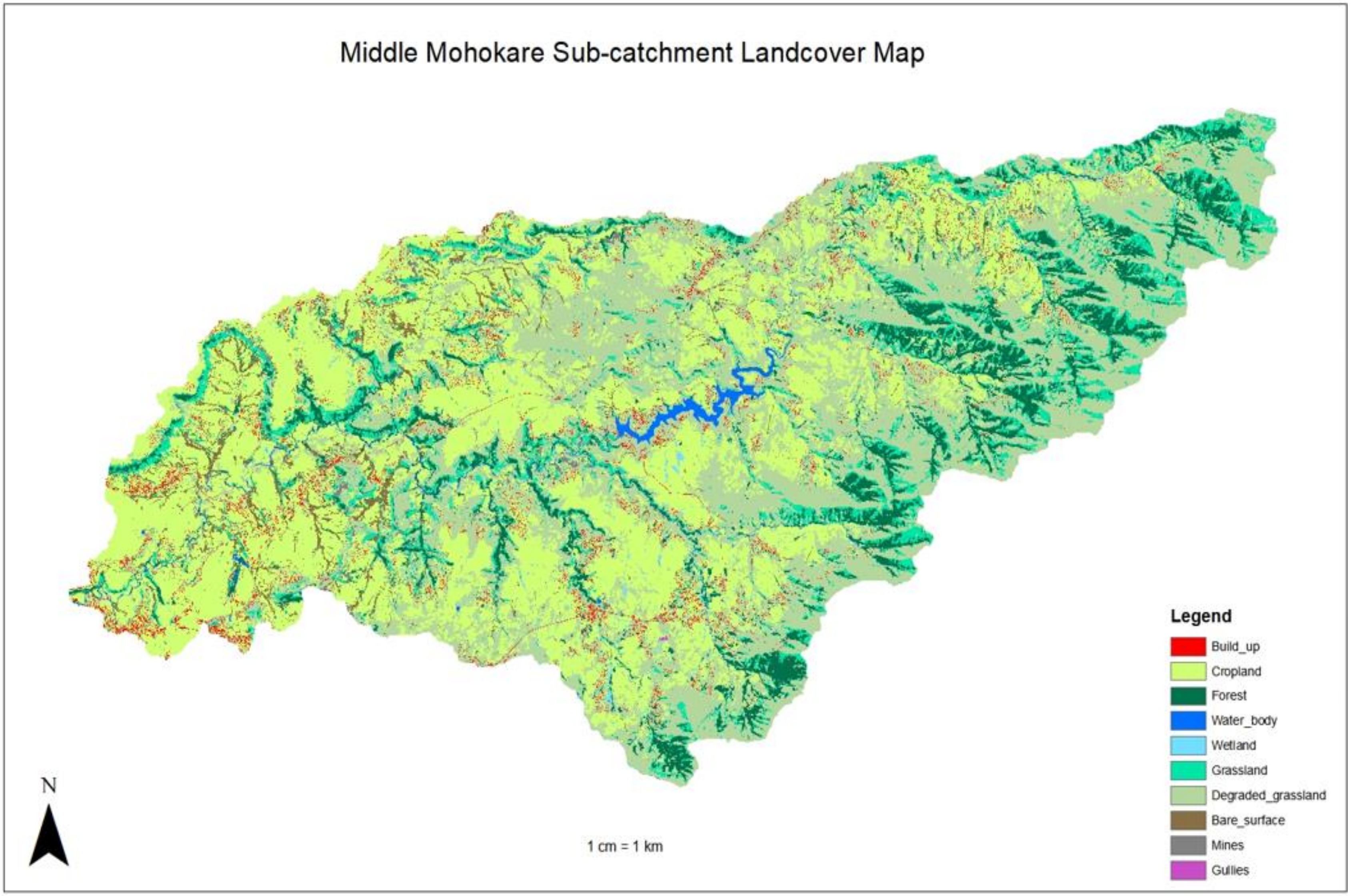


Figure 5: Landcover map of Middle Mohokare sub–catchment: UTM Zone 35S, WGS84

Table 2: Hectarage and percentage of land cover classes in the Middle Mohokare subcatchment (FAO, 2022)

Land cover class	Area (ha)	Percentage (%)
Build up	1,286.46	1.94
Cropland	24,588.82	37.15
Forest	5,573.73	8.42
Water body	512.23	0.77
Wetland	317.60	0.48
Grassland	6,254.97	9.45
Degraded grassland	25,406.40	38.38
Bare ground	1,692.79	2.56
Mines (sand and quarry)	549.43	0.83
Gullies	12.45	0.019

3.1.4 Soil types in the Middle Mohokare sub–catchment

The sub–catchment is predominantly characterized by soft rock and steep gradients, making it prone to high levels of soil erosion and increased sedimentation. The sub–catchment is dominated by Cambisols soils (GoL, 2018), which are mainly found in landscapes with high erosion rates (Jain, 2011). Cambisols soils are characterized by iron and aluminum compounds (Jain, 2011). The prevalence of Cambisols soils are commonly associated with erodible landscapes.

3.1.5 Middle Mohokare sub–catchment climate

The sub–catchment experiences warm, wet summers and cool, dry winters with an annual rainfall ranging from 800 – 1000 mm which comes down mostly during the summer months of December to April with temperatures ranging from 14–28 degrees Celsius in summer and 0–19 degrees Celsius in winter (LMS, 2020).

Table 3: Precipitation in the Middle Mohokare sub–catchment (LMS, 2024)

Rainfall Station	Longitude	Latitude	Annual Rainfall (mm)	
			2020	2022
Pulane (upstream)	27.92	–29.25	895.61	1134.84
Seeiso Metolong(downstream)	27.79	–29.33	784.23	862.23

3.2 Research Design

The quantitative causal–comparative research was employed in the study. A causal–comparative research design seeks to identify relationships between independent and dependent variables after an action event has already occurred, usually using secondary data (Lawrence, 2023). The study was based entirely on secondary data, which included historical sediment survey records and water quality datasets for 2018, 2020 and 2022 from WASCO.

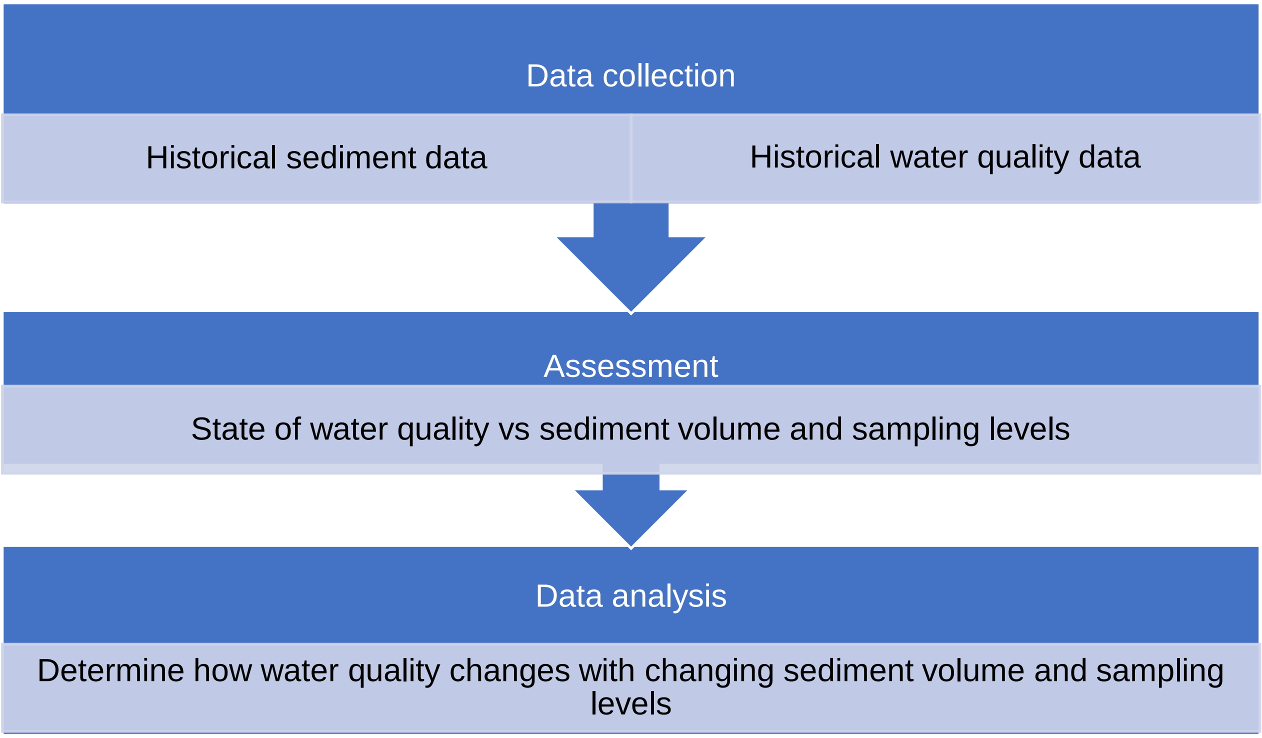


Figure 6: Methodological framework used in the study

3.3 Research Methods and Materials

This section details the methods, materials, and analytical approaches applied to evaluate sedimentation patterns and their relationship with water quality.

3.3.1 Data collection

3.3.1.1 Desktop studies

Using desk top studies, parameters that are said to be influenced by sedimentation according to literature were identified as the water parameters to be analyzed. The parameters included turbidity, TDS, EC and heavy metals (manganese, iron and aluminum) concentration, particularly aluminum and iron, which according to literature are found in soils around the study area.

3.3.1.2 Historical data sourcing

Historical bathymetric sediment survey data describing the underwater topography of the reservoir for 2020 and 2022 were obtained from LHDA, the agency that was engaged by the Commissioner of Water (CoW) to carry out the exercise. Water quality data for 2020 and 2022 were sourced from WASCO. The first available water quality data (2018), which was three (3) years after reservoir operation, was acquired as reference, to compare before and after scenario.

Table 4: Permanent water sampling sites

Water Quality Site	Longitude	Latitude	Depth Range (m)		
			2018 (as baseline data)	**2020**	**2022**
Metolong 1	27.777833	–29.334458	0,15	0,4,8,12,20	0,4,8
Metolong 2	27.792138	–29.329443	0,15	0,5,8,12,20	0,4,8,12
Metolong 3	27.806782	–29.324579	0,15	0, 4,8,20,21,30	0,1,5,9
Metolong 4	27.826949	–29.317914	0,15	0.4,8,12,20	0,4,8

Figure 7: WASCO's permanent water sampling points (Google Earth, 2025)

Table 5: Sampling periods showing hydrological seasons

2020	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sediment levels						🟥						
Water quality	🟦	🟦	🟦									
2022												
Sediment levels												
Water quality						🟥						🟦

Note: Months are abbreviated as follows — Jan (January), Feb (February), Mar (March), Apr (April), Jun (June), Oct (October), Dec (December) and wet season is represented by blue while dry is represented by red.

3.3.1.3 Field studies

Field studies were conducted to gather on–site information and to familiarize with the study area from the upper, middle and lower parts of the sub–catchment.

3.3.2 Data cleaning, processing and normalization

The secondary data collected showed inconsistencies in the water sampling depths and missing parameters. For instance, turbidity, TDS, nitrates and heavy metals were either missing or measured at irregular water depth intervals, leading to inconsistent analysis. However, data were cleaned and normalized using a systematic data cleaning and normalization procedure to ensure consistency and comparability across sampling depths before analysis. Missing values were identified and documented for each parameter and sampling depth, then data were aggregated to common depth categories. Data points such as temperature and pH that could not be reliably adjusted were excluded in the analysis.

3.3.3 Data Analysis

3.3.3.1 To assess the sediment levels in the Metolong Reservoir

Geographical Information Systems (GIS)'s ArcMap 10.8 was used as the platform for spatial analysis. To examine the spatial distribution of sedimentation, the bathymetric Latitude–Longitude–Elevation (XYZ) Microsoft Excel data for 2020 and 2022 supplied by LHDA were converted to CSV format and then imported into ArcMap. The XYZ tables were exported and georeferenced as shapefiles to allow further spatial analysis. Kriging interpolation was performed from the shapefiles, then triangulated irregular network (TIN) surfaces were created to generate raster images of sediment levels. The Metolong Reservoir shapefile was used as boundary to clip the raster images using the Extract by Mask tool to ensure that analysis focused only in the reservoir. Then using Cut/Fill tool, sediment accumulation and loss between 2020 and 2022 surfaces was computed to create rasters showcasing differential sedimentation where positive values indicate sediment deposition, whereas negative values indicate potential signs of erosion or data inconsistencies. The overall volume of sediment accumulation was determined using Spatial Analyst Tool and the Zonal Statistics function. The Cut/Fill raster image was reclassified to isolate sediment gain and loss zones. Sediment volumes were calculated based on pixel counts and cell size.

3.3.3.2 Assessing the impact of sedimentation on water quality

Water quality data were added as CSV into Arcmap 10.8, after which it was georeferenced. They were then exported to create shapefiles. The Cut/Fill raster layer created in 3.3.3.1 above was also added to the working environment. The Point Sampling Tool plugin in QGIS was used to extract sediment values at the exact locations of the water quality points from the Cut/Fill raster. To explore effects of sedimentation on water quality over time and with depth, water quality shapefiles were combined with the sediment deposition raster using a spatial overlay method. The Extract Values to Points tool linked sedimentation values to each water quality point. Then the Statistical Analysis combined dataset was exported to R for conducting correlation analysis between changes in sediment depth and water quality parameters to pinpoint statistically significant relationships. In addition, the status of water quality as influenced by sedimentation was determined by studying EC, turbidity, heavy metals (manganese, iron and aluminum), TDS and nutrients (sulphates, nitrites, nitrates and phosphates). Inferential and descriptive statistics were applied using R statistical software to evaluate the relationship between water depth, sediment volume and various water quality parameters. For each water quality parameter against depth, scatter plots with trend lines were created to show depth wise distribution. The results obtained were compared with the South African (SA) and WHO water quality standards for domestic (drinking) and industrial water standards. This analysis helps to determine the strength and direction of the relationship between the variables.

R version 4.2.2 was used for statistical analysis while data visualization utilized several R packages, including ggplot2 (Wickham, 2016), corrplot (Wei & Simko, 2024), ggpubr (Kassambara, 2023), and GGally (Schloerke et al., 2024) Pearson correlation coefficient (r) was calculated to measure the relationship between sediment volume and water quality parameters such as turbidity, EC, TDS and heavy metals. Values were assigned from –1 to 1 where 1 indicates a positive correlation while –1 indicates a negative one and 0 means there is no correlation between sediment levels and water quality.

Linear regression was computed to determine if changes in sediment levels influence change in water quality parameters to validate the research hypothesis. Scatterplots were created to visualize the relationships.

CHAPTER FOUR

RESULTS

4.1 The Sediment Levels from 2020 to 2022 in the Metolong Reservoir

Figure 8 shows an increase in sediment elevations (accumulation) from 2020 to 2022. The elevations ranging from 1336 to 1670 m indicate the highest sediment accumulation (represented by blue with dark blue being the most concentrated sediment zone), are more visible and dominant in 2022. 2020 has more zones of lower elevation ranges (0–1336 m) shown in brown, orange and greenish colours indicating less sediment accumulation in 2020 than 2022.

Figure 9 and 10 illustrate the spatial variations in sediment changes within the Metolong Reservoir between 2020 and 2022. The extensive presence of red regions throughout the majority of the reservoir (Figure 9) shows significant net sediment accumulation from 2020 to 2022. This is particularly noticeable in the middle and lower sections of the reservoir. Significant sediment accumulation (red) is in the middle of the reservoir and towards the dam whereas erosion (blue) occurs at bends and near constrictions, while there are no changes in the grey areas. In Figure 10, denoted by the darkest red, is the highest sediment deposition and accumulation occurring near the dam, moderate accumulation in the middle and the lowest at the reservoir inlet.

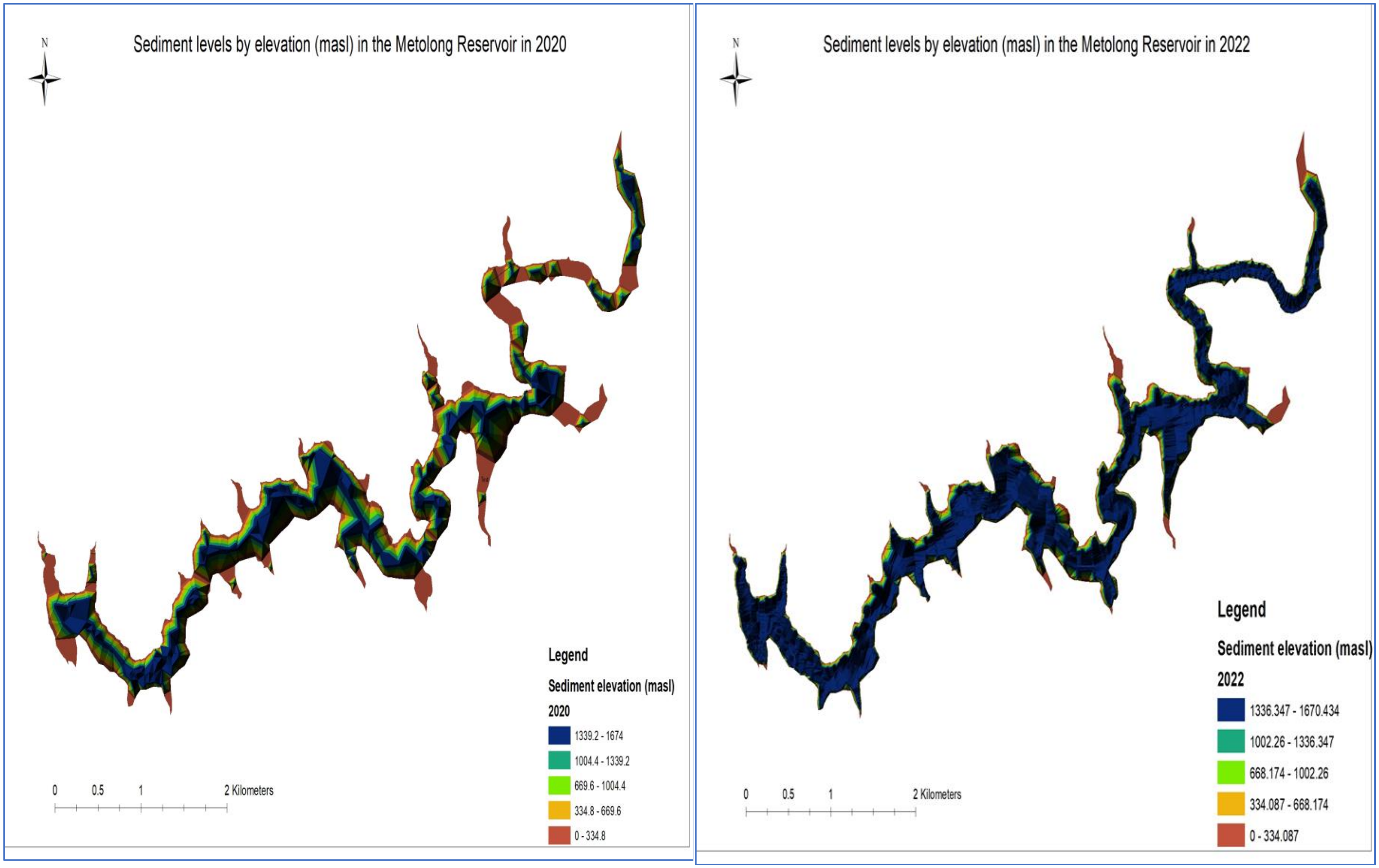


Figure 8: Sediment level elevation changes in meters in the Metolong Reservoir from 2020 to 2022: UTM Zone 35S, WGS84

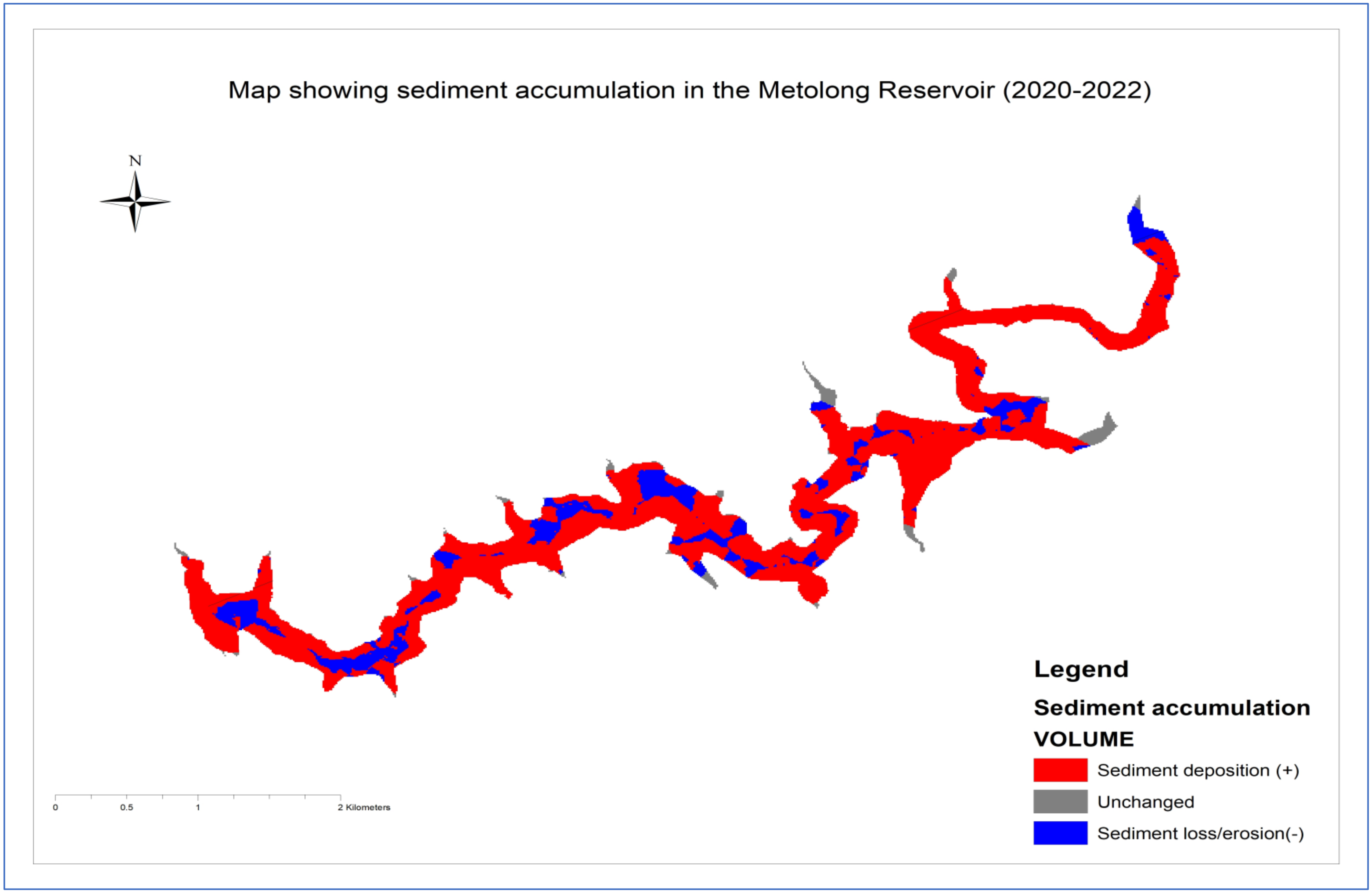


Figure 9: Sediment accumulation between 2020 and 2022: UTM Zone 35S, WGS84

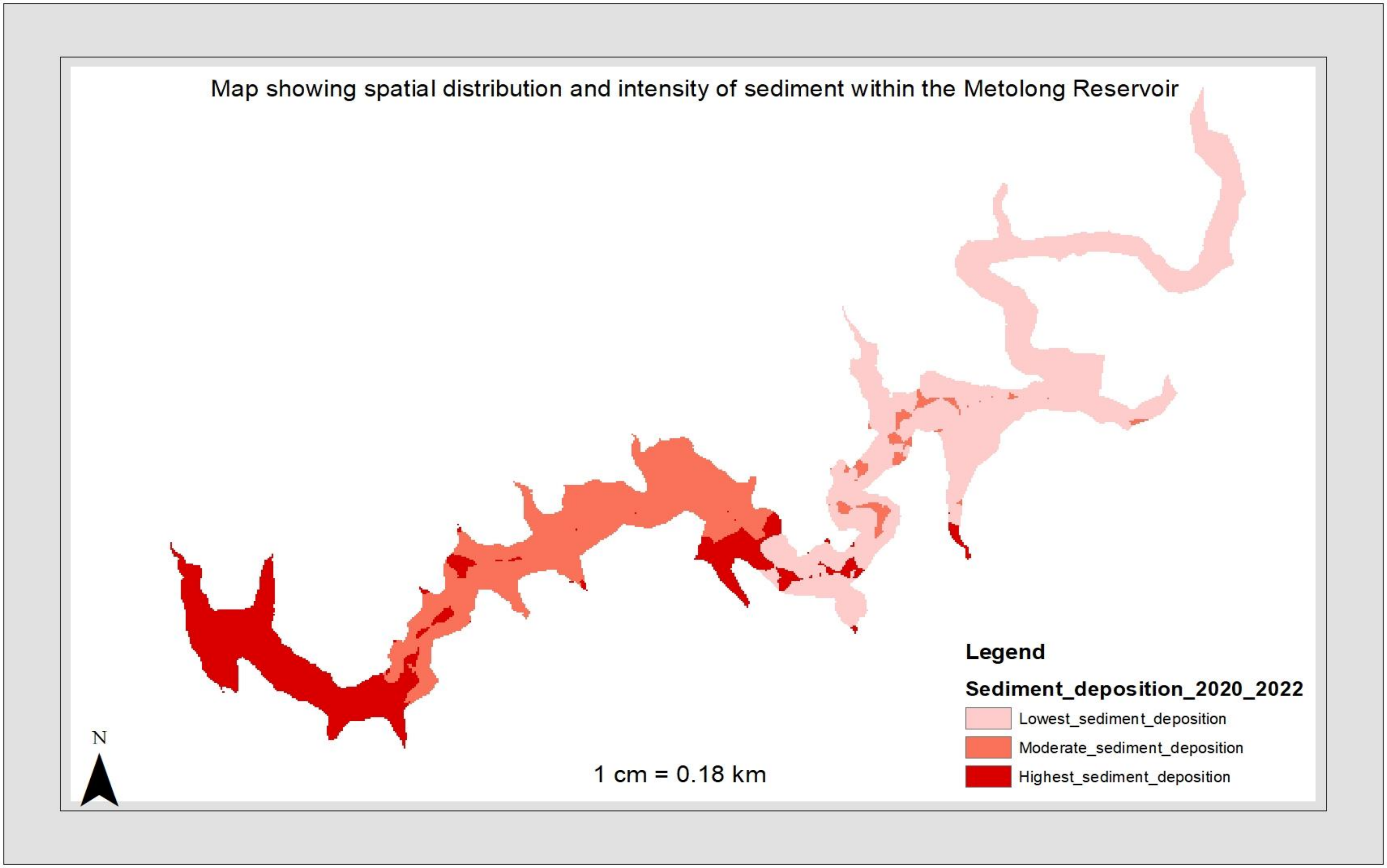


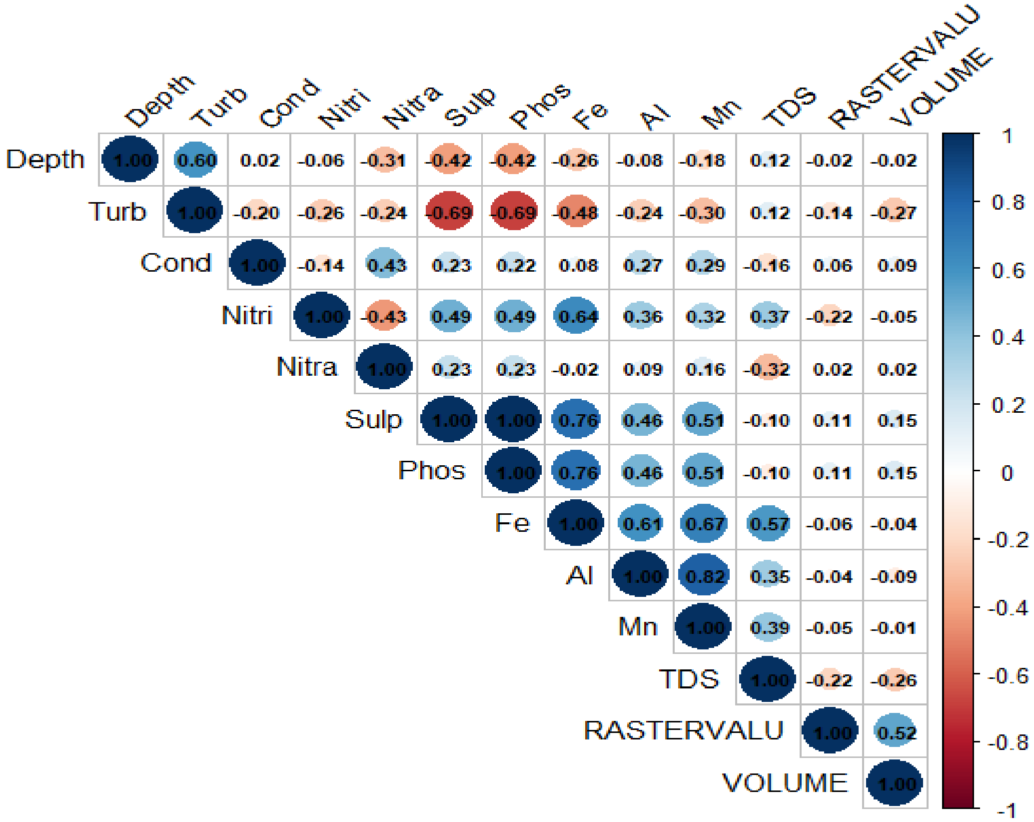
Figure 10: Spatial sediment distribution changes in 2020–2022: UTM Zone 35S, WGS8

Table 6: Statistics of sediment volume gained (m^3) from 2020 to 2022

Parameter	**Value**
Count of sediment zones within reservoir	178
Minimum sediment volume	1
Maximum sediment volume	178
Sum of accumulated sediment	1,705,583
Mean sediment volume	58.12572
Standard deviation	43.152292

The Metolong Reservoir can be categorized into 178 sediment zones, ranging from 1 to 178 m^3, summing up to the sediment volume of 1,705,583 m^3, equivalent to 1, 705, 583,000 litres (1.705583 billion litres) of sediment accumulated from 2020 to 2022. The average sediment volume by zones is around 58.13 m^3, a value larger than the standard deviation of 43 $m^{3,}$ indicating that there is significant variation in sediment volumes across different zones, as depicted in Figure 10.

4.2 The Relationship between Sedimentation and Water Quality



	Depth	Turb	Cond	Nitri	Nitra	Sulp	Phos	Fe	Al	Mn	TDS	RASTERVALU	VOLUME
Depth	1.00	0.60	0.02	-0.06	-0.31	-0.42	-0.42	-0.26	-0.08	-0.18	0.12	-0.02	-0.02
Turb		1.00	-0.20	-0.26	-0.24	-0.69	-0.69	-0.48	-0.24	-0.30	0.12	-0.14	-0.27
Cond			1.00	-0.14	0.43	0.23	0.22	0.08	0.27	0.29	-0.16	0.06	0.09
Nitri				1.00	-0.43	0.49	0.49	0.64	0.36	0.32	0.37	-0.22	-0.05
Nitra					1.00	0.23	0.23	-0.02	0.09	0.16	-0.32	0.02	0.02
Sulp						1.00	1.00	0.76	0.46	0.51	-0.10	0.11	0.15
Phos							1.00	0.76	0.46	0.51	-0.10	0.11	0.15
Fe								1.00	0.61	0.67	0.57	-0.06	-0.04
Al									1.00	0.82	0.35	-0.04	-0.09
Mn										1.00	0.39	-0.05	-0.01
TDS											1.00	-0.22	-0.26
RASTERVALU												1.00	0.52
VOLUME													1.00

Figure 11: Matrix showing strength and direction of correlation water quality parameters with depth and sediment volume

The correlation matrix displays Pearson correlation coefficients (r) which show the strength and direction of linear relationships between key water quality parameters and sediment volume and sampling depth ranging from –1 to +1. Values close to +1 indicate strong positive correlations (parameters increase together), and values close to −1 indicate strong negative correlations (one decreases as the other increases). Colour intensity represents the strength and direction of the correlations. Conductivity, turbidity and TDS indicate their association with increasing sediment volume with turbidity showing the strongest relationship. Iron, manganese, aluminum, nitrites, nitrates and sulphates show weak correlations with sampling depth and sediment volume.

Scatter plots (Figure 12) show that nitrates and sulphates increase with increasing sediment volume while conductivity decreases. TDS, conductivity and turbidity all increase down the reservoir.

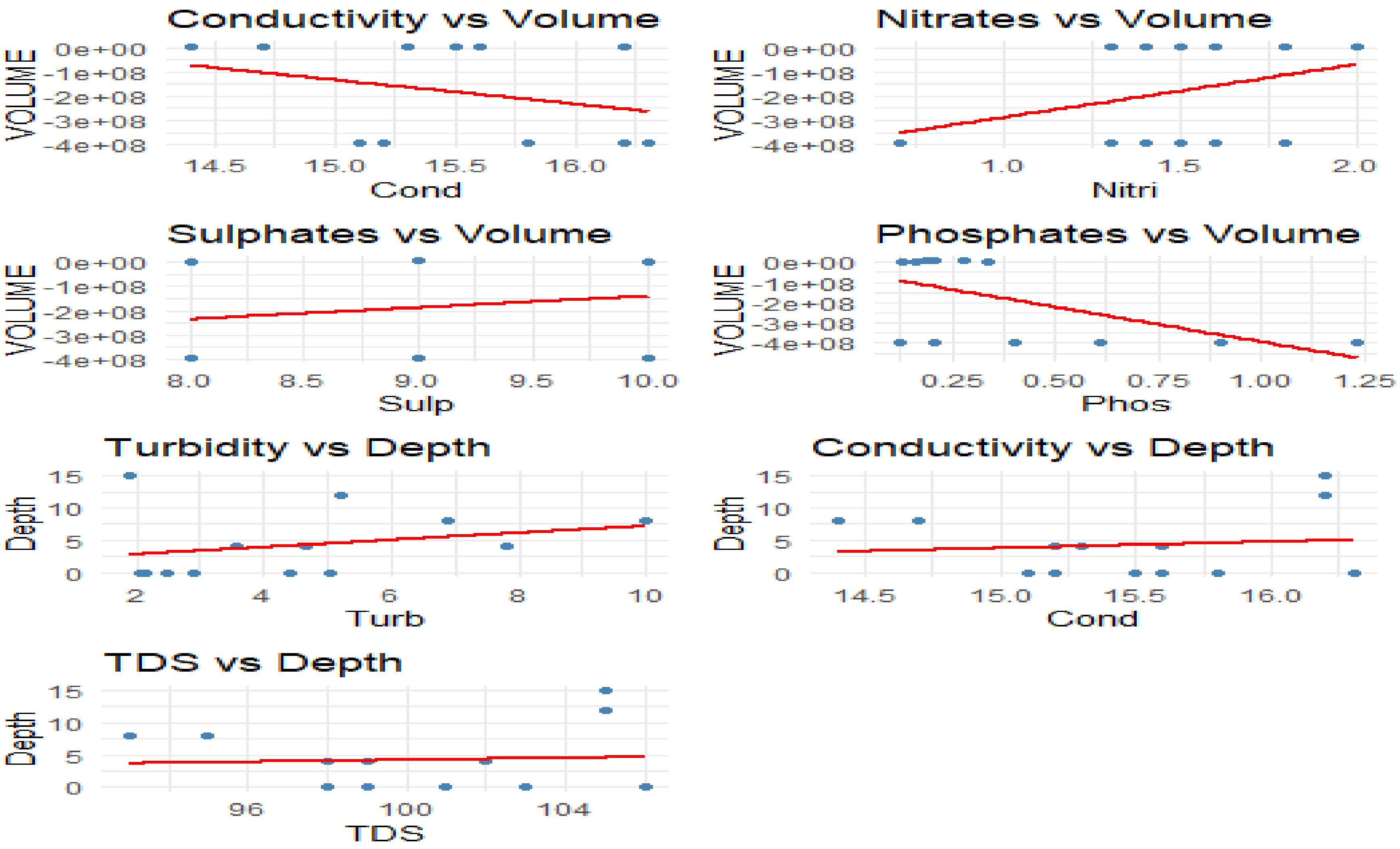


Figure 12: Water quality parameters that show positive correlation with depth and sediment volume

Table 7: Domestic and industrial implications of water parameters

Parameter	**Mean 2020**	**Mean 2022**	**Drinking Water Threshold**		**Industrial SA Standards**	**Status**
			SA	**WHO**		
Conductivity (mS/m)	14.4	15.43	<170	NA	Varies with process requirements	Safe
Sulphates (mg/L)	9.64	9.42	<250	500	Varies with process requirements	Safe
Phosphates (mg/L)	0.42	0.28	NA	NA	Varies with process requirements	Safe
TDS (mg/L)	93.57	100.15	1200	1000	<2000	Safe
Nitrates (mg/L)		22.72	50	50	50	Safe
Turbidity (NTU)	15.24	11.88	<100	1–5	<1000	Safe

Water quality parameters affected by sedimentation are within safe limits for both drinking and industrial use according to WHO and SA water quality standards.

Table 8: Linear regression analysis results

Parameter	Depth P value	Sediment Volume P value
Turbidity	7.86e–06 ***	0.0481 *
Conductivity	0.5539	0.9157
Nitrites	0.8496	0.4241
Nitrates	0.0277*	0.1804
Sulphates	0.7949	0.3530
Phosphates	0.9880	0.6557
Iron	0.8633	0.9607
Aluminum	0.7861	0.4822
TDS	0.8634	0.9619

Significance codes: *** = highly significant, *less significant,

Table 9: Model statistics for analysis

Model Statistics	Value
Sample size (n)	88
R^2	0.445
Adjusted R^2	0.381
Standard error of residuals (SE)	5.882
F–statistics (df)	F (9,78) = 6.953
Model p–value	2.69×10^{-7}

Nitrates and turbidity show a significant positive relationship with depth, while turbidity shows significant relationship with both depth and sediment volume, the relationship with depth the most significant. Nitrites, sulphates, phosphates, conductivity, iron, aluminum and TDS show no significance ($p > 0.05$).

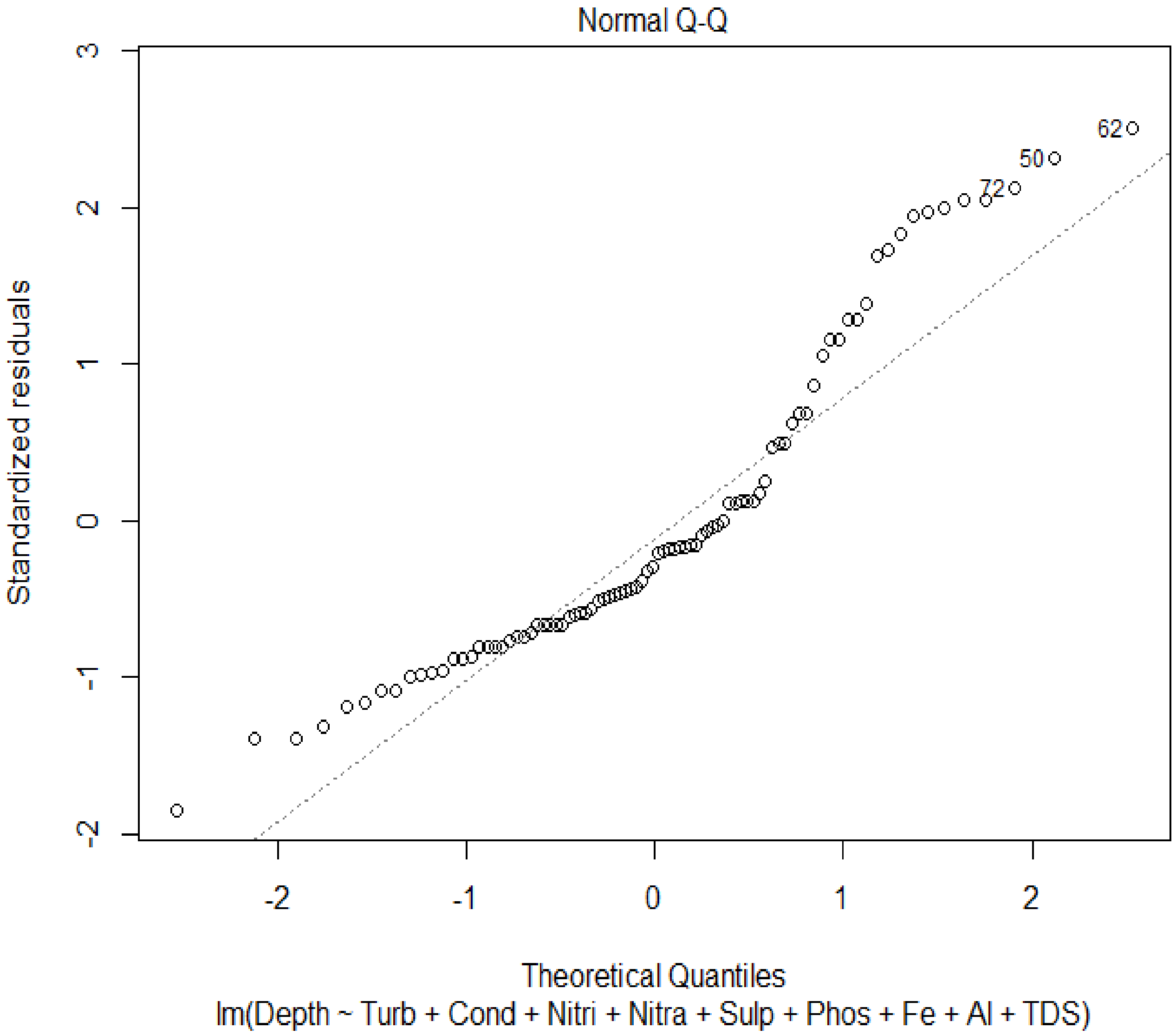


Figure 13: The distribution of residuals from a regression model with the expected normal distribution.

Figure 13 shows the relationship between water quality parameters and sediment depth in the Metolong Reservoir (n = 88). The fitted regression line (shows a strong positive relationship between turbidity and sediment depth ($r = 0.67$, $R^2 = 0.45$, $p < 0.001$). Normality of residuals was verified using the Shapiro–Wilk test ($p = 0.21$) and visual inspection of Q–Q plots showing points scattered along the straight line show normal residuals, with few outliers. All variables met normality assumptions, allowing the use of Pearson's correlation coefficients. Positive and negative values indicate the strength and direction of the associations between variables confirming that residuals were approximately normally distributed; hence, a parametric Pearson correlation and linear regression were appropriate. The trend demonstrates that turbidity increases with higher sediment volumes.

CHAPTER FIVE

DISCUSSION

The bathymetric analysis indicate that the volume of the sediment accumulated in 2 years (2020–2022) in the Metolong Reservoir is approximately 1,705,583 m^3 (Table 6), resulting in around 2.68% storage loss. This is largely driven by severe erosion and sediment transport upstream due to steep topography, seasonal runoff, overgrazing, extractive processes such as sand and quarry mining, poor land use and management practices. This aligns with Kidane and Alemu (2015) who identified land–use pressure and upstream erosion as drivers of increased sedimentation near dams and Yimer (2016) who linked land pressure to accelerated sedimentation deteriorating water quality downstream. The degraded rangelands covering over 25 000 ha together with poorly managed croplands further expose the soil to erosion, allowing nutrient–rich materials to be transported into the Reservoir. Thus posing a decline in water quality and health risks to the people and animals downstream (Haque, 2024). Hoaq (2017), similarly stated that the degraded rangelands in Lesotho increase runoff velocity and erosion, contributing sediment and organic matter to reservoirs.

This findings of the study align with those of Ayalew (2021); Water (2021); Tesfaye *et al*. (2020); Tundu *et al.* (2017) and Ndehedehe *et al. (*2016) who observed rapid sediment deposition in small African reservoirs under similar land pressures which also led to a decline in water quality. The spatial distribution of sedimentation within the reservoir in Figure 10 indicates high sediment accumulation areas near the dam where water is drawn for distribution in alignment with Kamtukule (2008); Gijsbertsen (2007). This leads to infrastructure challenges, increased water treatment and purification costs to WASCO which may result in increased water tariffs as well as potential health risks as found also by Amasi *et al*. (2021)

Figure 11 indicates that turbidity has a strong positive correlation with depth , aligning with Gwari and Ugoala (2009a).This also indicates strong correlation with nitrates, sulphates, phosphates, aluminum, manganese and iron due to absorption or settling within sediments or reduction in biological activity in deeper layers. This aligns with Estigoni et al. (2017) who reported that sedimentation might enhance downstream water quality by absorbing nutrients into the sediment particles as a result of disturbed bottom sediments or the accumulated particulate matter (Woldeab *et al.,* (2023). Conductivity, TDS, nitrites and aluminum show a weak correlation implying that influences are not directly tied to sediment layers.

Nitrates and conductivity indicate little relationship with sediment volume as well as phosphates and sulphates showing similar trend. The findings imply that the accumulated sediments could be acting as secondary sources, which slowly release these ions into the water column as suggested by Li *et al.* (2024). Other parameters showed an inverse relationship which could be due to compacted or stable sediments that minimize the resuspension of particles. Additionally, sedimentation may sequester dissolved solids and certain metals, especially iron, through adsorption or entrapment (Estigoni *et al.*, 2017).

The correlation matrix (Figure 11) supports the alternative hypothesis that sedimentation negatively affects water quality in the Metolong Reservoir. Turbidity, acting as an indicator for sedimentation (US EPA, 2020; Tundu *et al*., 2017), shows strong positive correlations with manganese in alignment with Ndungu *et al.* (2013) suggesting that higher sediment levels are associated with increased metal concentrations in the water and concluding that sediments can bind with heavy metals leading to water quality deterioration. These metals tend to adhere to particulates and are released into the water column during resuspension or inflow events.

Turbidity presents a strong negative correlation with depth, indicating that sediment buildup and resuspension are more acute in shallower areas. Turbidity also has a negative correlation with TDS, showing an inverse relationship between suspended and dissolved fractions, likely due to the binding effects of sediments.

TDS, another indicator related to sediment (US EPA, 2020; Tundu *et al*., 2017) positively correlates with several variables such as conductivity, iron, and aluminum. TDS sediment correlations align with Chabokpour, (2025); Heidarzadeh and Nejad, 2017). These correlations reinforce the notion that the dissolved elements of sediments, potentially from mineral dissolution, impact the ionic composition of the reservoir. These trends strongly advocate for the alternative hypothesis, suggesting that sedimentation through both particulate (turbidity) and dissolved (TDS) forms considerably deteriorates water quality in the Metolong Reservoir. As a result, the null hypothesis is rejected in favor of the alternative hypothesis. Markad *et al*. (2023) also found strong positive correlations between turbidity and heavy metals like iron and manganese; and inverse relationships between turbidity and depth.

Nitrates and turbidity display significant positive correlation with sediment volume as shown in Table 8, highlighting their importance as indicators of sedimentation. This finding is consistent with correlation analysis results and validates the alternative hypothesis (H_1). Nitrites show no significance with sediment volume, implying that higher levels of sedimentation may lower their availability, potentially due to adsorption onto sediment particles or diminished nitrification rates in turbid conditions.

With the GIS– based sediment mapping, the study contributes to global efforts as it aligns with Sustainable Development Goal six (SDG 6) on clean water and sanitation. The findings of the study align with studies of similar nature indicating some level of accuracy on the data, however some discrepancies were noted which might have affected some outcomes.

The study compares sediment accumulation (measured during the dry season via bathymetric surveys) with water quality (monitored mainly in the wet season). This timing mismatch introduces seasonal bias: wet–season data emphasize high inflows, turbidity, and contamination, whereas dry–season conditions reflect clearer water and lower sediment inputs. Sediment estimates represent long–term net deposition, while water quality highlights short–term wet–season dynamics. The contrast underscores the need to synchronize sediment and water quality monitoring across both seasons to capture intra–annual variability more accurately.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

The findings of the study highlight that within 2 years, sediment accumulation in the Metolong Reservoir is estimated to be 1,705,583 m^3, approximating the sediment deposition rate of 852 791.50m^3 per year and a storage loss of around 1.34% annually reflecting poor land management practices upstream.

The depth–sediment–water quality correlation findings indicate that sedimentation has a significant indirect effect on the chemical and physical properties of the Metolong Reservoir particularly turbidity and TDS which are key indicators of water quality. Nitrates and phosphates exhibit varied and weaker reactions, suggesting influences beyond sedimentation such as runoff and other inflows, biological processes or agricultural activities. This suggests that water quality in the Metolong Reservoir is governed by a complex interplay of factors highlighting the need for integrated catchment management.

The overall findings address the research objectives by reinforcing the rejection of the null hypothesis (H_0) and validating that sedimentation considerably affects water quality, through turbidity and nitrate channels.

The unexpected results for some parameters, possibly due to secondary water quality data with varying depth levels, sampling periods and missing data reveal limitations and emphasize the need for more consistent and comprehensive data collection in future studies.

6.2 Recommendations

- It is highly recommended that sustainable sediment control and catchment management interventions such as check dams be implemented from upstream to downstream to remedy the fast filling deposition of the reservoir, which threatens the reservoirs’ lifespan, health and lives of humans and other ecosystems due to declining water quality.

- The sustainable land management initiatives such as increasing vegetation cover through rotational grazing of rangelands, no or less tillage agriculture and sediment trapping mechanisms are highly recommended.
- Public education on environmental issues such as over fertilization is ideal to sensitize communities on how their activities are adversely affecting their environment, economy and health.
- Relevant stakeholders responsible for sustainable land and water management issue like local communities, local authorities, public and private sector and other non–governmental bodies should invest and explore sediment control mechanisms such as installation of check dams and revegetating the land base upstream and around the tributaries within the sub–catchment to trap sediments and reduce their transport into the reservoir.
- The sampling depths, interval and parameters must be consistent to avoid any discrepancies while analyzing data for more accurate results.

For future research, there is a need for studies on the effects of sedimentation on riparian plants and soil of the downstream environment.

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APPENDICES

Appendix 1:

Raw water quality data

Wasco water quality
data for analysis.xlsx

Appendix 2:

Water quality data completeness matrix

completeness data
matrix.xlsx

Appendix 3:

2020 Metolong bathymetric raw data (Source: LHDA)

2020Metolong.xlsx

Appendix 4:

2022 bathymetric raw data (Source: LHDA)

2022Metolong.xlsx

Appendix 5:

R script used in analysis

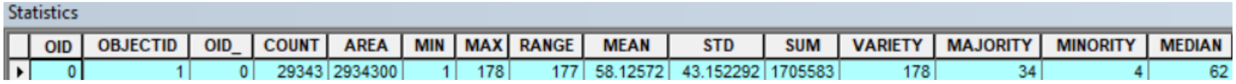
R script.docx

Appendix 6:

Steps to calculating accumulated sediment volume in Arcmap 10.8 and statistics table from Arcmap 10.8:

- Ensure Cut/Fill raster values are in meters and the raster is projected in meters

- Record pixel size (CellSizeX, CellSizeY) → compute CellArea (m2) = CellSizeX * CellSizeY.
- Create deposition–only raster: Deposition elevation (m) = Con ("CutFillRaster" > 0, "CutFillRaster", 0).
- Convert to per cell volume: DepVolume (m3) = Deposition_m * CellArea_m2.
- Sum all cells using Zonal Statistics as Table. Read SUM → Total Volume (m3).



Statistics

OID	OBJECTID	OID_	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	SUM	VARIETY	MAJORITY	MINORITY	MEDIAN
0	1	0	29343	2934300	1	178	177	58.12572	43.152292	1705583	178	34	4	62