

**MORPHOLOGICAL VARIATIONS OF THE NZHELELE RIVER BETWEEN 2000 -
2020 USING MULTI-TEMPORAL LANDSAT DATA**

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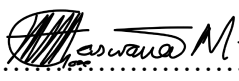
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Declaration

I, **MABOSHE PHASWANA**, hereby declare that the proposal for the Master of Sciences in Geography degree at the University of the Free State, hereby submitted by me, has not been submitted previously for a degree at this or any other university, that it is my own work in design and execution, and that all reference material contained therein has been duly acknowledged.

Signature.....

Date 26 February 2024.....

Abstract

River morphology gives a detailed account of the dynamics of river channel structures and direction over a period of time. Both natural and anthropogenic processes can be responsible for a river's morphological changes over a range of temporal and spatial measures. Erosion, accretion and lateral migration is evident within the Nzhelele River, a perennial river in the Limpopo Province of South Africa. However, little is known about the relationship between natural and anthropogenic processes on the Nzhelele River's channel morphology. The geomorphology, hydrology and anthropogenic activities affect river systems such as sediment load and the morphology. The geomorphic and anthropogenic impacts on the Nzhelele River were investigated between 2000 and 2020. ArcGIS 10.5 software, multi-temporal Landsat images were used to assess the evolution of Nzhelele River by determining erosion, accretion and lateral channel migration. In order to identify the controls on the changes of the river's morphology, sinuosity index, land-use and land-cover data, derived from the classified Landsat images were used. Lastly, the continued evolution of Nzhelele River morphology is forecasted using time series modelling in GIS. The overall average kappa statistics for the classified Landsat images were 0.60 for 2000, 0.58 for 2005, 0.58 for 2010, 0.64 for 2015 and 0.61 for 2020 study period. An overall total of 9.41 km³ river bank substance was eroded and a total of 7.98 km³ deposited on the right bank. A total of 8.8 km³ of river bank substance was eroded on the left bank of the river with 8.29 km³ being accreted on the left bank. The Nzhelele Dam construction, illegal sand mining, agriculture, and residential expansion were found to have significant impacts on the channel morphology. Sinuosity index varied from 1.57 in 2000 to 1.62 in 2020. Erosion on the left bank was forecasted to be 1.62 km³ and 1.90 km³ on the right bank, accretion on the left bank was forecasted to be 0.88 km³ and 1.23 km³ on the right bank for the year 2020 – 2025. The study showed a significant variation in the evolution of the Nzhelele River morphology and channel adjustment over time due to variations in sediments caused by erosion and accretion, channel sinuosity and a deterioration in river conditions from 2000 to 2020.

Key words: Nzhelele River, Erosion, Accretion, Sinuosity index, Time series analysis, Limpopo Province, South Africa.

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List of acronyms

<u>Acronym</u>	<u>Full name</u>
AR:	Autoregressive
ARIMA:	Autoregressive Integrated Moving Average
ANFIS:	Adaptive Neuro-Fuzzy Inference system
ANN:	Artificial Neural Network
ARMA:	Autoregressive Moving Average
CMT:	Channel Migration Toolbox
DN:	Digital Numbers
ECI:	Ecological Condition Index
ETM+:	Enhanced Thematic Mapper
GIS:	Geographic Information Systems
LULC:	Land-Use and Land-Cover
MSL:	Mean Sea Level
MNDWI:	Modified Normalized Difference Water Index
MA:	Moving Average
MSS:	Multi Spectral Scanner
NDWI:	Normalised Difference Water Index
OLI/TIRS:	Operational Land Imager and Thermal Infrared Sensor
SMZ:	Southern Marginal Zone
TM:	Thematic Mapper
TS:	Time Series
USGS:	United States Geological Survey

1 INTRODUCTION

The background, motivation and the primary aspects of the research are in this chapter. The background and overview of river morphology is broadly analysed. Past and present river morphological conditions are investigated. The primary conditions of river morphology are incorporated in the background, hence, the basic parts that caused the river morphology being the primary concern. These facilitated understanding the requirement for river morphological issues and mitigation inventions.

River systems that play a significant role in the water cycle for sustaining day-to-day human life. Freshwater form river systems and other water bodies such as lakes, estuaries, floodplains, amongst others, is a limited resource and only exist in less than 1% on the surface of the earth. River systems only account for 0.006% of the total accumulation of freshwater (Dudgeon et al., 2006; King and Brown, 2021). The African continent accommodates numerous distinguished rivers and 55 of these rivers are recognized as international rivers. These rivers contribute significantly socially, economically and environmentally through domestic, agricultural and industrial uses. Furthermore, freshwater biodiversity and environmental systems are sustained by these rivers by providing habitats for various wildlife, birds and species of endemic fish (Sadoff et al., 2002).

The limited freshwater resource is faced with challenges from the accelerating population growth, putting a significant strain on the river systems to supply the demand of the growing population in many African countries (Revenga et al., 2005). This is because the volume of freshwater on earth is 2.5%, and an average of 10% – 20% of total freshwater is used in urban areas in developing countries (Okello et al., 2015). The Intertropical Convergence Zone (ITCZ) has a significant impact on climate change in Africa, thus, determining precipitation that contributes to the extensive imbalance of inter-seasonal and interannual difference in the flow of rivers in Africa. Additionally, drought caused extreme shortage of food in eastern and southern Africa in the past decades (Sadoff et al., 2002). Drought significantly contributes to change in human and livestock interaction with the river systems (Sadoff et al., 2002). Furthermore, this has put enormous pressure on the fragile environments, resulting in the deterioration of river systems and land, significantly impacting the livelihoods of African communities (Sadoff et al., 2002; Revenga et al., 2005; Dudgeon et al., 2006).

River systems across the globe are significantly impacted by anthropogenic and natural activities. Human-induced soil erosion has caused the accumulation of sediments in river systems and as a result this caused the development of colluvial deposits. Additionally, land use and land cover change such as agriculture, urbanization and infrastructure development, amongst others, accelerated soil erosion, sediment accumulation, water runoff and peak water discharge due to the inability of water to penetrate the ground (Hoffmann et al., 2010; Ibisate et al., 2011; Maab et al., 2021). Moreover, anthropogenic activities such as urbanization, mining, commercial and subsistence farming resulted in significant deforestation. Deforested lands promoted sediment transportation to the river channels during heavy rainfall (Klimek and Latocha, 2007).

The modification of river basins caused by the construction of dams has resulted in the alteration of water discharge, sedimentation, instability of river channels, the seasonality of flood, sand mining, land use and land cover change, consequently impacting river channel morphology (e.g., Mahe et al., 2013; Ibitoye et al., 2016). Moreover, land use and land cover change exacerbate soil erosion and gully development to the river channels. Increased urbanization poses high risk of persistent and extreme floods in rivers, thus altering the rate of erosion and deposition of sediments (Mahe et al., 2013).

The application of Geographic Information Systems (GIS) and remotely sensed (RS) aerial photography and satellite images has facilitated scientific research worldwide to develop various techniques to monitor and evaluate the impacts of natural and anthropogenic activities on river systems morphology on various time periods (Lovric and Totic, 2016; Li, et al., 2021). Furthermore, ecologists and environmentalists utilize GIS and RS technology to monitor river morphological changes over time under various natural and anthropogenic processes, collect river morphological data such as erosion, accretion, lateral channel migration, and forecast river morphology into the future. Additionally, GIS and RS provides a distinctive interpretation of the development of river morphology through the use of multi-temporal analysis of remotely sensed satellite images. Remotely sensed images and GIS technology provide the methodologies to distinguish how river morphology changes under various natural and anthropogenic activities (Lovric and Totic, 2016; Masocha, et al., 2017; Ibitoye, 2021; Li, et al., 2021).

River morphology focusses on the relationship between the movement of waters in rivers and their environment. It gives a detailed account of the dynamics of river channel structures and direction over a period of time (Wang, et al., 2020). Natural conditions such as river flow condition that incorporates velocity and viscosity, riverbed condition that incorporates the slope, structure, roughness, and the composition of sediments, and boundary conditions that incorporates the width and depth of water, are principal in river channel morphological evolution (Church, 2002; Gupta and Liew, 2007; Wang, et al., 2020). Rivers have distinct attributes; their morphological differences are attributed to hydrological conditions, sediments properties, and historical geomorphological processes (Masocha, et al., 2017). However, natural and anthropogenic activities promote rapid changes on river channel morphology (Masocha, et al., 2017; Ibitoye, 2021).

South Africa is characterized by a semi-arid climate, having the average annual rainfall of 465 mm. droughts are usual and are frequently accompanied by disastrous flood events. The flow of rivers in South Africa is extremely fluctuating between seasons and years. The rivers in the eastern part of the country are perennial while rivers in the western region rarely flow or are ephemeral (Nel and Driver, 2012). Most large rivers are impounded by large dams for water supply as a result of high-water demand that exceed the availability of water. Natural and anthropogenic activities in South Africa are extremely impacting the natural condition and the functioning of river systems. Furthermore, 50% of the river ecosystems are declared threatened (Nel and Driver, 2012; Nel and Driver, 2015).

The South African National Water Act (Act 36 of 1998) necessitates the establishment of an ongoing, equitable stability between regulators' use and conservation of water resources. Additionally, the Act ensures that water resources are utilized, managed and conserved. The health of rivers in South Africa have drastically declined as indicated by the Ecological Condition Index (ECI). The ECI shows a general decrease from 83 in 1999 to 72 in 2011(Nel and Driver, 2015). There has been an extensive modification of instream and riparian habitat, as well as flow and quality of water of South African rivers between 1999 and 2011. Furthermore, the health of rivers (21%) in Limpopo province experienced substantial decline as a result of increased anthropogenic activities, with the decline of ECI from 83 to 62 between 1999 and 2011 (Department of Water Affairs, 1998; Gildenhuys, 1998; Nel and Driver, 2015).

Nzhelele River is a significant meandering river channel situated in the Limpopo Province of South Africa with a catchment area of 2436 km³ (Amponsah- Dacosta and Mathada, 2017). The river supports various anthropogenic activities such as agriculture, residential and commercial infrastructural developments, and sand mining. Natural activities include extreme drought and flood events (Makungo et al., 2010; Amponsah- Dacosta and Mathada, 2017). Figure 1.1 shows the map of Nzhelele River. Over the years the environmental and ecological condition of the Nzhelele River has been of significant concern. The Nzhelele River contributes to the biodiversity, agriculture, economy and the livelihood of the surrounding communities (Amponsah- Dacosta and Mathada 2017). Furthermore, the Nzhelele River channel has been extremely impacted by anthropogenic activities which resulted in floodplain degradation, riparian zone damage, erosion, and sedimentation (Kori and Mathada, 2012). The Nzhelele River channel morphological analysis is required to promote river ecosystem planning and management, disaster reduction and morphology prediction for sustainable development of the river. It is the intention of this study to assess the Nzhelele River channel morphology from 2000 to 2020, thus, assessing the anthropogenic impacts in the Nzhelele River basin.

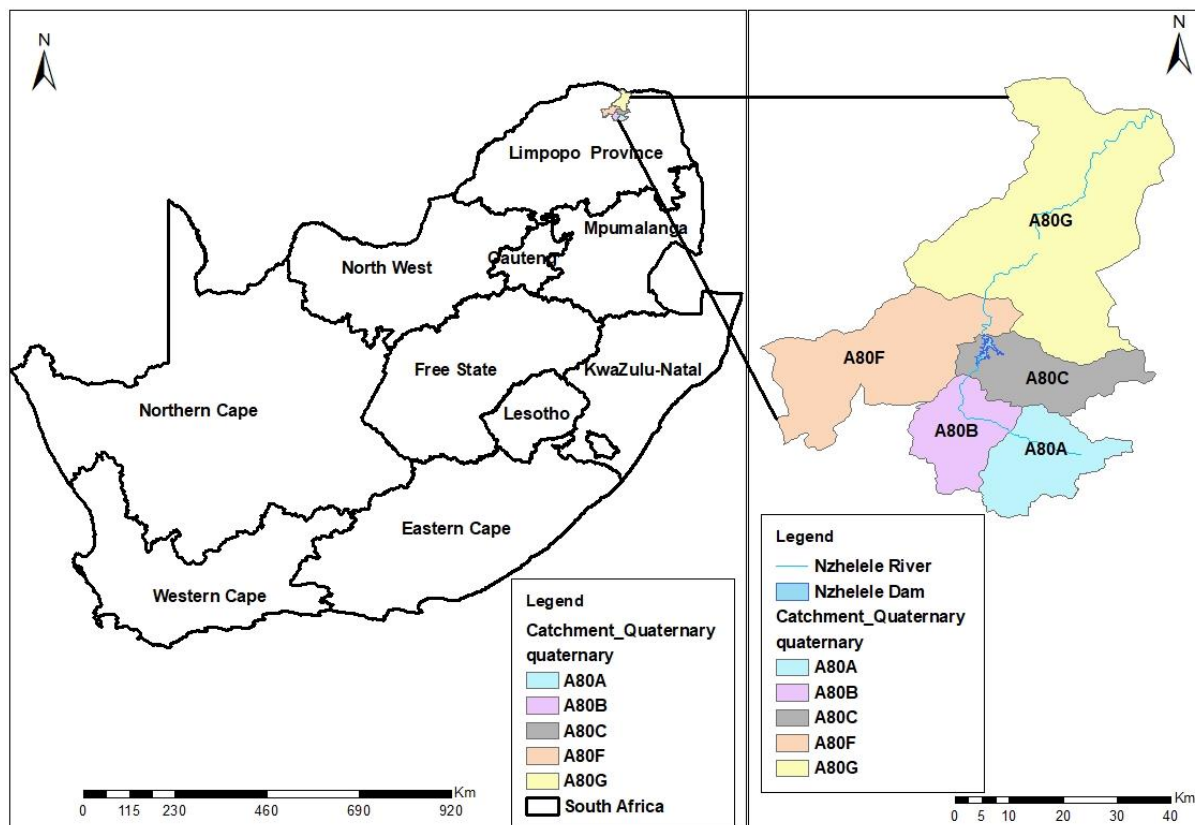


Figure 1.1: The location of the Nzhelele River near Biaba within the Limpopo Province, South Africa.

1.1 Problem statement

The Nzhelele River (22°21'08" S and 30°22'19" E) is a meandering river that covers a catchment area of 2436 km³ in Limpopo Province of South Africa (Kori and Mathada, 2012; Amponsah- Dacosta and Mathada, 2017). The rivers such as the Mufungudi, Wyllie, Tshiruru, and Mutamba are the tributaries to the Nzhelele River (Gondo et al., 2019). The river catchment is dominated by irrigation and it is characterized by a mean annual precipitation of 422 mm and evaporation of 2160 mm (Edokpayi et al., 2018). The Nzhelele River region is semi-arid and it is attributed to seasonal rainfall (Edokpayi et al., 2018). The Nzhelele River contribute to the livelihood of the surrounding communities. Additionally, it is rich in biodiversity that incorporates various large mammals including giraffes, and wildebeests. Moreover, the river plays a significant role to the water supply and agriculture in the surrounding communities during wet and dry seasons.

Several authors have shown that sand mining is the predominant anthropogenic activity with extensive impacts on the Nzhelele River channel (Kori and Mathada, 2012; Amponsah- Dacosta and Mathada, 2017; Gondo et al., 2019; Sengani and Zvarivadza, 2019). The mining of sand instream and on the floodplain of the Nzhelele River is prevalent in the eastern part of the river channel as a result of reduced water flow. The increased activities of sand mining have impacted the river channel due to the degradation of floodplain, riparian zones and the collapsing of riverbanks. Additionally, the collapsing of the Nzhelele riverbanks has caused the river channel to widen, thus, contributing to the reduction of the channel depth, and increase in sediment load. Furthermore, the ecological functioning of the Nzhelele River channel has been disrupted by sand mining activities (Kori and Mathada, 2012). Floodplains are a significant and productive ecosystem that contribute to the biological, geomorphic and hydrological functions. Floodplains control water supply, disruption caused by flood attenuation, and the treatment of waste and they are extremely of great value globally (Rajib et al., 2021).

Anthropogenic activities are present at the Nzhelele River basin, however, the extent to which they shape the Nzhelele River morphology over the years and their long-term effects are scientifically not known. River channel morphology studies have drawn much interest from international scientific researchers (Dong, 2003; Bhuiyan, et al., 2015; Ibitoye, et al., 2016; Li, et al., 2022). Several studies exist in the scientific literature about the impacts of sand mining

on the Nzhelele river (Kori and Mathada, 2012; Amponsah- Dacosta and Mathada, 2017; Gondo et al., 2019; Sengani and Zvarivadza, 2019). However, there is lack of coordination of the morphological attributes of the Nzhelele River.

This study assessed the spatio-temporal variation of Nzhelele River morphology from 2000 to 2020 using GIS and remote sensing techniques. The study assessed the selected geomorphological attributes such as river bank erosion, river bank accretion as well as river lateral migration as they contribute to river morphology (Lovric, and Tosic, 2016; Li, et al., 2021). Further, this study determined the relationship between geomorphic and anthropogenic activities, and assessed their impacts on Nzhelele River channel morphology from 2000 to 2020 as a result of the increased anthropogenic activities in river basins using GIS and remote sensing.

1.2 Research aim and objectives

1.2.1 Aim of the study

To investigate the morphological variation of the Nzhelele River, Limpopo Province, South Africa, for time periods between 2000 and 2020.

1.2.2 Objectives

- To assess the spatio-temporal variation of Nzhelele River morphology
- To assess the potential impacts of geomorphic and anthropogenic activities on channel morphology.
- To forecast the spatio-temporal evolution of Nzhelele River channel morphology using GIS and time series modelling five years into the future.

1.3 Research questions

- What is the spatio-temporal variation of Nzhelele River morphology?
- What are the geomorphic and anthropogenic activities that can potentially impact the channel morphology?
- How will the channel morphology change in the next five years?

1.4 Justification and significance of the study

It is forecasted that 40% of population in the world will use water from deteriorated rivers catchments by the year 2050 (Wang et al., 2017) . At a global scale, the land use and land cover around rivers has significantly changed as a result of anthropogenic activities that has severely impacted the ecology and planform of rivers. Furthermore, the anthropogenic impacts on river morphology incorporates runoff and water availability, water accumulation, water discharge, morphology and structure and river impoundment by dams (Wang et al., 2017; Yousefi et al., 2018; Kang and Kanniah, 2022).

Natural and anthropogenic activities are demonstrated by recent scientific literature to be the major causes of changes in river morphology (Edokpayi et al., 2018; Gondo et al., 2019; Mokgoebo, 2019; Sengani and Zvarivadza, 2019). The Nzhelele River channel in the Limpopo Province is located in a semi-arid environment and it contributes to local water supply for the surrounding communities. Droughts, floods, dam construction, land use and land cover change surrounding the river channel has impacted the naturalness of the Nzhelele River, consequently, impacting the morphology of the river. The Nzhelele River channel in recent years, is the most sought-after study area for scientific research from a number researcher from various disciplines relating to hydrology, ecology, geography and micro biology studies amongst others, including sand mining, rainfall–runoff modelling, water quality, microbiological and physicochemical evaluations (Makungo et al., 2010; Kori and Mathada, 2012; Amponsah-Dacosta and Mathada 2017; Edokpayi et al., 2018; Gondo et al., 2019; Mokgoebo, 2019; Sengani and Zvarivadza, 2019).

2 LITERATURE REVIEW

This chapter reviews already published literature on river morphology. It is led by the discussion of the literature and theory on river morphology and dynamics, followed by the methodologies of assessing and monitoring river morphology. The application of GIS and RS methods that are employed to assess river channel morphology from regional to global scale were reviewed in this chapter. Additionally, it also includes a discussion on the natural river morphology. Lastly, a discussion on natural and anthropogenic impacts on river channel morphology is also included in this chapter. Various literature on river channel morphology, anthropogenic impact on river morphology and the forecasting of river channel morphology was reviewed in this chapter, thus, providing various techniques on the subject matter. The degradation of river channel is a worldwide issue that has brought about numerous research studies. This chapter establishes previously employed methodologies of river channel morphology assessment, mapping and forecast adopted by other researchers. It also highlights the problems that exist within the study of river channel morphology assessment, mapping and forecasting.

2.1 Theory on river morphology and dynamics

There are two schools of thought, one empirical and the other theoretical. They have evolved theories that are suitable for predicting river channel behavior (Simons, 1957). Theoretical models for river morphology and river evolution are discussed below:

2.1.1 Theory of nonlinear dynamic process

The theory of nonlinear dynamic process is derived from nonlinear mathematical theory. It incorporates the river bedform and the evolution of river morphology including periodic change of wandering river, dynamic stability of a river and the consequences associated with riverbed development (Bai and Wang, 2014). The evolution of river morphology is investigated through the dynamic process of nonlinear theory for the rivers that are exposed to natural and anthropogenic disruption, on condition that the disruption and the reaction of the river will diminish to zero, the restoration of a river to its new balanced condition can be achieved, thus, there is stability in the dynamic process of a river. Several methodologies of the nonlinear mathematical theory have been employed in river micro-dynamic process with respect to the

nonlinear attributes in the river dynamic process (Bai et al., 2008; Xu et al., 2011; Bai and Wang, 2014).

Issues that are associated with the stability of engineering, investigation of bifurcation functioning, and engineering structure that is characterized by disorganized processes post modification of several variables have been examined using the nonlinear theory (Wang et al., 2014). A sequence of river problems including principles that controls the response of river to anthropogenic activities, stable river morphology, stable river pattern and stable bedform are introduced when investigating river dynamic process corresponding to significant ecological problem of rivers (Hu and Guo, 2004; Clarke et al., 2010; Wang et al., 2014).

2.1.2 Stable channel theory

A stable channel is defined as a smooth watercourse that is characterized by smooth riverbanks and riverbed and it is free of objectionable sediment deposit. Additionally, the slope, depth, width, bed material size distribution and bed elevation of the component reaches are continuous indefinitely (Griffiths, 1983). The channel dimension of a river may be varied locally in space or time with the general stability free of obstructions, on condition that the variation on channel dimension alternate on constant values. The application of stable channel theory is extensive including in the discipline of civil and agricultural engineering, and considerably in the design and operation of drainage and wastewater channels, including the design of power canals, as well as the prohibiting and managing scour (Simons, 1957; Griffiths, 1983).

According to Simons (1957) Variables including water discharge, water cross-sectional area, the sediment deposit volume, sediment discharge, the proportion of bed sediment bulk density to sediment density, average concentration of sediment in each unit of water volume, given that there are no unnecessary inputs or outflows in a one-dimensional channel, the down channel's time and position are variables that are crucial to the preservation of the accumulation. Rational analysis of issues related to riverbank scour that is caused by the increase of normal flow in channels, the effect of changes of slope caused by meander cut-offs on channel stability, and issues of erosion above and below hydraulic structures that obstruct channels requires sufficient understanding of the variables that controls channel stability (Simons, 1957).

2.1.3 The regime theory

The regime theory was developed as a result of the empirical observations made in rivers and watercourses. The live or mobile-bed conditions that support the complete establishment of the motion of channel bed material, its design method is provided for by the regime theory (Griffiths, 1983). The regime of a channel such as channel shape and stability are controlled by the interconnection between channel resistance, flow, bank stability and the transportation of sediments. The objective of the regime theory is to forecast the shape, slope and size of a stable alluvial channel. A regime channel is neither scoured nor filled. However, a channel that is established in alluvium has a tendency to slowly scour or fill in bed and banks. The amount of scour corresponds to the amount of fill in a regime channel and it is in a stable condition. A channel is regarded as a stable channel when it is in a stable condition due to its gradual scouring and filling. The width, depth, and gradient of a channel conveying flow that is filled with sediment is regarded fixed, however, the dimension of the channel correlate with the long-term average. Inherent to rivers is erosion and accretion of sediments because they modify the landscape in the long term (Wolman, 1955; Singh, 2022).

The illustration of rivers should include bed forms and planforms as well as the outline of the margins of river characteristics at three different scales including the ripple scale that deals with the size of particles, the dunes and bars scale that deals with channel depth and lastly, the shoals and meanders scale that deals with channel width (Ackers, 1992). Channel stability must be taken into consideration for successful river management. The magnitude of change and the prevalent channel stability determines how the channel respond to natural or anthropogenic modifications. Therefore, it is fundamental to identify the controls on erosion and accretion and the channel's reaction to the modifications in the catchment basin. This is achieved by taking into consideration the interrelationship between the transportation of sediments, flow regime, and channel form. Moreover, total sediment load and the variation between input and output of sediment where erosion, accretion and channel geometry alteration are controlled (Singh, 2022).

The application of the development of the regime theory utilized considerable information that involves the laws regarding the self-formation of regime channels including the width calculation between incised river banks based on the maximum discharge of a fairly straight full flowing river using the wetted stream perimeter method (Lane, 1937); the calculation of

scour between bridge piers that involves estimating the depth of scour between piers using the bed and side factors method (Blench, 1952); the calculation of scour downstream of piers, groins and at spur heads using the bed and side factors method; aggradation upstream from reservoir as a result of flow obstruction that causes the drop in velocity and rise in flow depth for one and the same discharge resulting in aggradation, thus, disrupting the river regime by elevating the bed slope, consequently, establishing a new regime for the river to adapt; degradation downstream from reservoirs due to the dam construction that traps sediments and deposits, thus, degrading the riverbed downstream; dredging estimation; model scales calculation and meandering that is related to the discharge of a stream (Blench, 1952; Singh, 2022).

2.1.4 Leopold–Maddock (LM) theory

The Leopold-Maddock (LM) theory deals with the geometry of natural rivers including downstream hydraulic geometry and hydraulic geometry at a station. The hydraulic geometry considers the association between slope, depth, width, velocity and roughness, which are predominantly demonstrated according to discharge, despite the fact that slope and roughness are also affected by transportation and size of sediments. Additionally, the association is significant for channel design that incorporate stream restoration, canals for irrigation and river training works. In a general sense, width, depth, slope, roughness and velocity can be demonstrated as a function of the independent variables including the size and load of sediments, and discharge (Leopold and Maddock, 1953).

The velocity, width and depth are the result of sediment load that is considered as the total sediment load index, when employing field measurement of mean depth, velocity, width, suspended sediment load and discharge. Furthermore, the width increases at a velocity that is constant correlate with suspended sediment load decline for a specified discharge, since there is a decline of flow depth when slope and roughness are constant and would maintain small amount of suspended sediment. Conversely, width increase correlate with bed load increase for a constant discharge and velocity, since substantial bed surface is in connection with water and substantial sediment will settle on the reduced depth (Leopold and Maddock, 1953).

2.2 Application of gis and rs for river morphology assessment

The utilization of GIS and RS techniques has effectively employed to conduct river morphological studies in recent years. River bank erosion, accretion and lateral river channel migration assessment have successfully been conducted due to the vast availability of remotely sensed satellite images and GIS methodologies. Remote sensing-based studies on river channel evolution with the integration of historical hydrological maps, and surveys effectively provided an opportunity for river channel time series analysis (Manjusree, et al., 2013; Morais, et al., 2016).

The application of multi-temporal high-resolution remotely sensed satellite images have provided an opportunity for river geography, dynamics of river channel, river bank erosion and accretion, river channel formation and migration to be assessed and mapped at numerous spatial and temporal scales. The application of various remotely sensed satellite images for river morphology analysis is widely acknowledged in various remote sensing literature (Ibitoye, 2021; Li et al., 2021; Suresh et al., 2022). The application of the sensor type, the spatial and temporal resolution, and the tools to be used within the GIS software environment are responsible for the variations in satellite images on both spatial and temporal scales.

Other river morphology assessment opportunities include the flood monitoring and control, the identification of erosion exposed reaches, river bank protection and management and river drainage management (Manjusree, et al., 2013). According to Thornton et al., (2007), remote sensing provides improved techniques of river channel assessment over localized equipment-based methods of river channel assessment. The application of GIS and RS techniques are facilitating the effectiveness of hydrological and geomorphological research studies and they are developing in South Africa and in the continent of African over both spatial and temporal scales (Sawunyama, et al., 2006; Masocha, et al., 2017; Ibitoye, 2021). Furthermore, remotely sensed satellite images have effectively been used to assess past and present river channel morphology across the globe (Chohan et al., 2015).

Chohan et al., (2015) conducted an investigation of Chenab River, Asia, from 1972 to 2020 using 60m spatial resolution Landsat 1 – 4, 30m resolution Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper plus (ETM+), and Landsat 8 Operational Land Imager and Thermal Infrared Sensor (OLI/TIRS). The unsupervised image classification technique

was used (Norzaki and Tahar, 2019; Lynch et al., 2020), to classify the images and the principal component analysis (PCA) (Colihueque et al., 2017) was performed on Landsat satellite images to identify active river channel patterns. The study revealed that increased flooding caused abrupt changes on the river channel that led to the widening of river, shifting and migration of river channel. Lovric and Tosic, (2016) evaluated the Bosna River's lateral channel migration, river bank accretion, and erosion rate in Bosnia and Herzegovina, from 1958 to 2013 using aerial images and digital orthophoto plans. River banks were determined using the ArcGIS software thus, delineating areas of erosion and accretion. The study revealed 8.3430 km³ of erosion and 10.7074 km³ of accretion attributed to large scale flooding events, intensive urbanization and constructions.

Mukherjee et al., (2017) conducted a study to evaluate Ramganga's river bank erosion and bank accretion in India, from 1923 to 2014 using toposheets, 60m spatial resolution Landsat 5 Multi Spectral Scanner (MSS) and 30m spatial resolution Landsat 7 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 8 Operational Land Imager (OLI). The study used the Normalised Difference Water Index (NDWI) (Sahu, 2014), to delineate the Ramganga river and bank lines on Landsat images in the ArcGIS environment. Erosion and accretion were determined by digitizing from the images resulting in the creation of polygons, thus, the total area was calculated using geometry calculator in ArcGIS. The study revealed that the river experienced bank erosion and accretion for 91 years that resulted in widening of river channel, meander bends extension and channel migration.

Ibitoye (2021) assessed morphological characteristics of Niger River, Nigeria, from 1990 to 2017 using 30m spatial resolution Landsat 5 TM, Landsat 7 (ETM +) and Landsat 8 (OLI). The GIS techniques that the study adopted incorporated land use and land cover delineation using supervised classification technique in ArcGIS (Bhuiyan et al., 2015). Change detection technique to estimate change of land cover, and cartesian coordinate method in ArcGIS to measure river channel width, polygon to centreline extension in ArcGIS to determine river centreline. The study indicated a decrease in riparian vegetation and surface water, increased sediment yield, river centreline shifting, and morphological changes attributed to erosion and accretion.

Suresh et al (2022) studied the dynamically changing pattern of the Brahmaputra River using a geospatial approach, from 1990 to 2021 using Landsat 4/5, Landsat 8, Sentinel 2 MSI, and

12.5-m resolution ALOS PALSAR digital elevation model. ArcGIS HWATH's was used to determine river sinuosity, and polygon to centreline tool was used to determine the river centreline. The ArcGIS overlay tool was used to compute areas of erosion and accretion, and the clip tool used to clip eroded and deposited polygons and the extent was calculated using geometry calculator in ArcGIS. The study revealed river shifting, sinuosity index of 4.43, high erosion and low deposition.

Wang et al., (2020) assessed the human-induced morphological changes of Lancang River, China, from 1993 to 2016 using Landsat TM and Landsat 8 OLI, QuickBird, Worldview-2, IKonos image, and GF-2 image. The study used both the normalized difference water index (NDWI) and modified normalized difference water index (MNDWI) to delineate the river and ArcGIS 10.4 software was used for the calculation of parameter value and spatial analysis river planforms. The study revealed increasing erosion and a decreasing sedimentation area, changes in the river planforms, increasing channel width, decreasing central bar and marginal bar.

2.2.1 River channel morphology modelling and forecasting

The effective performance of modelling techniques is always limited to space, time and circumstances; thus, the suitability and modelling technique preference is a challenge due to the limitation of the technique to produce an estimated result of reality (Galavi et al., 2013). Figure 2.1 shows the methodological flow diagram of modelling and forecasting. Globally, numerous large rivers have experienced substantial morphological changes (Pourbakhshian and Pouraminian, 2015). Historically, river channel morphological studies were rooted on deterministic theories. However, the disadvantage is attributed to the inability to forecast river channel morphology. River channel morphology evolves over both spatial and temporal scales (Ziliani, and Surian, 2012; Mount, et al., 2013). The forecasting of how the river will respond to both natural and anthropogenic processes is challenging (Pourbakhshian and Pouraminian, 2015). However, forecasting floods and inundation prone areas, erosion, accretion, and flow discharge is crucial for prevention of floods, degradation and management of natural and anthropogenic disasters associated with river systems. Natural factors affecting river channel morphology are periodical in nature, thus, erosion, accretion, river lateral migration and flow discharge are also periodical (Livina et al., 2003; Maher and Eyre, 2012).

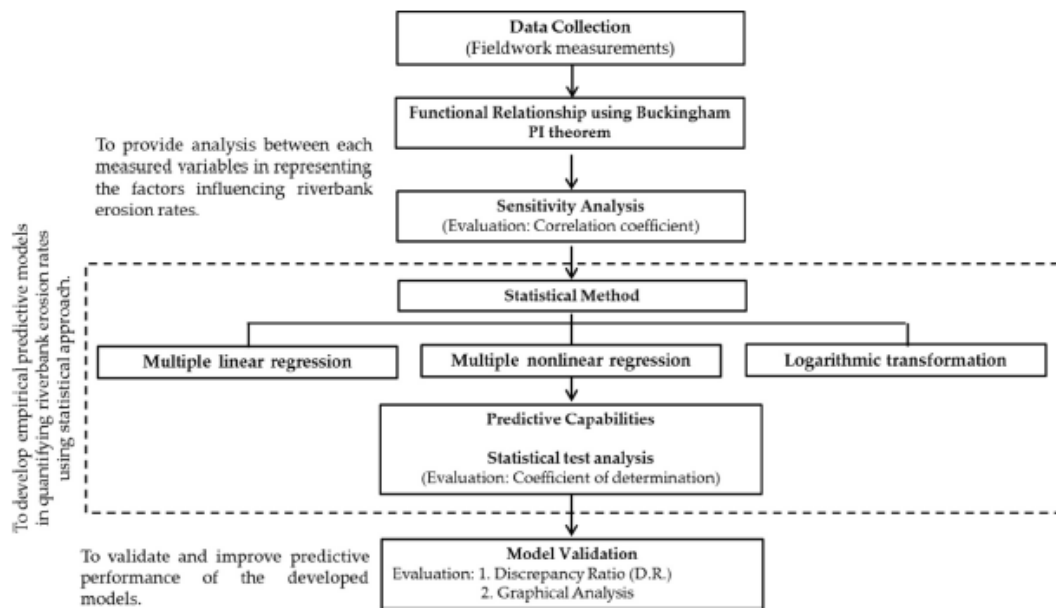


Figure 2.1: Flow chart of the methodology (Adapted from Saadon et al., 2021)

A time series (TS) incorporates a collection of data that is observed, gathered, and documented at regular intervals. This makes time series analysis to be a significant method for river channel morphological studies, and this is because mathematical models are employed for data trend identification and to forecast new set of records. The hypothesis in time series analysis is that the observed data is characterized by a systematic pattern consisting of trend and seasonality (Fashae, et al., 2019). The application of mathematical models in time series analysis for river studies is widely acknowledged in the scientific literature (Livina et al., 2003; Galavi et al., 2013; Pourbakhshian and Pouraminian, 2015; Fashae, et al., 2019)

A TS is series of observations of a variable that are gathered, scrutinized, and documented at consistent intervals. In hydrological research studies, TS analysis is crucial because it helps identify trends and predict new records using mathematical models. More recently, the majority of significant tasks in hydrology problem solving have been replaced by mathematical models. (Zhang et al., 2022; Kavetski et al., 2018). It is assumed in TS analysis that the data are composed of random noise (error) and a systematic pattern with a set of distinguishable components. Trend and seasonality are the two fundamental classes of components that can be used to characterize the TS patterns.

The autoregressive integrated moving average (ARIMA) time-series model is widely used in the scientific literature to give a detailed account of various time series behaviour (Box and Jenkins, 1976; Galavi et al., 2013; Fashae, et al., 2019). The ARIMA model is well incorporated within the linear stochastic models. Moreover, it is primarily consisting of the autoregressive (AR), moving average (MA), autoregressive moving average (ARMA), seasonal ARMA, and ARIMA models (Box and Jenkins, 1976; Box et al., 2015). Galavi et al., (2013) forecasted the water level in the Klang River by analyzing the autoregressive integrated moving average (ARIMA) and adaptive neuro-fuzzy inference system (ANFIS) models. Pourbakhshian and Pouraminian, (2015) predicted Yahagi River morphological changes using ARIMA models.

Akhter et al., (2019) employed the ARIMA model, spatial autocorrelation index, and Landsat data to predict the mid-line channel shifting between 1972 and 2031 and the spatiotemporal changes of Teesta River channel morphology. Fashae et al., (2019) investigated the applicability of ARIMA and artificial neural network (ANN) in predicting the discharge of Opeki River from 1982 to 2010, the effective model was then used to predict river discharge 2010 to 2020.

2.3 Natural river morphology

The river channel structure and changes in its area and its lateral migration over a period of time contributes to its morphology. River morphology is a sophisticated geoscience subdivision and it is a notable subject in geomorphology, fluvial science, hydrology and geology. Furthermore, it deals with the arrangements of rivers and the neighboring land as a result of erosion, transportation and the accretion of sediments. Additionally, river morphology is a descriptive science that is rooted on methodological observation and analysis of the natural processes. It has been for many years, an issue of great concern to hydrologists and engineers because they understood that any attempt toward river management required established consideration of the morphological attributes and how they respond to the changes (Lane, 1955; Chang, 2008; Mangelsdorf et al., 2013; Kang and Kanniah; 2022). Figure 2.2 shows the methodological flow diagram of the determinants of river channel morphology.

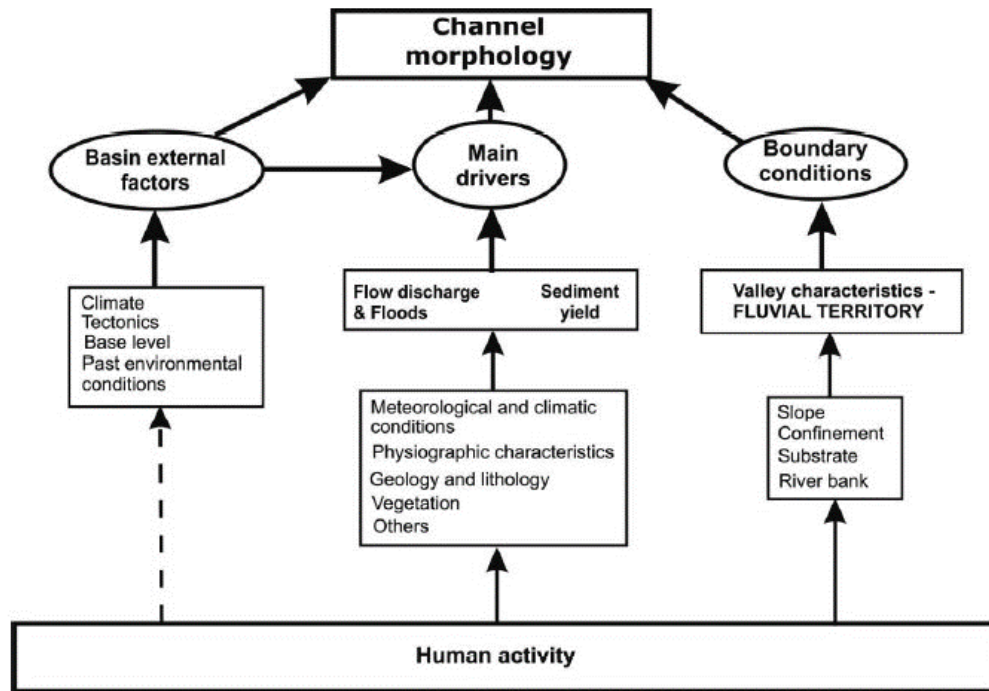


Figure 2.2: The illustration of the primary determinants of river channel morphology (adapted from Ibisate et al., 2011)

River morphology is a significant subject matter to various scientists and engineers because the transportation and deposition of sediments in the river by hydraulic processes result in significant effects in the river (Kanniah; 2022). The successful management of river problems requires knowledge and understanding of river morphology principles. This can assist communities around the world living in close proximity to the river banks to steer developments away from potential river channel migration zones and contribute to the reduction of natural disasters such as floods. Furthermore, increased developments on rivers causes the movement of sediments to change, hence the knowledge and understanding of river morphological principles is significant to effectively manage river problems (Lane, 1955; Kang and Kanniah; 2022).

The erosion cycle shapes the morphology of rivers. The slope of the river declines downstream, thus, bearing a concave profile. Additionally, due to the decline of slope downstream, a sorting process takes place where the coarser material that the river cannot transport are deposited on the river bed, hence the downstream of a river is characterized by thin bed material as compared to the river bed upstream. Moreover, the river discharge intensifies downstream, most especially in humid regions as a result of tributaries connecting to the main river. However,

this process differs in the arid region, the river discharge lessens downstream as a result of seepage and evaporation (Mangelsdorf, 2013). The sediments in the river comes from the upper part of the catchment area regardless of the decreased runoff. However, the remainder of the catchment area is characterized by increased runoff with decreased sediments. The knowledge of variation in sediment attributes in a river is significant to river morphologists. Processes including weathering, abrasion, dissolution, fragmentation and hydraulic sorting causes the reduction in sediment size in rivers. When the river loses its ability to transport sediments as it decreases with distance downstream, hydraulic sorting takes place (Lane, 1955; Garde, 2006; Mangelsdorf, 2013).

River morphology is caused by the complex influence of geomorphic activities that take place in a catchment basin at various spatial and temporal scales. There is a principal relationship between catchment basin and river morphology. At a large-scale, the topography, geology, land use and climate of catchment is controlled by its geographical location. Sequentially, these attributes control the transportation and accumulation of sediments and water to the channel of the river. Catchment basins are classified according to the geomorphic processes such as erosion, transportation and sedimentation (Ibisate et al., 2011; Park et al., 2019).

2.3.1 Primary drivers of river morphology

The primary drivers of river morphology include discharge regime (flow, floods and sediment discharge) and sediment budgets, the valley and catchment characteristics or external factors (Ibisate et al., 2011). The section below is the discussion of the primary drivers of river morphology.

2.3.1.1 Flow, floods and sediment discharges

The process of erosion, transportation and sedimentation is determined by the relationship between discharge and sediments. Consequently, the variation in river morphologies is caused by the variation of flow regimes or sediment budget (Schumm, 1977). Natural events such as floods increases the morphological processes of erosion, transport and sedimentation. Bankfull river discharge that result from normal floods influence channel forms as a result of excessive velocity of water, on the other hand, abnormal floods influence the definitive form of the channel as a result of increased competence (Church, 2002). Furthermore, sediment load determines river channel morphology. Furthermore, this is because erosion and sedimentation of material determines the geomorphic features. Variation in sediment load is in accordance

with its transportation from the upstream catchment. Immediately after the deposition of sediments in the river channel, the amount and size of sediments determines the sediments transport regime and the nature alluvial deposits in the river channel. Anthropogenic activities such as water diversion and land use change modify the factors influencing the hydrological response and the delivery of sediment of a catchment basin (Schumm, 1977; Church, 2002; Ibisate et al., 2011).

2.3.1.2 Valley characteristics and fluvial territory: boundary conditions

Valley and reach variables such as the floodplain attributes, slope, valley morphology, confinement and bed material, restrict the outcome of the relationship between flow and sediment regimes. The variation in channel equilibrium profiles is as a result of incision and aggradation that is controlled by valley slope (Lane, 1955; Charlton, 2008). The adaptation of the river channel to the outgrowth of the terrain and valley floor concavities is induced by the tributary confluences or the variation in bedrock hardness that result in changes in the material of the valley floor. For example, the contrasting planforms and river forms of the Arag'ón-Subordan River in the western Pyrenees is produced by the slope and valley confinement changes along the course of the river (Ibisate et al., 2011). The confinement of the valley is controlled by the width and floor shape of the valley, and it is a principal environment for river channel morphology. Moreover, the formation of river channels takes place in confined valleys that are confined by valley walls that exacerbate the resistance of flow and the inputs of sediments as a result of the hillslopes that are in close proximity to the river channel (Nanson and Croke, 1992; Thorne, 1997; Ibisate et al., 2011).

2.3.1.3 Anthropogenic activities impact on river morphology

Majority of rivers worldwide are affected by anthropogenic activities. Anthropogenic activities have a significant impact on river systems at various scales from the watershed to the river channel. Land use and land cover change including agriculture, urbanization, deforestation and mining, taking place in the catchment basin influence runoff and sediment yield (Charlton, 2008). Moreover, the construction of dams, water abstraction activities, canalization and sand mining modify the river channel and floodplain. The construction of dams significantly impacts river systems. For example, numerous dams and inter-basin schemes that are aimed at improving water supply have been constructed in South Africa. Additionally, 98% of large rivers in South Africa are impounded (Nel, 2015). The river channel morphology is greatly

modified upstream from dams, and sediments are greatly trapped downstream the dam. Consequently, erosion is increased, thus, resulting in incision and embeddedness of sediments (Rinaldi and Simon, 1998). The accumulation of sediments in numerous dams in the world is a crucial demonstration of how dams are successful in trapping sediments, thus, causing serious environmental concerns (Ibisate et al., 2011).

2.4 Identifying geomorphic and anthropogenic activities within nzhelele river

River channel morphology is controlled by a combination of complex anthropogenic and geomorphic factors that occurs at various spatial and temporal scales in a river basin (Dufour and Piégay, 2009). These factors are dynamic at various spatial and temporal scales; thus, a combination of complex geomorphic and anthropogenic factors can concurrently or separately affect the morphology of a river channel (Luchi, et al., 2010; Baena-Escudero, et al., 2019; Li, et al., 2021). The river channel morphological trend and changes over time is directly dependent on how the river respond to geomorphic and anthropogenic factors (Baena-Escudero, et al., 2019).

2.5 Natural and anthropogenic impacts on river channel morphology

The relationship between water, sediment and the composition of the riverbed shapes the morphology of a river. Furthermore, flow conditions, riverbed conditions and boundary conditions are principal in the evolution of river morphology (Gupta and Liew, 2007; Wang et al., 2021). Moreover, Yin et al., (2012) indicated that river morphological evolution is attributed to erosion, transport and deposition as a result of change in stability. The combination of natural and anthropogenic processes determines river channel evolution in both spatial and temporal scales. River channel evolution is increased by anthropogenic processes such as damming, reservoir construction, land use change and sediment mining as well as natural processes such as increased flooding, high temperatures and rainfall, and sediment accumulation. All these processes result in river channel incision and river bank erosion (Preciso et al., 2012; Yousefi et al., 2018; Malik, and Pal., 2019; Li et al., 2021).

The evaluation of the effects of land-use change on the morphology of river channels in northeastern Puerto Rico was carried out by Clark and Wilcock, (2000). The study measured channel formation and runoff events using historical data from hurricanes, floods, and tropical storms. The study revealed increased runoff and sediment supply. Moreover, the clearance of land resulted increased gullying, landslides and sediments deposit into the river channel.

Variations can be noted in the study results, as sediments deposit into the river channel decreased as a result of a shift in land use from agriculture to industrial and residential land uses. However, gravel bar deposits increased with a decline in channel depth, and an increase in overbank flooding downstream the river channel.

Preciso et al., (2012) carried out a case study on the Reno River in Italy to evaluate the effects on river channel morphology and sediment flux of land use changes, torrent control projects, and sediment mining. The study analysed riverbed incision and channel narrowing using data such as rainfall and discharge data, historical maps and aerial photographs, topographic surveys and field measurements. The study revealed a decline in flow discharge, streambed degradation, narrowing of upstream reach, and changes in planform structure.

A case study on the Karoon River in Iran was conducted by Yousefi et al., (2018), to evaluate how the extreme flood of 2016 affected the morphology of the river. Landsat 8 OLI collected both before and after the flood event was used in the study. Moreover, Support Vector Machine tool in ENVI 4.8 software was applied to categorize the images in order to extract the active channel before and after flooding. Using Fluvial Corridor 10.1 software, the active channel width was calculated along with the sinuosity index, bank retreat index, river network change index, straight meander length index, centerline flow length index, erosion area index, sedimentation area index, and study time period. The differences between land cover types and active river channel change were analyzed, compared, and established using statistical techniques like the paired sample T-tests, one-way ANOVA tests, and the Duncan's grouping test. The study found that increased sediment movement brought on by floods and bank erosion in the meandering reaches of the river affected the width of the channel.

Malik and Pal (2019) explored how groynes influenced channel morphology in a Dwarkeswar River, West Bengal, from 2003 to 2018. The study assessed the channel instability indices, aggradation and degradation ratio, bar occupied area, braided index, hydraulic geometry, sedimentological works, and braided index. The study analysed flow behaviour using HEC RAS 5.0. software. The impacts of groynes on river channel morphology were highlighted by the computation of principal component analysis, the generation of non-parametric tests and the application of the Canonical Discriminant Function models. The study revealed the alteration of flow, sedimentology, hydrology and river channel morphology. Moreover, the study revealed a decline in the sand-bedded river's length, cross-sectional area, mean depth,

and channel width. Studies on the impacts of groynes on river channel morphology bearing similar results exist in the scientific literature (Ohmoto et al., 2009; Giglou et al., 2018).

Kang and Kanniah, (2022) conducted an investigative study for Johor River Basin, Malaysia, by generating a time series analysis to assess the impacts of land use and land cover changes on river channel morphology. The study classified Landsat 5 TM and Landsat 8 OLI images using software's such as Google Earth Engine and ArcGIS. The study vectorized the classified images and extracted the river channel polygon, and generated the river channel centreline using the Create Thiessen Polygon function in ArcGIS. The assessment of changes in morphology was achieved by using the Channel Migration Toolbox (CMT) in ArcGIS. The study revealed increased river centreline migration, thus, determining morphological changes in the river channel due to changes in land cover and intensified land use brought on by faster economic and population growth.

3. STUDY AREA AND METHODOLOGY

This chapter introduces the study area and methodological aspects of the research. It draws attention to the techniques covered in Chapter 2 that are appropriate for this research. The research design, data collection, and data analysis are all included in this chapter.

3.1 Description of the Study Area

Nzhelele River is situated in Makhado Local Municipality in the Vhembe District of Limpopo Province in South Africa. The Nzhelele River valley is situated between the Soutpansberg mountain ranges, approximately 903 meters above mean sea level (MSL). As it is shown in figure 1.1, its latitudes are 22° 20' S and 23° 05' S, and its longitudes are 29° 45' E and 30° 25' E. The research area has a subtropical climate, with the northern Lowveld region of the Soutpansberg mountain range displaying characteristics of a hot, dry climate with sporadic rainfall of 200–350 mm annually (Mathada, 2011). The valley's summers are hot, with temperatures ranging from 16 to 40 degrees Celsius, and its winters are mild, with 16 to 22 degrees Celsius (Mathada, 2011). The study area includes savannas, shrublands, tropical and subtropical grasslands, and mopane woodlands. Additionally, there are shrubs that are made up of certain invasive species. The study area is classified as arid to semi-arid, with xerophytic species making up the majority of the vegetation (Mucina and Rutherford, 2006).

The morphology of the Nzhelele Village is shaped by Soutpansberg group rocks within the Southern Marginal Zone (SMZ) of the Limpopo Mobile Belt as well as the Nzhelele Dam. The LMB constitute distinctly metamorphosed and highly deformed rocks. The LMB connects the granite-greenstone terrane of the Kaapvaal Craton in the south and the deformed poly-metamorphosed rocks of the Central Zone (Barton et al., 1983). There are two types of soil in the area: sandy soil and loamy soil (Haughton, 1969). Although the study area's soil originated from the weathering of sedimentary and igneous rocks, some areas have mixed soils that result in sandy-loamy soil (Haughton, 1969).

The Department of Water Affairs, now known as the Department of Water and Sanitation constructed the Nzhelele Dam in 1948 with a capacity of 55.3 million m³ near Pfumembe Viillage in Limpopo Province, South Africa (Makungo et al., 2010). The main aim of the dam was to provide water for irrigation and it has a high hazard potential. It is nested in the quaternary catchment A80C of the Nzhelele River Catchment in the Limpopo River Basin

(Makungo et al., 2010). Sand mining activities in shallow waters by the surrounding Nzhelele communities has since been increasing causing serious environmental concerns. Furthermore, these problems correspond with global concern regarding the sand mining impacts on the environment (Gondo et al., 2019).

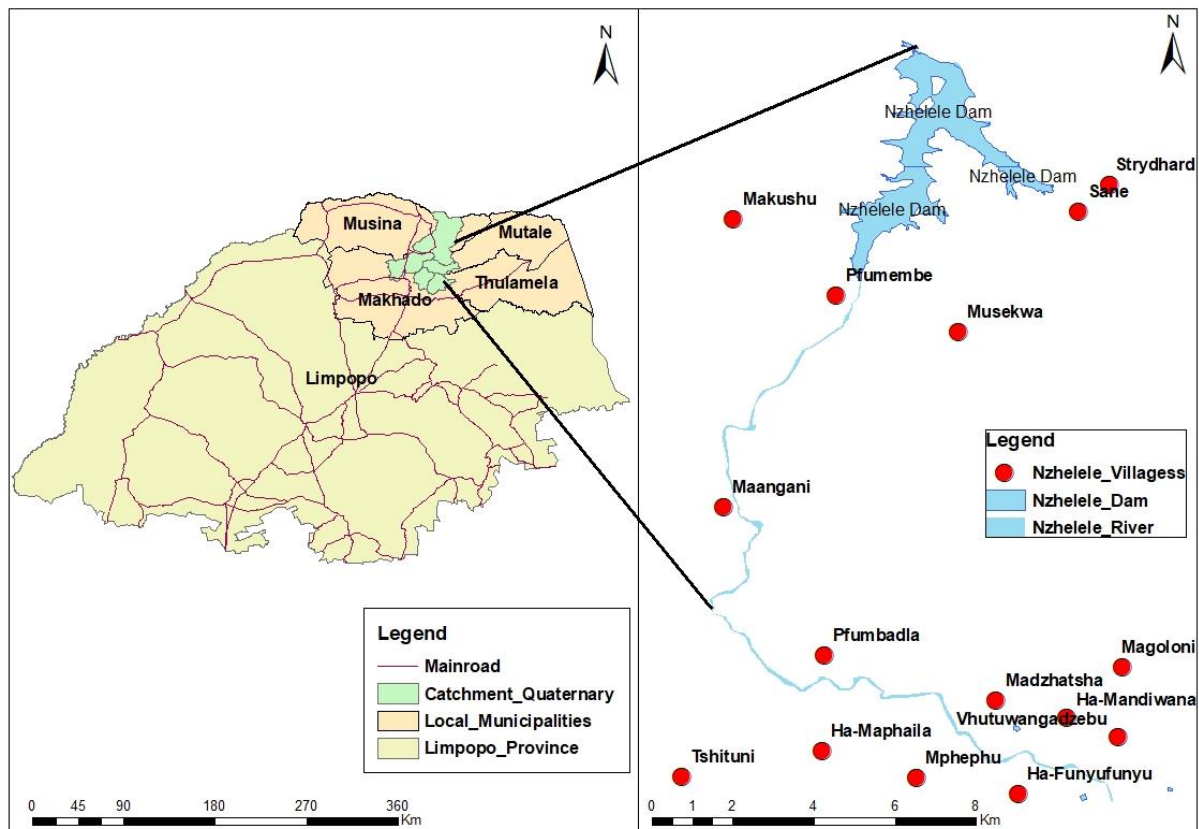


Figure 3.1: Study area map showing the local municipalities, quaternary catchment, Nzhelele Dam and Nzhelele River, in the Limpopo Province.

3.2 Research Design

The study employed quantitative research design. The research design used to accomplish the goals of the study is depicted in Figure 3.2. The data that was gathered for this study, their processing, and their analysis are all included in the research design.

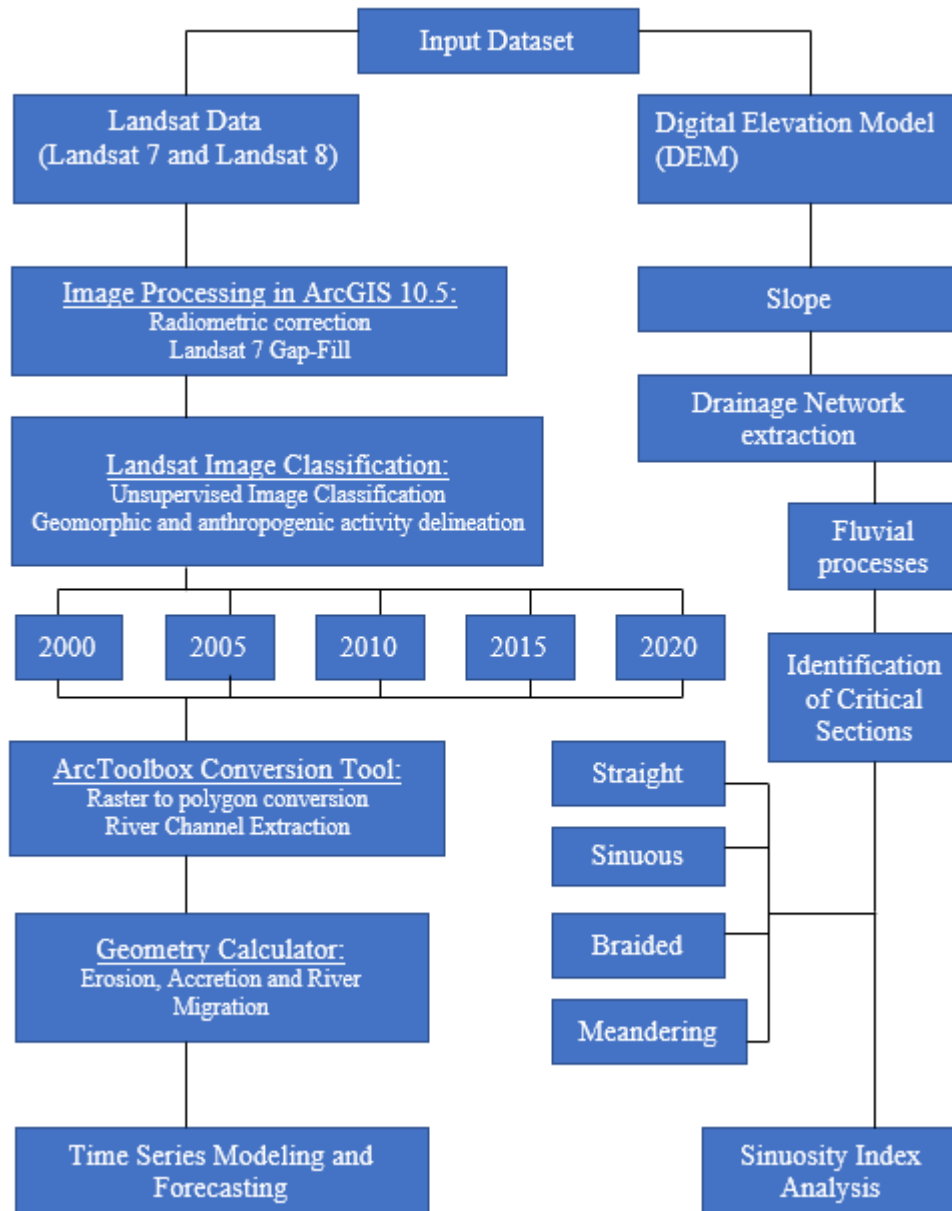


Figure 3.2: Conceptual framework of the research design showing the different process flow of the methodology.

3.3 Data Collection

Multitemporal remotely sensed 30 m resolution Landsat satellite data with cloud free coverage over the study area were obtained from the United States Geological Survey (USGS) from its free data portal (<https://www.usgs.gov/>) to assess the spatiotemporal variation of Nzhelele River morphology as well as the impacts of geomorphic and anthropogenic activities on channel morphology. The study used the Landsat data captured at an interval of five (5) years between the year 2000 to 2020, namely 2000 (Landsat 7 ETM+), 2005 (Landsat ETM+), 2010 (Landsat ETM+), 2015 (Landsat 8 OLI) and 2020 (Landsat 8 OLI).

3.3.1 Landsat Satellite Data

This study employed the multi-temporal Landsat data to assess the morphological attributes, geomorphic and anthropogenic footprint on the Nzhelele River, as well as forecasting the spatio-temporal variation of channel centre line shifting. Landsat images confers advantage because it has been freely accessible via the internet to the public since 2008 and it is a distinctive data source with a high spatial resolution of 30m and a temporal resolution of 16 days that can be used to map land surface dynamics at global scale. (Woodcock et al., 2008; Roy et al., 2014b; Spada et al., 2018). Furthermore, numerous research projects have been effectively achieved regularly at local, regional, national and continental levels because of Landsat's spatial and temporal information (Rowberry et al., 2011; Spada et al., 2018; Wulder et al., 2019). Landsat satellite data was suitable and applicable for this study because it will be focussing on a large river basin at local level and generating long time series analysis from 2000 to 2021 as well as forecasting.

The Landsat's spatial and temporal resolutions allowed historic data analysis and quantification of Nzhelele River morphology at local level making it time and cost effective as compared to the traditional geomorphological methods of river morphology assessment. The study used cloud free Landsat 7 Enhanced Thematic Mapper (ETM+) that incorporates eight (8) spectral bands with 30m spatial resolution from band 1 to band 7 with band 8 characterized with a 15m spatial resolution (Roy et al., 2016). Moreover, the study used the most recent launched Landsat 8 (OLI) with nine (9) narrower spectral bands with a resolution of 30m. Landsat 8 is more advanced as compared to the previous Landsat 7 in terms of radiometric resolution of 12-bit, calibration and signal to noise characteristics. Data from Landsat 8 has been employed for various hydrological studies since its launch in 2013 (Roy et al., 2014a; Roy et al., 2016). Table 3.1 below is the summary of satellite data that were acquired for the study.

Table 3.1: Summary of satellite data that were acquired to achieve research objectives

Imagery	Resolution	Date of acquisition	K/J scene path/ row
Landsat 7 ETM+	30 m	10/ 10/ 2000	169/ 76
Landsat 7 ETM+	30 m	21/ 09/ 2005	169/ 76
Landsat 7 ETM+	30 m	19/ 09/ 2010	169/ 76
Landsat 8 OLI	30 m	25/ 09/ 2015	169/ 76
Landsat 8 OLI	30 m	09/ 11/ 2020	169/ 76

3.4 Data processing

3.4.1 Processing of Landsat imagery

The USGS offers Level 1B data that has been geometrically and radiometrically calibrated for Landsat 7 ETM+ scenes. However, a radiometric correction was applied using a digital elevation model and the exoatmospheric solar irradiance, atmospheric optical depth, and sensor calibration parameters to convert digital numbers (DN) to reflectance values (Pons and Sole-Sugranes, 1994). Landsat gapfill tool in ENVI 5.3 was used to fill the gaps in Landsat 7 ETM+ of 2005 and 2010 study period caused by Scan Line Corrector (SLC) error. The Landsat 7 ETM+ that are obtained after May 2003 are attributed to wedge-shaped scan-to-scan gaps caused by scan line corrector (SLC) error (Maxwell et al., 2007).

3.5 Data analysis

3.5.1 Unsupervised image classification

This study used the unsupervised image classification method (Lynch et al., 2020), to classify all the Landsat images from 2000 to 2020 at a 5-years interval to obtain the land-use and land-cover (LULC) maps of the study area using ArcGIS 10.5 software (See appendix A). Unsupervised image classification involves the groupings of pixels with common attributes, wherein the outcomes are based on the software analysis of an image. The pixels that are related are determined by the computer and it groups them into classes. Furthermore, these pixels are grouped according to their reflectance attributes. However, the number of clusters to generate and the bands to use is determined by the user (Menzel and Purdom, 1994). Unsupervised classification uses clustering of algorithm when classifying an image data, thus, foreknowledge

of classes is not necessary (Norzaki and Tahar, 2019). This means that the approach is totally data-driven and objective. It works especially well with targets' images or places without any ground truth. Unsupervised categorization may uncover certain spectral properties that were previously hidden, even for a well-mapped region (Lynch et al., 2020).

The conversion tool in ArcToolbox was used to convert the LULC classified images from raster to polygon for the extraction of the Nzhelele River channel. The extraction of the Nzhelele River facilitated the assessment of the spatio-temporal variation of river morphology. Furthermore, the LULC maps were used to investigate the human induced impacts on Nzhelele River morphology. The classification of Landsat images for river morphology analysis is widely acknowledged in various remote sensing literature (Ibitoye, 2021; Li et al., 2021; Suresh et al., 2022). Six (6) land-use and land-cover classes were classified that include: water body, dense forest, sparse forest, grassland, residential/ bare land and agriculture.

3.5.2 Image classification accuracy assessment

In order to analyse the results and use classified images to make decisions about the Nzhelele River morphology, accuracy assessment is essential. The main cause of the challenges in assessing accuracy for the unsupervised image classification is the temporal remote sensing data collection issues (Thakkar et al., 2017). The most often used technique for expressing accuracy as a component of the correct classification is to do so by creating an error matrix, sometimes called a confusion matrix (Thakkar et al., 2017). Due to the variations in the classes, this matrix provides insight into the relationship between the ground truth data and the outcomes of the segmentation process. For this study, the accuracy parameters that were calculated based on the error matrix include the error of omission, error of commission, producer's accuracy, user's accuracy and Kappa coefficient (Thakkar et al., 2017; Zhuang et al., 2018).

Producer's accuracy is the result of dividing the number of correctly classified pixels in each class by the number of ground truth pixels in the same class. This is a measure of the omission error. By dividing the total number of categorized pixels in a class by the number of correctly classified pixels in that class, one may calculate the user's accuracy, which is a measure of the commission error. One statistic used to assess the effectiveness of the detection algorithm is the kappa coefficient (Thakkar et al., 2017; Zhuang et al., 2018).

3.5.3 Determining areas of erosion and accretion

The locations of the river banks from 2000 to 2020 were compared in this study, and distinct polygons of erosion and accretion of the left and right banks of the Nzhelele River were made in the GIS software. Erosion was classified considering any situation in which the polygon representing the current river bank was previously positioned outside the river bank, and accretion was classified by considering any situation in which the river bank was previously shifted inside the channel (Yao et al., 2011; Baki and Gan, 2012). The area located between the current right bank and the former channel was identified as an erosion polygon, while the area that lies between the current left bank and the former channel was identified as an accretion polygon, and vice versa. The ArcGIS calculating geometry command was used to calculate the area of the polygon following the determination of the erosion and accretion polygons (Yao et al., 2011; Baki and Gan, 2012).

3.5.4 Spatio-temporal evolution of river channel morphology

The study evaluated the geomorphological processes—river bank erosion, river bank accretion, and lateral channel migration—that govern the evolution of river channel morphology (Lovric, and Totic, 2016; Li, et al., 2021). The study used historical Landsat images together with GIS techniques to quantify the Nzhelele River bank erosion, accretion and lateral channel migration. Data obtained from the Landsat images from 2000 to 2020 was quantitatively compared using ArcGIS 10.5 in order to define the evolution of Nzhelele River morphology over time. The Nzhelele River polygon was extracted from the classified images and the river banks was assessed to determine changes over time, therefore, riverbank erosion and accretion was quantified separately and channel migration was determined (Lovric and Totic, 2016; Li, et al., 2021; Suresh et al., 2022).

3.5.5 Geomorphic and anthropogenic activities on river channel morphology

This study used sinuosity index, land-use and land-cover data from the classified Landsat images in order to effectively assess the impacts of geomorphic and anthropogenic activities on channel morphology. The flow and morphological attributes of a river channel are determined by the sinuosity index (Karki et al., 2019; Suresh et al., 2022). On the other hand, a river's sinuosity is shaped by how much its channel meanders. The variations of a river channel are determined by the sine movement index (Rhea, 1993). This represents the ratio between the shortest distance (valley length) and the range of the river channel (channel length)

from beginning to end (Suresh et al., 2022). This study assessed how the geomorphic and anthropogenic processes has impacted the Nzhelele River morphology from 2000 to 2021. Sinuosity index was estimated using the equation (Mueller, 1968; Suresh et al., 2022):

$$\text{Sinuosity index (SI)} = \text{Channel Length (CL)} / \text{Valley Length (VL)}$$

The study used ArcGIS 10.2 to estimate the sinuosity of the Nzhelele River. The study used the Fluvial Corridor ArcGIS toolbox package within the ArcGIS environment to compute the sinuosity index (Alber and Piégay, 2011; Roux et al., 2015; Baena-Escudero, et al., 2019). The sinuosity index was estimated on all Landsat images from 2000 to 2020 at an interval of 5-years (2000, 2005, 2010, 2015, and 2020), in combination with LU-LC data to assess the impacts of geomorphic and anthropogenic activities on channel morphology.

3.5.6 Spatio-temporal evolution forecast of Nzhelele River channel morphology

River bank erosion and river bank accretion, as well as, geomorphic and anthropogenic processes affect the evolution of river morphology under various spatial and temporal scales (Ziliani, and Surian, 2012). Further, the evolution of river morphology facilitated the forecasting of Nzhelele River morphology using GIS and time series modelling. The study determined the Nzhelele River centreline and its spatio-temporal variations from 2000 to 2022 and forecasted its evolution for 2025 to determine the Nzhelele River morphological evolution and pattern. This is to enhance comprehension of the dynamics of the Nzhelele River morphology both now and in the future. According to Montgomery and Buffington (1997), the change in direction of a river centreline is a good indicator of variations in river behaviour and processes. The forecast of the Nzhelele River centreline evolution and dynamics was generated using GIS and the time series model in Microsoft excel. Time series modelling (Fuller, 1995; Montgomery et al., 2015), which incorporate the seasonal component, trend component and irregular component was used to analyse the trends and patterns of Nzhelele River morphology by determining the river centreline and its migration. Time series analysis is expressed as equation five below (Montgomery et al., 2015):

$$X_t = S_t \times I_t \times T_t$$

Where: X_t is the value of the series at time t , S_t is the seasonal component with a period S , it is the irregular component and T_t is the trend component of the series.

The primary goal of TS modelling is to create a model of the data-producing process so that comprehensive explanation and understanding of the producing process can be provided (Brockwell and Davis, 2016). Brockwell and Davis, (2016) indicated that pre-processing involves the estimation and subtraction of trend and seasonal components from the data to produce a noise sequence. Further, it entails dissecting time series into their constituent parts (i.e., seasonal, trend, and irregular components). Pre-processing improves the accuracy of forecasts when it is applied on the time series because it enables the analyses of the behaviour of each component individually (Armstrong, 2001). The decomposition of time series is expressed as equation (Brockwell and Davis, 2016):

$$\begin{aligned} \text{Observed series} &= \text{Trend} \times \text{Seasonal} \times \text{Irregular} \\ Ot &= TCt \times St \times I \end{aligned}$$

A time series' patterns of change over the course of a year are modelled by the seasonal component. The yearly recurrence of the patterns of change is ascribed to periodic fluctuations of constant length. The irregular component indicates variations not covered by the seasonal and trend components, while the trend component shows changes in the time series' level (Armstrong, 2001; Brockwell and Davis, 2016). Combining (post-processing) account for model selection instability and unnecessary high variability in the final forecast. Combining forecasting models assumes that while individual models may not be able to identify the underlying process, they may be able to capture distinct aspects of the available data for forecasting (Armstrong, 2001). When applied on time series, combining improves the accuracy of forecasts. Time series analysis seeks to distinguish time series observations in order to describe historical patterns in the data and create forecasts by extrapolating known historical patterns into the future. This is because time series analysis encompasses both patterns and random variations (Montgomery et al., 2015).

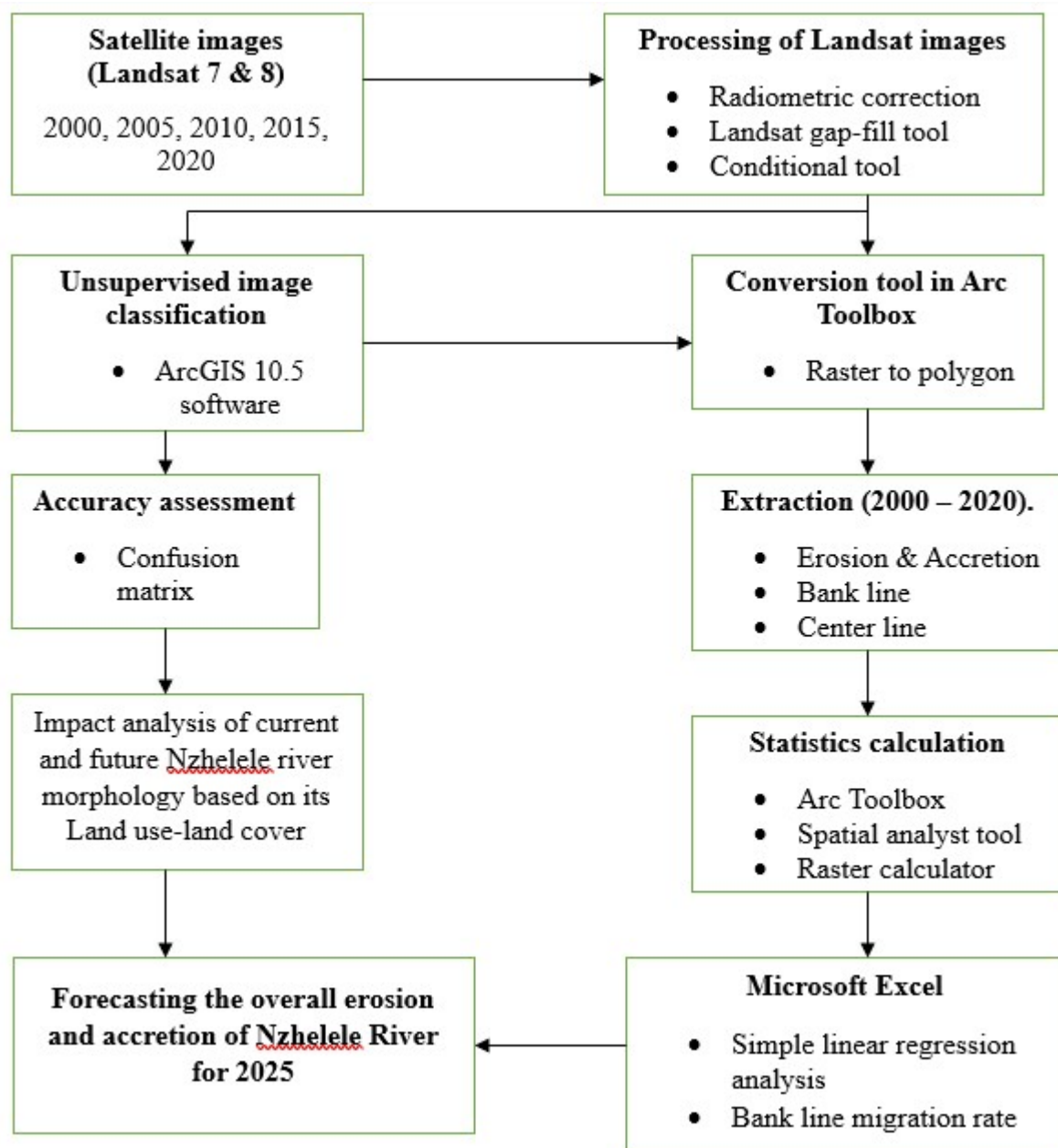


Figure 3.3: Flow chart of the forecast methodology employed in the present study.

4 RESULTS

The data gathered throughout the study period is presented and interpreted in this chapter. To meet the study's goals, the data was gathered and examined. This chapter also includes the spatio-temporal variation of the Nzhelele River morphology, the effects of anthropogenic and geomorphic activities on channel morphology, an explanation for data discrepancies, trend analysis, and forecast.

4.1 The spatio-temporal variation of Nzhelele River morphology

This section describes the spatio-temporal variation of Nzhelele River morphology over the period of twenty years (20) from 2000 to 2020 on a 5-years interval. The study assessed the Nzhelele River bank erosion, accretion and lateral channel migration. The total areas of the rates of erosion and accretion of the left and right banks of the Nzhelele River from 2000 to 2020 are given in Table 4.1 below. Figure 4.1 A and B demonstrate lateral channel migration of the left and right bank of the Nzhelele river and appendix A demonstrate erosion and accretion of the left and right banks of the Nzhelele River channel.

Table 4.1: Nzhelele river erosion and accretion

Bank	Left Bank		Right Bank	
Year	Erosion (km³)	Accretion (km³)	Erosion (km³)	Accretion (km³)
2000-2005	2.32	3.77	4.35	0.97
2005-2010	2.72	3.29	1.06	4.71
2010-2015	3.17	0.44	1.86	1.18
2015-2020	0.59	0.79	2.14	1.12
Total	8.8	8.29	9.41	7.98

From the data presented in table 4.1, it shows that on the left river bank the highest erosion was found to be 3.17 km³ between 2010 – 2015, and the highest accretion was found to be 3.77 km³ between 2000 – 2005 owing to the widening of river channel and meander bends extension and development. Moreover, these were pronounced in the northern and south-eastern parts of the study area. In the beginning of the study period, erosion was initially greater and gradually decreased over time during the study period. Moreover, erosion on the right bank is more noticeable than on the left bank of the Nzhelele River channel. The minimum erosion recorded was 0.59 km³ between 2015 – 2020 and the minimum accretion recorded was 0.44 km³ between 2010 – 2015 on the left bank. On the other hand, highest erosion recorded on the right side of the river bank was 4.35 km³ in 2000 – 2005 and the highest accretion recorded was 4.71 km³ between 2005 – 2010. The minimum erosion on the right river bank was 1.06 km³. A distinction

of meandering can be observed from both left and right banks of the Nzhelele River, these banks accompany each other everywhere on the alluvial plain. This is because the right bank conforms to an opposite movement in relation to the left bank with higher erosion than accretion in 2000 – 2005, and higher accretion than erosion in 2005 – 2010.

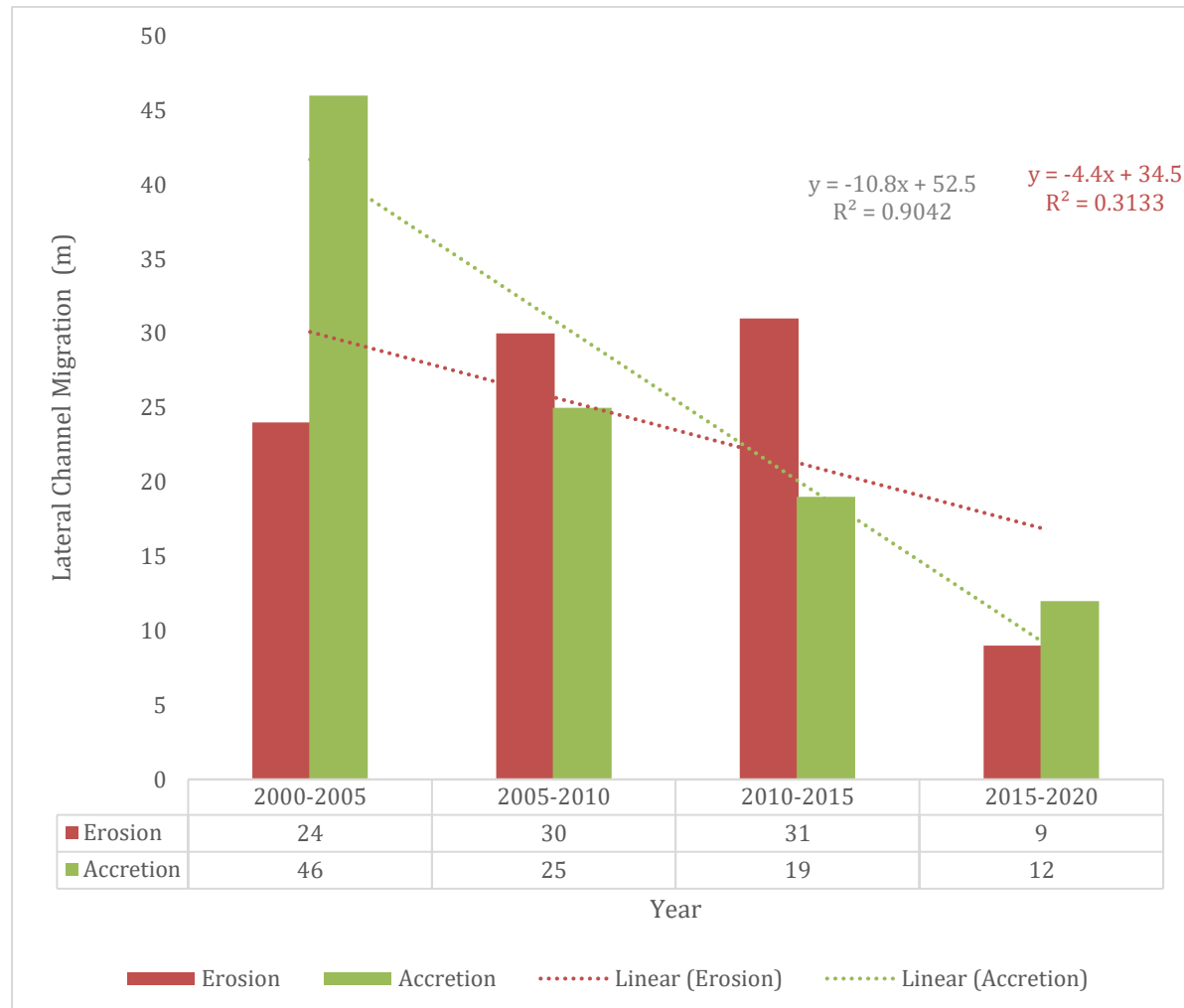


Figure 4.1 A: Left bank migration from 2000 – 2020

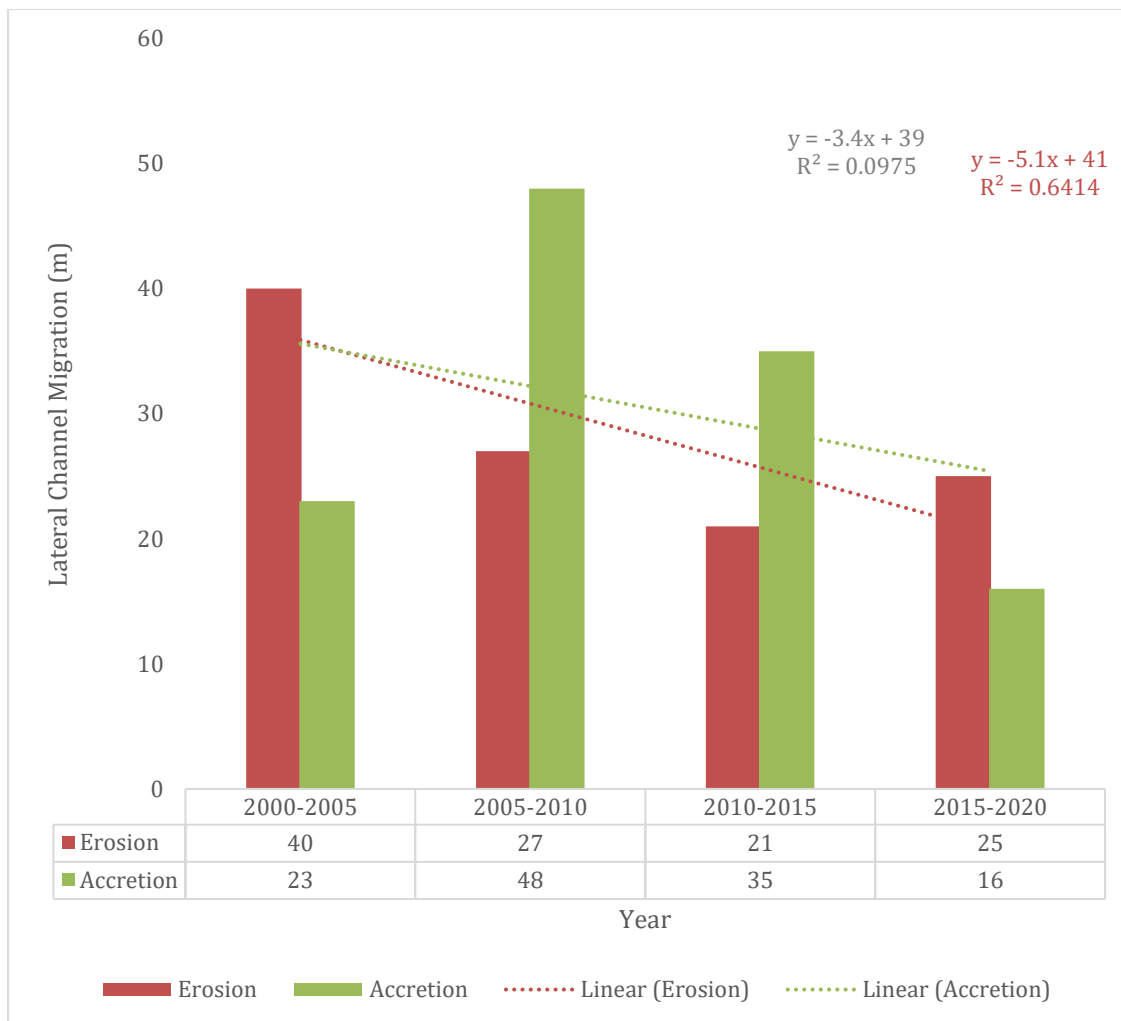


Figure 4.1 B: Right bank migration from 2000 – 2020

In 2000 – 2005, it was observed that the Nzhelele River flow channel was widened in the northern part near Pfumembe Village. During this period the gradual East ward and South-East ward shift of the Nzhelele channel resulted on a massive erosion on both the left and right banks. During this period erosion on the right bank was more noticeable than the left bank. About 4.35 km³ was eroded on the right bank at a rate of 40 m per year and on the left bank was 2.32 km³ at a rate of 24 m per year (see Table 4.1 and Figure 4.1 A and B above). Erosion on the right bank was highly intense mostly on the northern part and south-eastern part of the study. The gradual development and extension of the meander bend with the downward lateral channel migration upstream Maangani Village exacerbated erosion of the right bank with minimal erosion of 2.32 km³ on the left bank. The downward lateral channel migration resulted on a pronounced accretion of 3.77 km³ on the left bank upstream near Maangani Village, and on the central part of the study area downstream Maangani Village, as well as on the South-

eastern parts of the study area near Ha-Mandiwana and Ha-Raliphaswa village. The left bank, Figure 4.2, accretion is more noticeable than the accretion on the right bank according to its special scale and intensity with 0.97 km^3 recorded on the right bank.

During the 2005 – 2010 study period, the erosion on the left bank was 2.72 km^3 at a rate of 30 m per year with a slight increase from the previous study period and the intensity and spatial scale of erosion on the right bank was low with 1.06 km^3 at a rate of 27 m per year (see Table 4.1 and Figure 4.1 A and B). The left bank erosion occurred upstream near Maangani Village with meander bends extension on the northern, south-eastward parts of the study area near Ha-Mandiwana and Mphephu village. The left bank erosion was subjected to the gradual migration of the right bank to the westward direction and the right bank erosion was due to the slight extension of meander bends on the Westward direction downstream Maangani village (See Figure 4.3). The rate of accretion was all-time high during this period with 4.71 km^3 area accreted on the right bank at a rate of 48 m per year. The left bank experienced 3.29 km^3 of accretion at a rate of 25 m per year. As presented in Figure 4.3, the accretion was more pronounced on the right bank in the study area as a result of downward migration of meander bends near Pfumbada, Ha-Mandiwana and Mphephu Village and the Westward shift of the entire channel in the study area

The Nzhelele channel enlargement and the downward migration of the river bank caused 3.17 km^3 of area to be eroded on the left bank at a rate of 31 m per year during the 2010 – 2015 study period (see table 4.1 and Figure 4.1 A and B). Most erosion occurred upstream near Pfumembe village toward Maangani Village in the Northern part of the study area. Moreover, the erosion downstream Maangani was accelerated by the supplementary building of meander bends in a downward direction Upstream near Maangani Village and the compound bend development near Pfumbada, Ha-Maphaila, and Mphephu Villages. About 1.86 km^3 of erosion occurred on the right bank mostly concentrated downstream near Maangani Village toward Pfumbada Village in the South-Eastern part of the study area at a rate of 21 m per year. About 0.44 km^3 was accreted on the left bank at a rate of 19 m per year during this period. The accretion was more pronounced near Pfumbada and Ha-Raliphaswa Villages as result of the Westward migration of the bank line. However, accretion on the right bank was 1.18 km^3 at a rate of 29 m per year due to the slight Eastward migration of the channel upstream near Pfumembe Village and South-Eastward downstream Maangani Village (See Figure 4.4).

During the 2015 – 2020 study period, the left bank erosion was very low for the first time as compared to the previous study periods with 0.59 km^3 eroded at the rate of 9 m per year, thus being the lowest among all evaluated study periods (see table 4.1 and Figure 4.1 A and B). It was noted in the Northern parts of the study area between Pfumembe and Maangani village as a result of river channel decline and meander bends decline as well as the inward shift of the bank line. However, erosion on the right bank was 2.14 km^3 at a rate of 25 m per year concentrated in the Northern part of the study area near Pfumembe Village due to westward migration of the bank line and near Pfumbada and Ha-Mandiwana as a result of slight meander bends rotation in the South-Eastern parts of the study area (see Figure 4.5). The rate of left bank accretion on the left bank was 0.79 km^3 at a rate of 12 m per year in small portions (See Figure 4.6). The right bank accretion was 1.12 km^3 at a rate of 16 m per year. It was noticeable upstream and downstream near Maangani Village in the central parts of the study area and in the South-Eastern parts of the study area near Ha-Mandiwana and Ha-Funyufunyu Village as a result of meander bend translation and a decline in channel width (See Figure 4.7).

River bank erosion was higher than accretion on the right bank from 2000 – 2020, demonstrating a huge loss of river bank substance. A total of 9.41 km^3 river bank substance was eroded over time and a total of 7.98 km^3 deposited over time on the right bank, thus, the right river bank experienced a net loss 1.43 km^3 of river bank substance. Moreover, erosion and accretion patterns on the right river bank were completely different from the left river bank patterns. A total of 8.8 km^3 of river bank substance was eroded on the left bank of the river with 8.29 km^3 being accreted over time. The left river bank experienced a net loss of 0.51 km^3 of river bank substance as compare to the right river bank. This demonstrates an almost restoration of the left river bank regime.

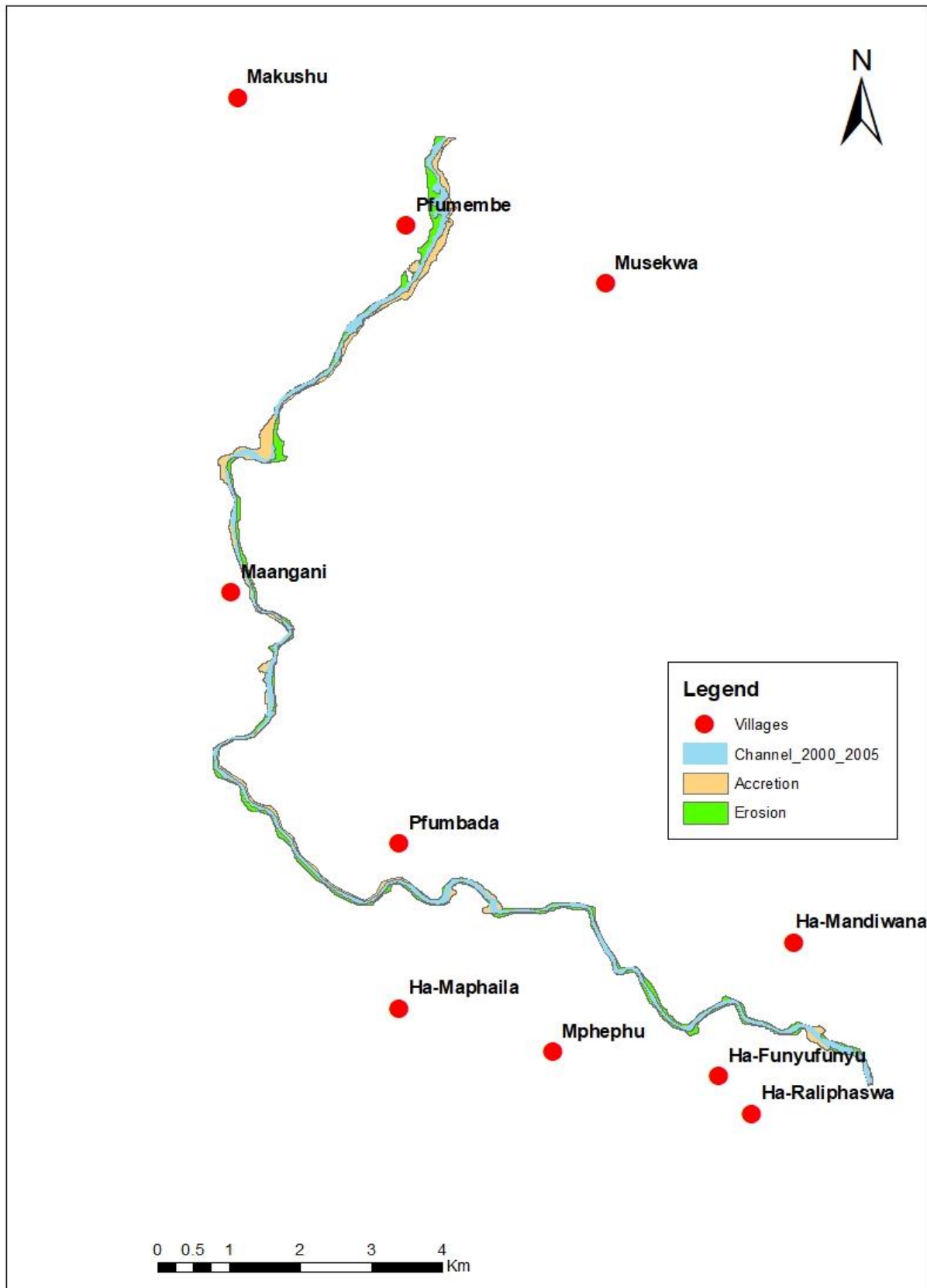


Figure 4.2: Erosion and accretion during 2000 – 2005

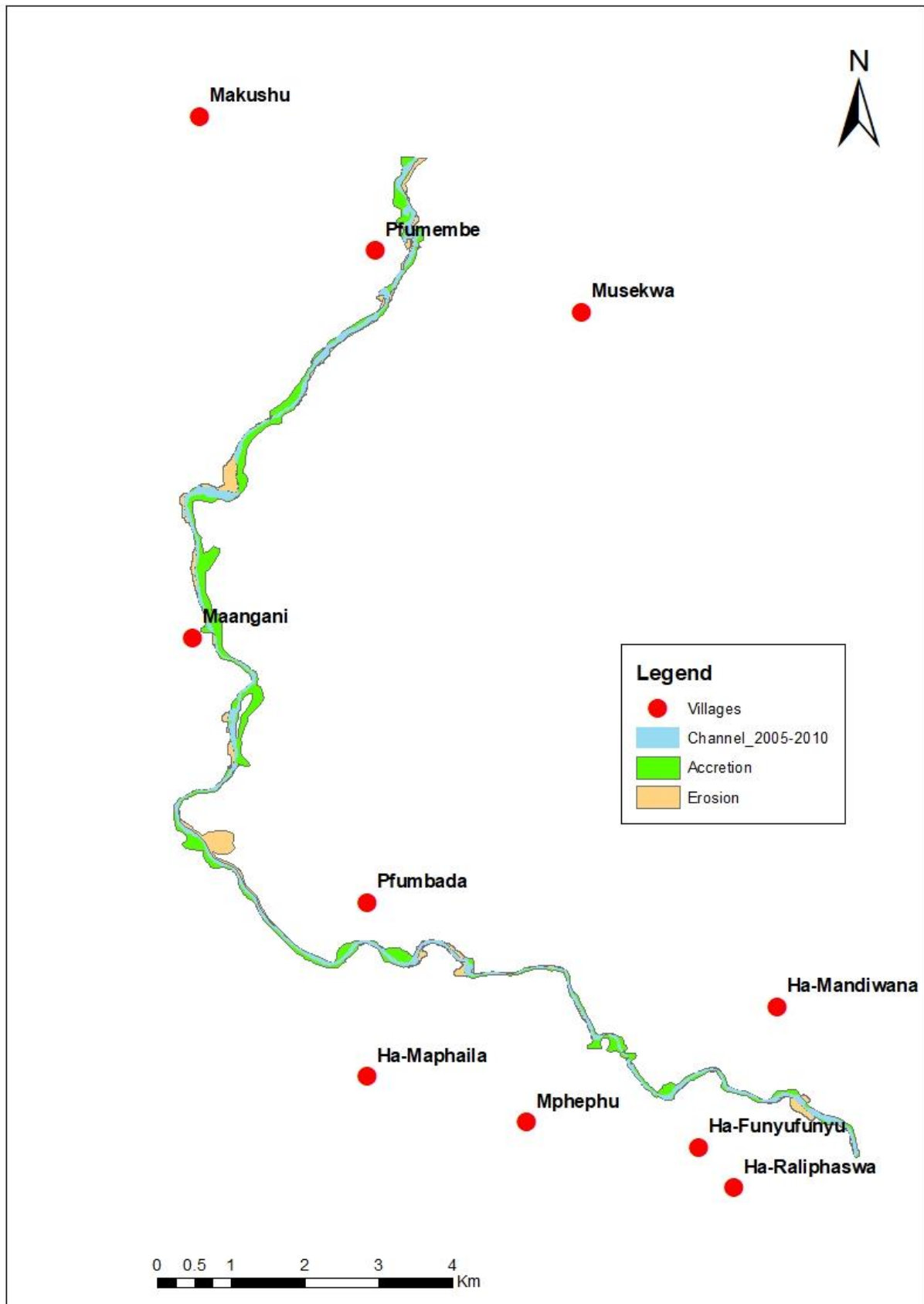


Figure 4.3: Erosion and accretion during 2005 – 2010

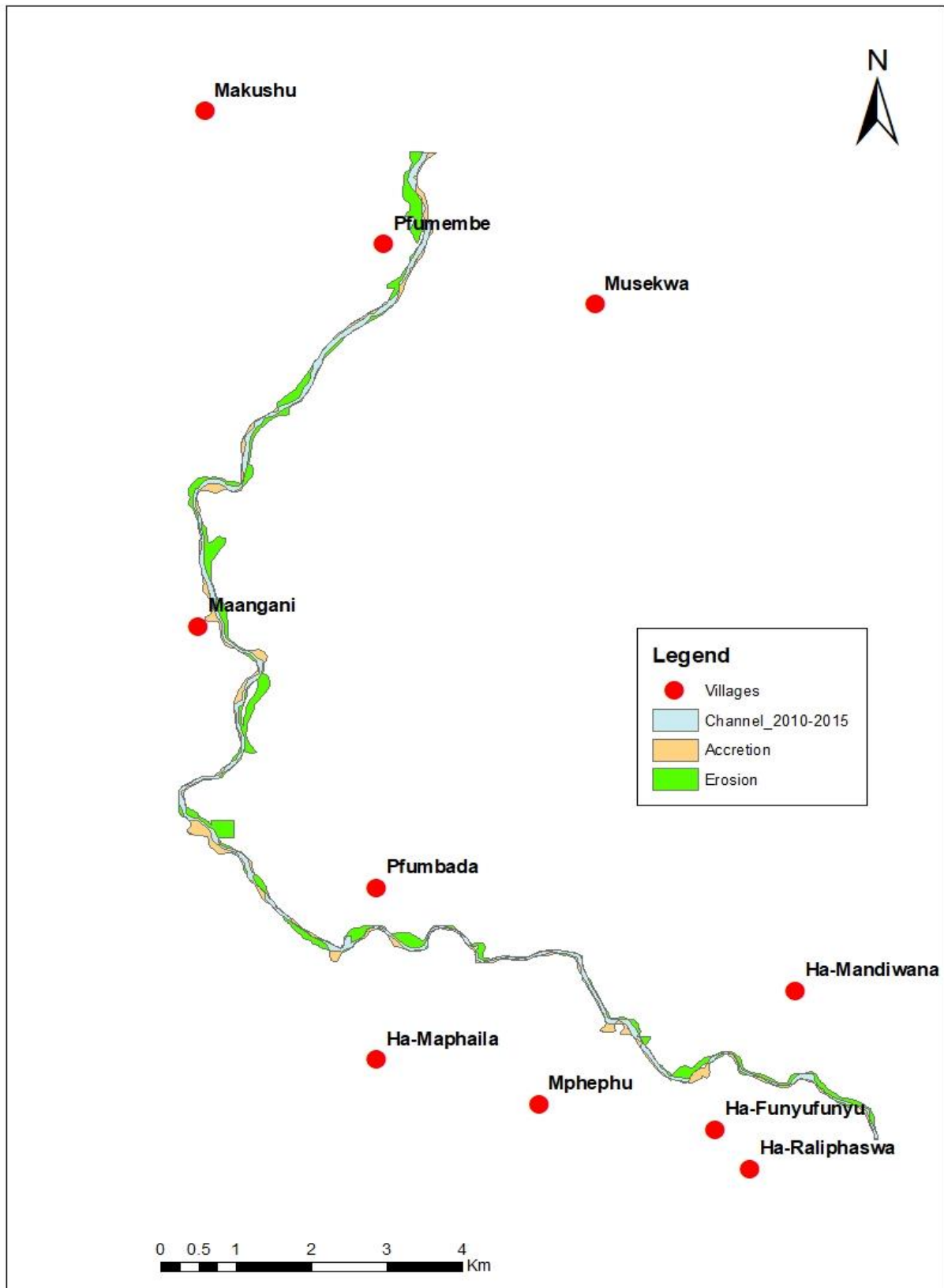


Figure 4.4: Erosion and accretion during 2010 – 2015



Figure 4.5: Evidence of riverbank erosion near Maangani Village



Figure 4.6: Evidence of accretion near Ha-mandiwana Village

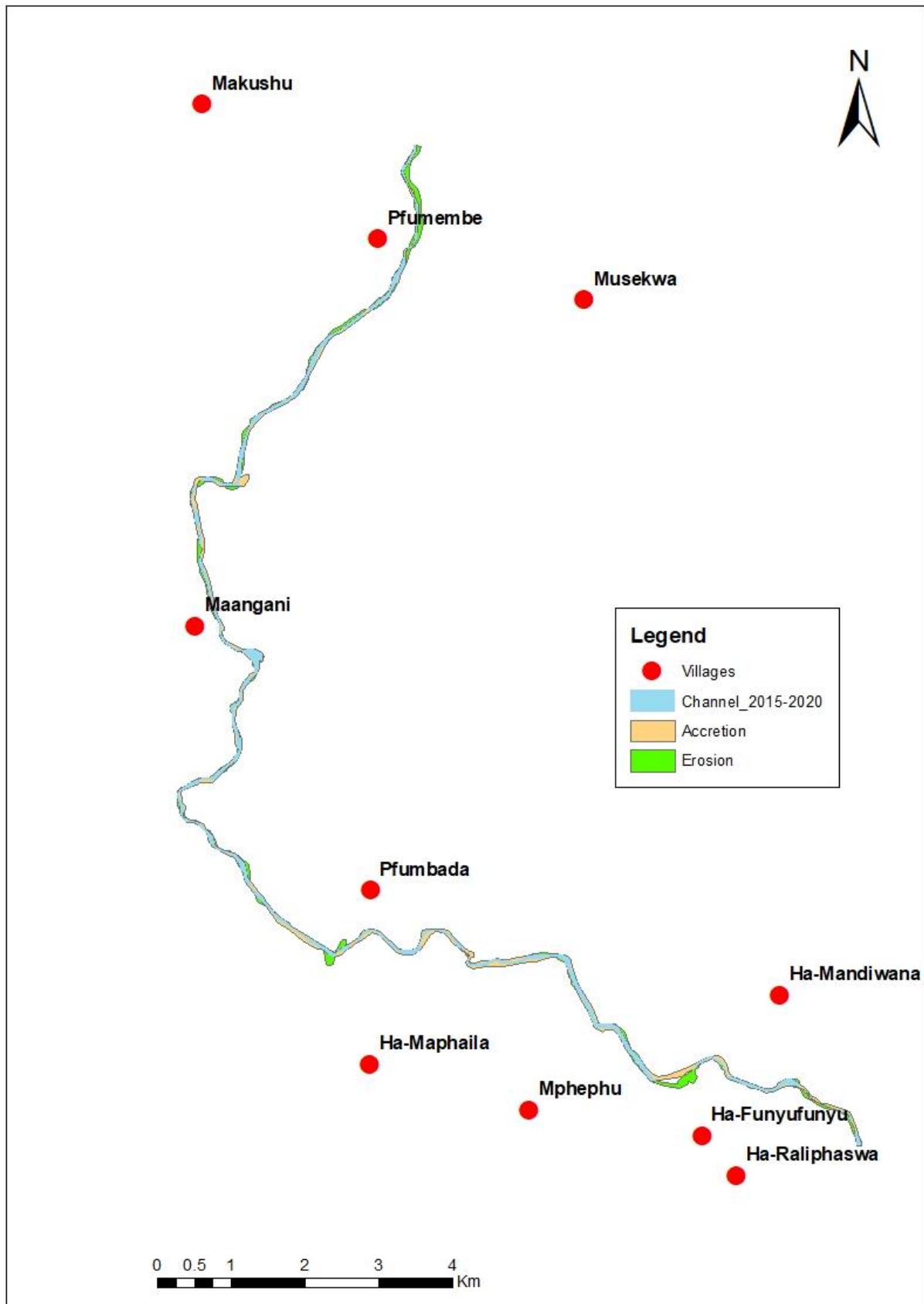


Figure 4.7: Erosion and accretion during 2015 – 2020

4.2 The potential impacts of geomorphic and anthropogenic activities on channel morphology.

This section addresses objective number two, which seeks to assess the impacts of geomorphic and anthropogenic activities on channel morphology employing sinuosity index and land-use and land-cover data derived from the classified Landsat images from 2000 to 2020. Furthermore, the sinuosity indices for 2000, 2005, 2010, 2015 and 2020 were calculate to determine the morphology of the Nzhelele River channel.

4.2.1 Spatio-temporal pattern of land-use and land-cover between 2000 and 2020

Table 4.2 shows the results of land-use and land-cover analysis of the study area and table A1 in Appendix A shows the accuracy assessment summary of the classified images that incorporates the error of omission, error of commission, producer accuracy, user accuracy and the kappa coefficient. Figure 4.8 shows the graph of classification of land-use and land-cover in the study area.

Table 4.2: Land-use and land-cover classes of the study area and coverage

Land use	2000 (%)	2005 (%)	2010 (%)	2015 (%)	2020 (%)
Water Body	2	1	2	1	1
Dense Forest	41	21	30	16	12
Sparse Forest	32	22	17	40	40
Grassland	13	26	25	22	36
Residential/ Bareland	11	28	25	20	10
Agriculture	1	2	1	1	1

In the table dense forest occupies the greatest percentage of the study area with a total area coverage of 41% and agriculture with the lowest proportion of 1% coverage in 2000, while in from 2005 to 2020 the proportion got reduced to 21% in 2005, 30% in 2010, 16% in 2015 and 12% in 2020. The proportion of agriculture remained constant in the study area with 1% coverage. There was considerable increase in residential/ bare-land coverage in 2005 with 28% of area coverage. However, there was a gradual decrease in 2010 to 2020 with 25% in 2010, 20% in 2015 and 10% in 2020. Spares forest and grassland showed similar fluctuation trend during the study period. The area coverage of spares forest was 32% in 2000, 22% in 2005, 17% in 2010 and drastically increased in 2015 with an area coverage of 40% and remaining constant in 2020 with a 40% coverage. Grassland covered an area of 13% in 2000 and increased

to 26% in 2005, then gradually decreased to 25% in 2010, 22% in 2015 and drastically increased to 36% in 2020. This is shown in Figure 4.8 below.

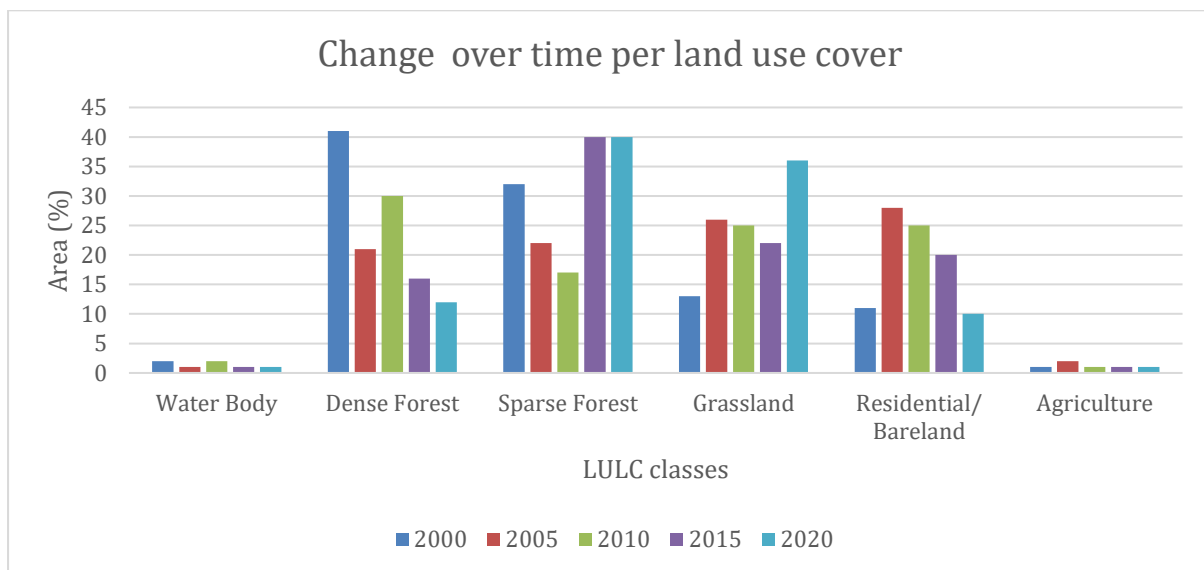


Figure 4.8: Land-use and land-cover of the study area

The land-use and land-cover pattern observed in the catchment of the study area revealed that the gradual decrease in the proportion of residential/bareland area coverage between 2005 and 2010 accounted for the decrease observed in dense forest and spares forest. Furthermore, the removal of riparian vegetation along the Nzhelele channel reach upstream and downstream Pfumembe, near Maangani village, Pfumbada, Mphephu and Ha-funyufunyu and floods that occurred in the year 2000 encouraged high rate of accretion. The changes observed in residential/ bareland in the study area primarily fell where riparian vegetation (dense Forest and spares forest) was removed indicating anthropogenic activities mainly for residential purposes and soil mining. The reliability of the classification of the land-use and land-cover classes of the study area is presented in Table A1 and the classification results of the six classes showed a substantial conformity between the classified Landsat images and the ground truth between 2000 – 2020 with overall kappa values ranging from 0.50 to 0.76.

4.2.2 The impacts of Nzhelele Dam construction

In 1948 the then Department of Water Affairs, now Department of Water and Sanitation constructed the Nzhelele Dam with a capacity of 55.3 million m³ upstream Pfumembe Village near Makushu Village. The Nzhelele Dam have since altered the runoff process, sediment transport rates and load in the Nzhelele river. The construction of the Nzhelele Dam accelerated

anthropogenic activities in the upper reaches of the Nzhelele River and these activities can be noted by downstream sediments. A total of 8.8 km³ on the left bank and 9.41 km³ on the right bank was eroded from 2000 to 2020 and the erosion was higher than accretion of 8.29 km³ on the left bank and 7.98 km³ on the right bank. The observed erosion and accretion relationship in the Nzhelele River channel existed as a result of the Nzhelele Dam that has since resulted in the reduction of the river peak flow and increase low flow conditions. Moreover, the Nzhelele Dam resulted in downstream reduction in the concentration of sediments, thus altering the erosion patterns. Additionally, the condition of river flow boundary upstream and downstream Pfumembe Village throughout Maangani Village to Ha-Funyufunyu Village resulting in the reduction of sediment discharge, the emergence of new bars and the increase of vegetation colonization. Furthermore, the reduction of the Nzhelele River flood level resulted in the alteration of the planforms of the Nzhelele River bed. The change in the Nzhelele River morphology is as a result of drastic change of sediment runoff caused by the construction of the Nzhelele Dam.

4.2.3 The potential impacts of sand mining in the Nzhelele River

Sand mining is a common anthropogenic activity frequently practiced in the Nzhelele River for many decades. There has been an increasing demand of sand in the Nzhelele communities as a result of the increase projects related to the construction of infrastructure and other developments. Consequently, severe habitat destruction, deforestation, river deterioration, floodplain destruction and the alteration of river channel structure and functionality has been recorded as the environmental impacts of sand mining in the area. Furthermore, the majority of sand mining activities along the Nzhelele River are illegal and do not consider environmental protection (Amponsah- Dacosta and Mathada 2017).

The Nzhelele River has been a source of sand supply for many decades due to its sediments on both the left and right banks for the construction of infrastructure around the Musina and Makhado local municipalities. Figure 4.8 show sand mining activities at the Nzhelele River channel and Figure 4.9 shows the major sand-mining hotspot along the Nzhelele River channel. According to the field survey conducted on the 2nd of September 2023. Seven (7) major sand-mining hotspots were detected. Two were on the left bank downstream near Pfumbe Village and the other Five (5) were on the right bank near Ha-Mphaphu, Ha-maphaila and Pfumbe Village. Excessive sand mining on both the left and right banks of the Nzhelele River has ruined the sediment transport balance and ultimately altered the planform and structure of the Nzhelele

River bed. The riverbed upstream Pfumembe Village has widened and deepened as a result of sand mining. Additionally, there is no stability between the river banks and the river channel. Sand mining has exacerbated river bank erosion upstream and downstream Maangani Village and ultimately resulted in the lateral channel migration. The Nzhelele river morphology is increasingly altered as a result of sand mining, this is because it was observed that sediment load decreased from upstream of the river due to the Nzhelele Dam, the sand mining pits downstream were difficult to be filled because of reduced sediment supply, thus leaving the river channel highly degraded resulting in excessive bank erosion downstream near Pfumembe and Pfumbada Village. Additionally, it was observed throughout the seven sand mining hotspots that the sediments discharge and the geomorphological form of the Nzhelele River was highly impacted and the sediment storage of the river was altered.



Figure 4.8: Sand mining activities at Nzhelele River

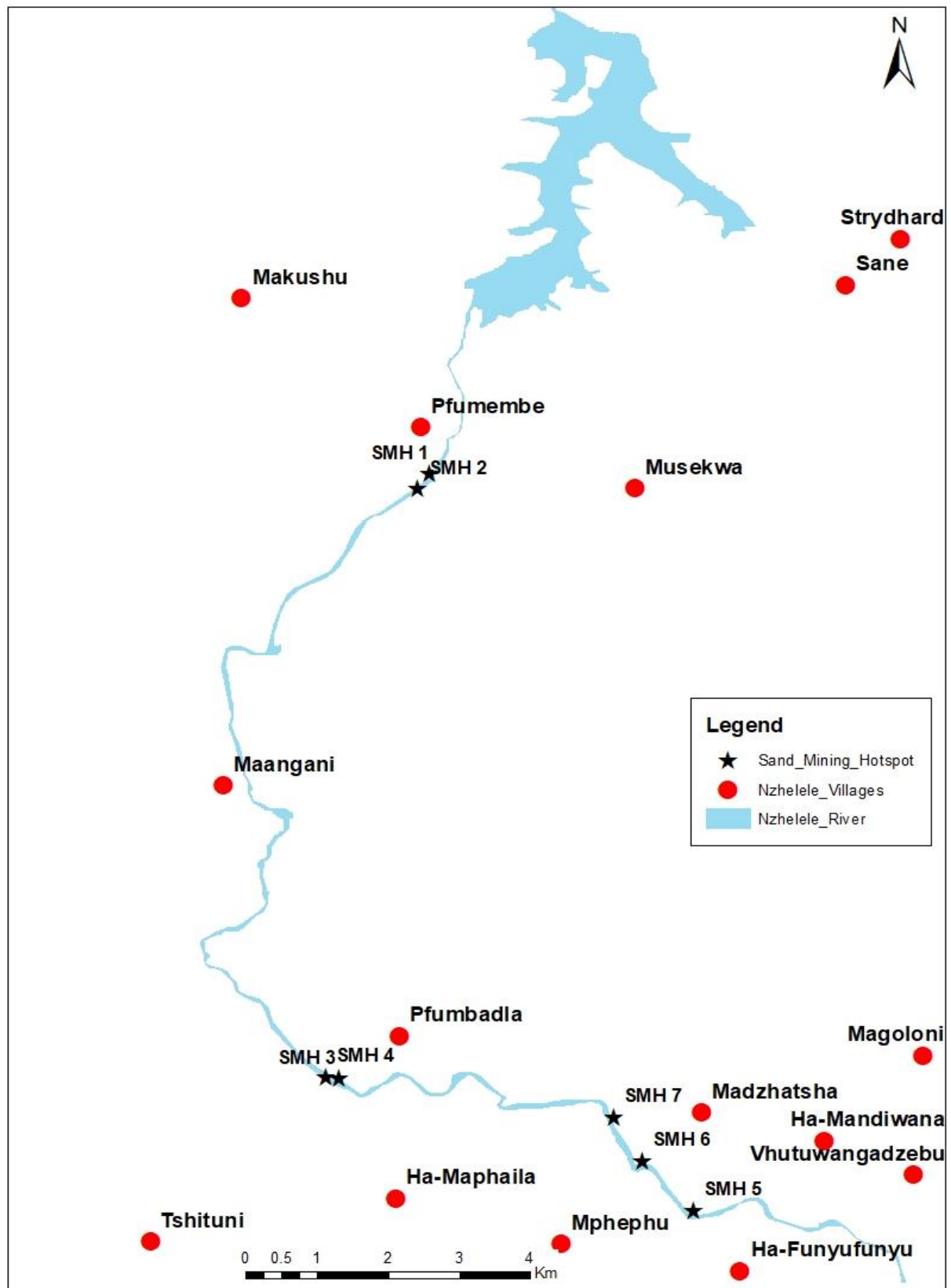


Figure 4.9: Sand mining hotspots in Nzhelele River

4.2.4 The potential impacts of residential area expansion

The extensive expansion of residential area in the study area has impacted the morphology of Nhelele River. It was observed that between 2005 and 2015 the residential area/ bareland coverage was high. Furthermore, with the extensive expansion, change was observed on channel width. The Nzhelele River channel width has been narrowing since 2005 with the expansion of residential area in the study area. The land-use and land-cover evolution maps shows that since 2005 dense forest, sparse forest as well as riparian vegetation were cleared and residential/ barelands have appeared next to the Nzhelele River channel near Pfumembe village, Maangani Village, Pfumbada Village, Ha-Maphaila and Ha-Funyufunyu Village, thus, the width of the river channel near these villages has narrowed. With the expansion of residential area, the practice of excessive sand and gravel mining in these areas also increased too, causing changes in the Nzhelele River sediment dynamics. The Nzhelele River sediments in these areas is over exploited, thus causing high river bank erosion to recover for the lost sediments.

4.2.5 The potential impacts of agriculture

It was observed during the field survey that maize and vegetables were the most common crops being farmed along the Nzhelele River channel for food and to be sold locally. It was noted that the bank erosion change from 2000 to 2020 shaped the land-use and land-cover of the study area, thus vegetation cover clearance and agriculture caused major river bank erosion near Mphephu and Ha-Maphaila villages. Additionally, near Pfumbada Village, the Nzhelele floodplain was altered, soils were affected and eroded from near-by farm causing distinct bank erosion and accretion process over time. The eroded soils from the near-by farm resulted on the accretion on the left river bank and high erosion on the right bank. Furthermore, in villages such as Mphephu, Ha-Maphaila and Pfumbada, it was observed that the Nzhelele River channel was narrowed and flow discharge was increased in small sections. Figure 4.10 shows agricultural practices along the Nzhelele River channel.

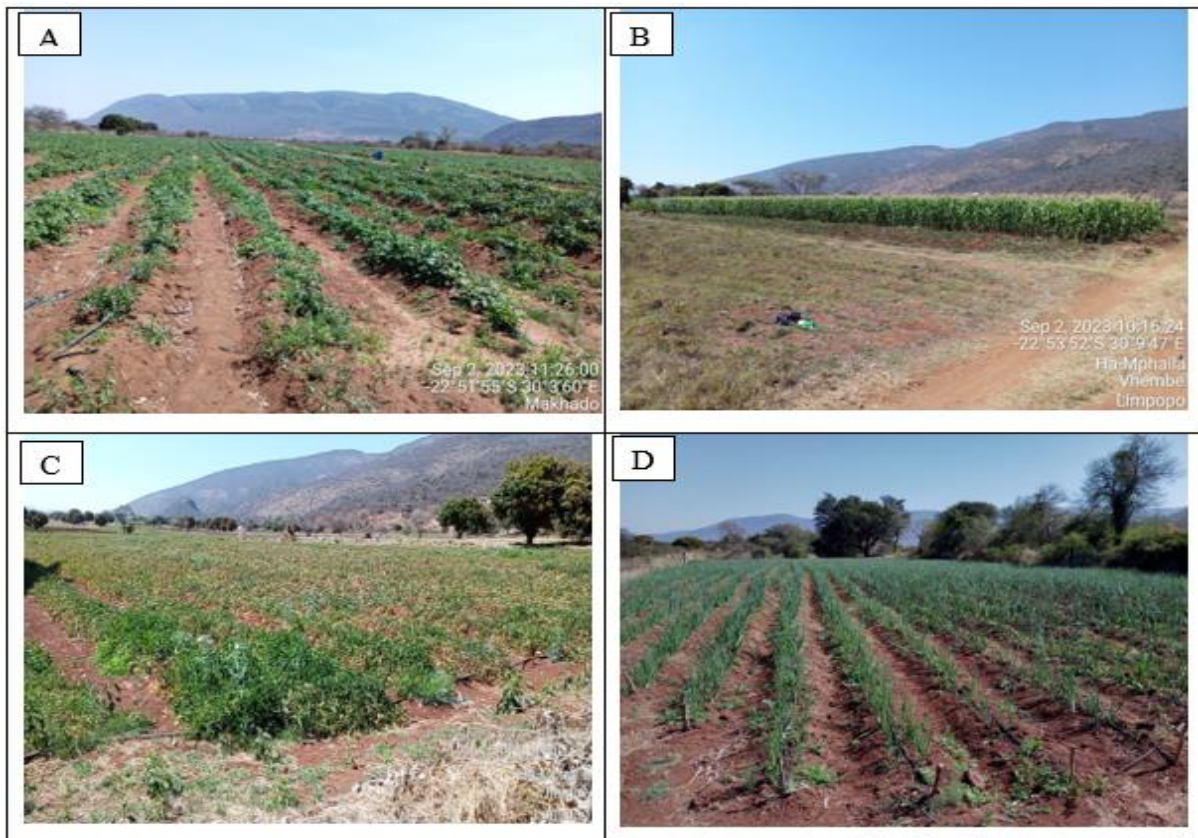


Figure 4.10: Agricultural activities present along Nzhelele River channel. A potato farm at Pfumbada Village; B Maize farm at Ha-Maphaila Village; C Tomato farm at Ha-maphaila Village, and D Onion Farm at Mphephu Village

4.3 The assessment of Nzhelele River Sinuosity index

The Nzhelele River sinuosity index exhibited an increasing trend from 2000 to 2010, and it gradually declined thereafter. The discrepancy of sinuosity index assessment presents an estimation of the Nzhelele River erosion, accretion and lateral channel migration. The discrepancy of the Nzhelele River sinuosity index assessment can be directly associated with its discrepancy in erosion and accretion. Figure 4.11 show the Nzhelele River sinuosity index.

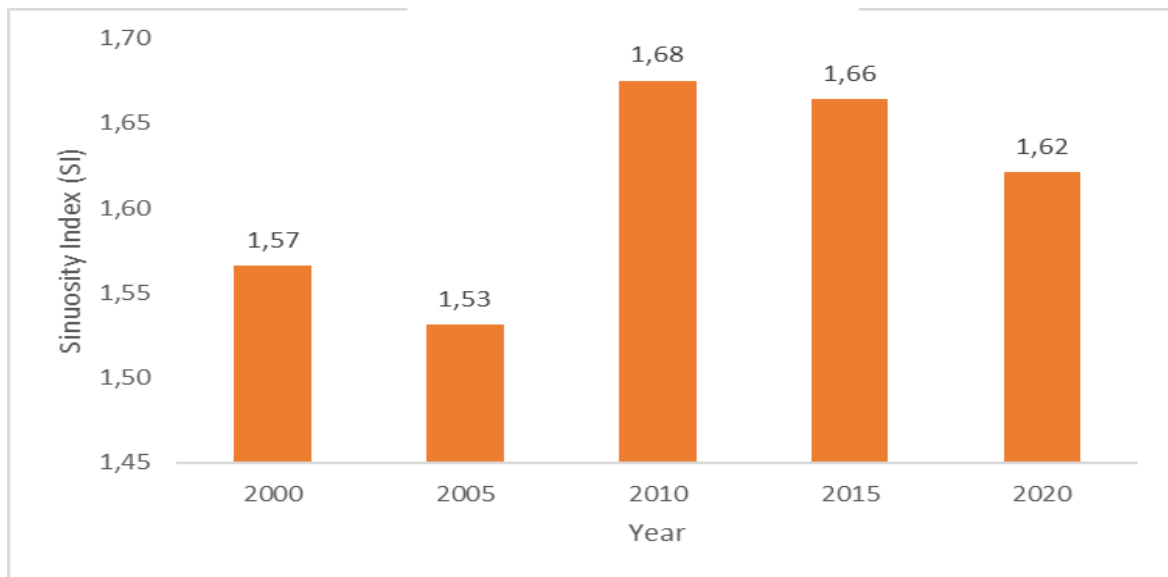


Figure 4.11: Nzhelele River sinuosity index

It was observed that the increase in erosion during the study period must have resulted in the increase of sinuosity, thus triggering a westward lateral migration of the Nzhelele River channel from 2000 to 2020. The Nzhelele River length in 2000 was 23 km and the sinuosity index was 1.57, 22.436 km in 2005 and sinuosity was 1.53, 24.44 km in 2010 and sinuosity was 1.68, 24.124 km in 2015 and sinuosity was 1.66 and 23.809 km in 2020 and sinuosity was 1.62 as presented in Figure 4.11. The Nzhelele River is a meandering river according to the assessment of sinuosity index. It was observed that the Nzhelele River channel migration was low in 2005 with the lowest sinuosity index of 1.53 and the erosion during this period was 2.72 km³ on the left bank and 1.06 km³ on the right bank. Moreover, the channel migration then increased in 2010 and during this period the erosion was 3.17 km³ on the left bank and 1.86 km³ on the right bank. However, the sinuosity then declined in 2015 to 2020 with the sinuosity of 1.66 and 1.62 respectively and during this period erosion was 0.59 km³ on the left bank and 2.14 km³ on the right bank (see Table 4.1). The decline in sinuosity is associated with reduced river dynamics, and channel bars reduction as a result of the present anthropogenic activities in the study area. It was observed that there was no drastic change on stream length, rather a slight change in length from 2000 to 2020 since the lowest length was 22.346 km in 2005 and the highest length being 24.44 km in 2010. It is observed that over the periods, the Nzhelele River channel length showed a constant trend with slight changes, which means that the channel has maintained its meandering course.

4.4 Spatio-temporal evolution of Nzhelele River channel morphology

This section presents the time series modeling and forecast of the erosion and accretion of the Nzhelele River channel. The time series analysis components such as the seasonal component and the trend component were employed to forecast erosion and accretion of the left and right banks of the Nzhelele River channel. Table 4.3 represents the forecast of the Nzhelele River channel morphology based on the erosion and accretion, with the corresponding graphs in Figure 4.12 A and B.

Table 4.3: Nzhelele River channel morphology forecast

Bank	Left Bank			
Year	Erosion (km ³)	Erosion Forecast (km ³)	Accretion (km ³)	Accretion Forecast (km ³)
2000-2005	2.32	2.71	3.77	3.84
2005-2010	2.72	2.94	3.29	2.66
2010-2015	3.17	3.96	0.44	1.48
2015-2020	0.59	1.40	0.79	0.30
2020-2025		1.62		0.88
Bank	Right Bank			
Year	Erosion (km ³)	Erosion Forecast (km ³)	Accretion (km ³)	Accretion Forecast (km ³)
2000-2005	4.35	4.63	0.97	2.46
2005-2010	1.06	2.84	4.71	5.15
2010-2015	1.86	2.06	1.18	1.84
2015-2020	2.14	2.38	1.12	1.73
2020-2025		2.40		1.23

It is of vital importance to acknowledge that the forecast of erosion and accretion of the Nzhelele River channel may not correspond exactly with the reality at the study area. According to the forecast computed by the time series analysis, the erosion on the left bank is forecasted to be 1.62 km³ and 1.90 km³ on the right bank for the year 2020 – 2025. Additionally, the accretion on the left bank is forecasted to be 0.88 km³ and 1.23 km³ on the right bank for the year 2020 – 2025. The forecast in the study area indicates that the right bank of the Nzhelele River channel will continue to be more vulnerable to erosion than the left bank in the near future. The time series analysis forecasted results are lower than the calculated historical data of erosion and accretion from 2000 – 2020 in the study area. During the 2020 – 2025 period, the forecasted results indicate a gradual widening of the river channel from the narrowed river channel of the previous years of 2015 – 2020 as a result of higher forecasted erosion rate most

especially on the right bank. Additionally, the left bank will experience low erosion and accretion as compared to the right bank. However, the forecasted values of erosion and accretion are higher than of the previous study period suggesting channel expansion.

The forecast brought forth awareness to 9 villages, including Pfumembe, Musekwa, Maangani, Pfumbada, Ha-Maphaila, Mphephu, Ha-Mandiwana, Ha-Funyufunyu, and Ha-Raliphaswa will susceptible to high risk of erosion in the future. Only 3 villages out of 9 are located on the right bank of the Nzhelele River channel. The forecast results of erosion and accretion emphasizes the importance of setting out a plan of action designed to achieve long term erosion and accretion management in the Nzhelele River channel given the wide spread erosion on the right bank.

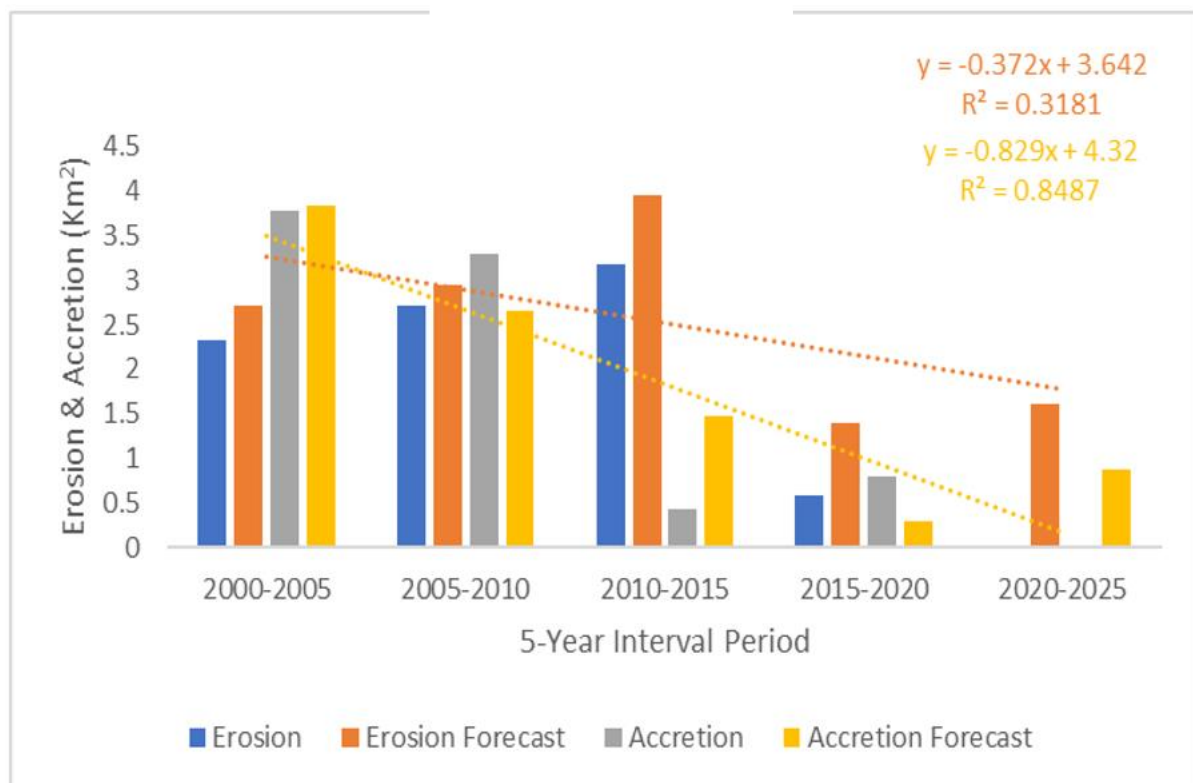


Figure 4.12 A: Left bank erosion and accretion forecast graph

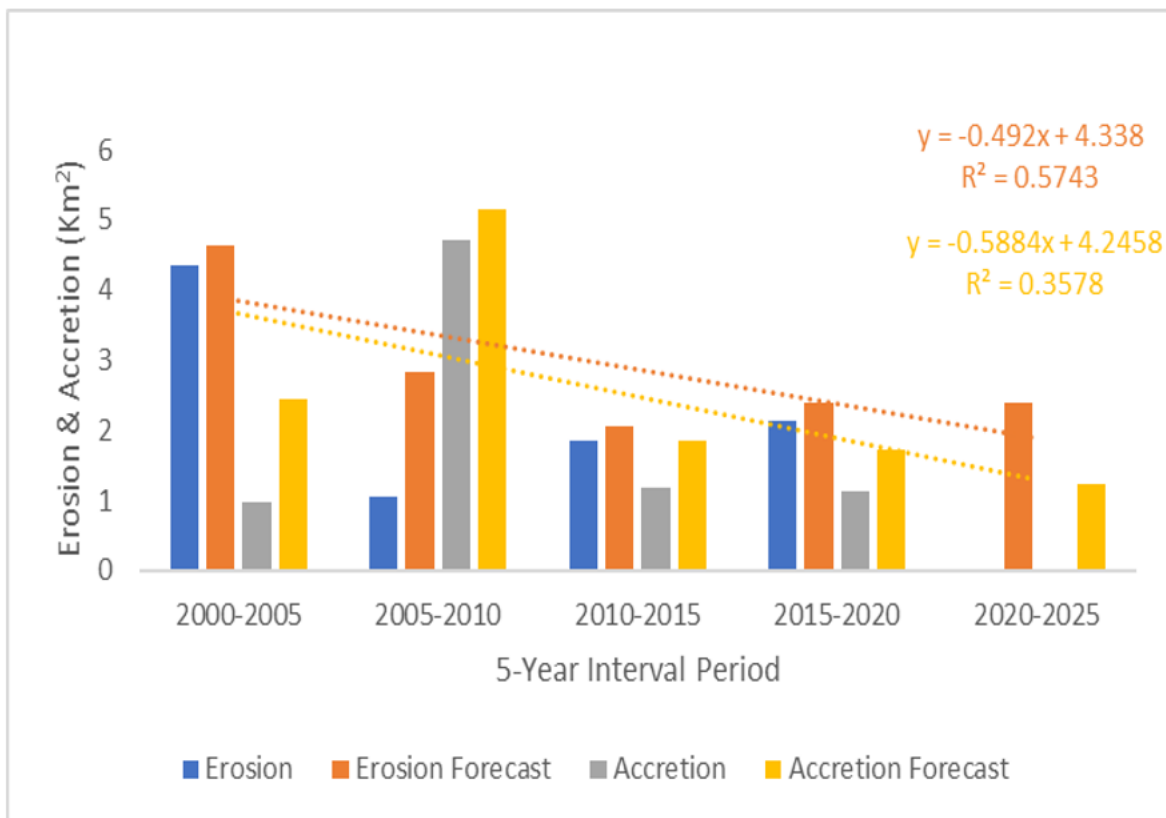


Figure 4.12 B: Right bank erosion and accretion forecast graph

5 DISCUSSIONS

The study's objectives and outcome form the basis for the analysis and interpretation of the findings. The results presented in Chapter 4 are discussed and interpreted in this chapter. The discussion and analysis of the findings are also consistent with the study's anticipated outcomes. The study's findings are backed up in this section by the body of current scientific research. It is also discussed whether the approaches taken to achieve the objectives are valid. This section provides answers to the research questions that were posed in the first chapter based on the information gathered and provided in this chapter.

The first objective was to assess the spatio-temporal variation of Nzhelele River morphology. This was followed by the assessment of the impacts of geomorphic and anthropogenic activities on channel morphology. The third objective was to forecast the spatio-temporal evolution of Nzhelele River channel morphology using GIS and time series modelling. Based on the literature review, the following outcomes were expected for each objective. The application of remotely sensed satellite data should show all the attributes of Nzhelele River, as well as the interplay of both natural and anthropogenic factors, shaping the Nzhelele River morphology from 2000 to 2020. The projection of the Nzhelele River morphology evolution will provide effective information to various scientific disciplines locally and nationally that will facilitate the management and sustainable use of the Nzhelele River resources.

5.1 Nzhelele River sinuosity index

The analysis of the study shows that the variation in sinuosity index from 2000 to 2020 demonstrate the meandering of the Nzhelele River is fluctuating. The Nzhelele River is sinuous, among the river five study periods such as 2000, 2005, 2010, 2015, and 2020 the Nzhelele River of 2010 is more sinuous (1.68) than the preceding years and post 2010. The Nzhelele River vary in sinuosity index from 1.57 in 2000 to 1.62 in 2020. In 2000, the sinuosity was attributed by the preexisting morphology and the lateral migration process of the Nzhelele River, whereby the planform was altered by the spatial patterns of erosion and accretion on the river banks. The Nzhelele River's sinuosity index dropped to 1.53 in 2005 due to a decrease in lateral river migration and erosion. Lateral channel migration determines sinuosity in meandering rivers such as the Nzhelele River (Schumm, 1977).

Varying river sinuosity in Africa is well documented in the scientific literature (Mvondo et al., 2011; Eze and Knight, 2018; Flemming and Martin, 2021; Knight and Evans, 2022). The downstream of river channels is characterized by a declining slope that can be described by the concavity of a river. Concavity of a river is the extent to which the slope of a channel declines with distance downstream (Whipple, 2004; Whipple et al., 2022). The present study did not analyse the concavity of Nzhelele River; however, it can be argued that with the increase of sinuosity in 2010, the concavity of the Nzhelele River channel also increased during 2010. The variation in the geometry of the Nzhelele River caused by the increase in sinuosity resulted in excessive left bank erosion during this period (see table 4.1). this variation in geometry also resulted in the formation islands within the river. Additionally, the variation in meandering of the Nzhelele River upstream and downstream Maangani Village, near Pfumbada and Mphephu Village and near Ha-Funyufunyu may be argued to be characterized by the decline of water discharge, erosion and accretion and the geomorphological attributes of both the left and right banks. The variation in the Nzhelele River morphology affect the river's sinuosity index. Hence, the gradual decline in sinuosity index from 2015 to 2020. The anthropogenic activities along the river channel need to be taken into consideration due to their long-term effect on sinuosity upstream and downstream

5.2 Patterns on the Nzhelele River morphology and the potential impacts of anthropogenic activities

The Nzhelele River channel assessment of bank erosion, accretion and lateral channel migration were conducted from 2000 to 2020. Figure 5.1 shows the overall erosion and accretion from 2000 to 2020. The analysis of the Nzhelele River channel morphology showed both minor and major variations on the study reach. The present study demonstrated that the analysis of the spatio-temporal variation of the Nzhelele River morphology describes the evolutionary trajectory of the Nzhelele River.

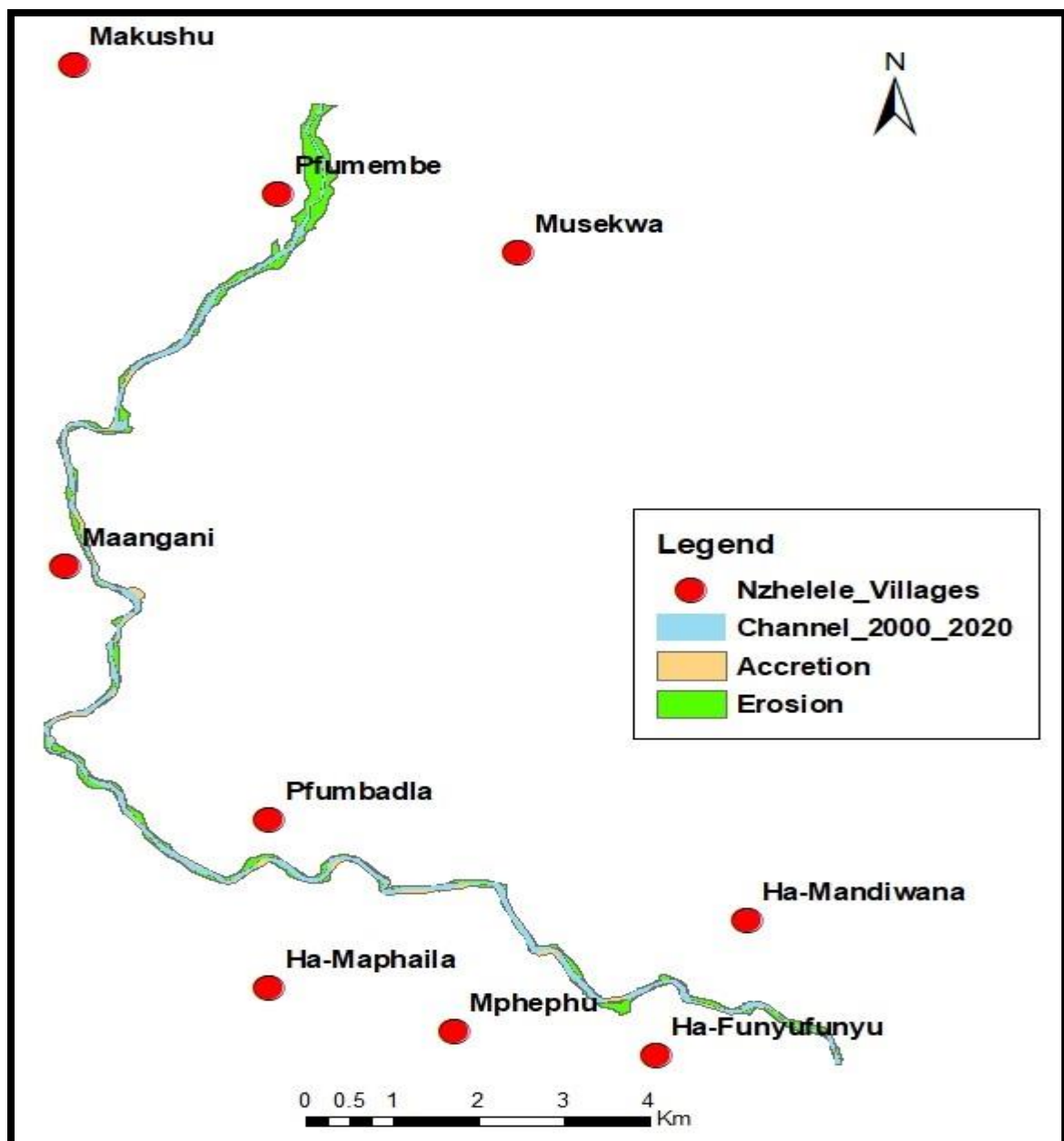


Figure 5.1: Overall erosion and accretion from 2000 - 2020

It was observed that widening of the Nzhelele River channel, extension, translation, and rotation of the meander bends caused major bank erosion and accretion as well as the lateral channel migration. These resulted on the Nzhelele River banks changing their positions over the study period thus principally contributing to the morphological variations of the channel primarily along the alluvial reaches. Furthermore, taking into consideration the trends of erosion, accretion and lateral channel migration. The right bank experiences high erosion that the left bank and accretion was high on the left bank. Erosion and accretion were all time high in 2000 – 2005. It can be argued that natural factor such as the 2000 flooding event and other

anthropogenic factors such as sand mining, Agriculture, and expansion of settlement exacerbated erosion and accretion during this study period. The impacts of natural and anthropogenic factor on river bank erosion and accretion are widely acknowledged in the scientific literature (Mahe et al., 2013; Ibitoye, et al., 2016; Wang et al.,2020).

During the 2015 – 2020 study period, the planform of the Nzhelele River bends became narrower, thus, indicating that the meander bend extensions noted in the study area cannot determine the spatio-temporal evolution of the Nzhelele River. Moreover, in several areas such as downstream Pfumembe, Maangani, Mphephu and Ha-Maphaila village, meander bend extension, translation and rotation were observed. These could be associated with the natural and anthropogenic factors present in the study reach. Brookes (1987) indicated that increased erosion result in the increase of stream velocity. There is a significant breakthrough in the assessment of the influence of natural and anthropogenic factors in the rate of planform evolution since the mapping of the interplay between these factors is effective when GIS and remote sensing methodologies are employed. The decline in the Nzhelele River bed has led to an increase in river bank height as observed during site survey on the 2nd of September 2023. This result in the variability of river bank substance, that causes the primary development river bank erosion and meander bends. It is imperative to indicate that the present study did not conduct river bank heights analysis, however, it was evident during site survey.

The operation of exhaustive river bank erosion has been discussed by Gautier et al., (2007) and Rusnak et al., (2016) to be a result of effective river discharge in the absence of riparian vegetation. Additionally, geomorphic, hydrological factors, river bank substance (Rhoads and Welford, 1991; Konsoer et al., 2016), variation in flood frequencies, water discharge and land use (Phillips, 2002; Micheli et al., 2004; Rusnak and Lehotsky, 2014; Gumiero et al., 2015), is scientifically acknowledged as the root cause of meander bends extension, rotation, and translation. The assessment of the Nzhelele River erosion, accretion and channel migration will facilitate effective erosion and accretion management, it is very crucial to determine its intensity rate. This is because the rate of river bank erosion and accretion can range from a few square kilometers to several square kilometers per year. During the 2000 – 2005 study period an exceptional river bank erosion of 4.35 km³ and 0.97 km³ accretion on the right bank were observed.

The management of the Nzhelele River channel needs the understanding of the conditions of its bank erosion and accretion. It can be argued that the March 2000 flood event that occurred on the Nzhelele River channel caused the river to rise at an accelerated rate, thus causing an intensive scouring and accretion on the Nzhelele River banks. Additionally, with the type and density of riparian vegetation (Perucca et al., 2007) present during the flood, determined the rate and intensity of erosion and accretion. Locally, scientific studies about the Nzhelele River are concentrated on modelling rainfall run-off (Makungo et al., 2010), drinking water quality (Edokpayi et al., 2018), river health assessment (Mokgoebo, 2019), impacts of sand mining (Sengani, and Zvarivadza, 2019), and community livelihoods and landscape change (Musakwa et al., 2020; Vessal et al., 2020). Little attention has been given with regard to the Nzhelele River bank erosion, accretion and lateral channel migration. Studies on the morphology of the Nzhelele River are limited. Anthropogenic activities were observed from the study results near Pfumembe, Maangani, Pfumbada, Mphephu and Ha-Maphaila villages where meander bend extension was developed. These activities resulted in a significant meander bend extension, rotation and translation according to the study results.

The Nzhelele River channel spatio-temporal morphological variation is impacted by natural and anthropogenic activities. Research studies of anthropogenic impacts on river morphology are widely acknowledged in the scientific community (Gupta and Liew, 2007; Preciso et al., 2012; Wang et al., 2020). Concerning the Nzhelele spatio-temporal morphological variation, although there is paucity of historical data, the analysis of the present study shows that the river channel has been narrowing since 2005. The 2000 flood event has triggered alarming morphological changes on the Nzhelele River. Although floods are occasional, the 2000 flood event has caused major changes on stream flow and sediment discharge during the 2000 – 2005 study period. The analysis shows that the Nzhelele River has been shifting while river bank substance attributes together with the variation of high and low water area, thus, causing adverse bank erosion and accretion.

The stage 3 of anthropocene, where river morphological studies, including this present study and others similar studies, will effectively bring-forth knowledge and skills to pinpoint anthropogenic and natural processes and trends such as global warming impacts on floodplain and will have significant contribution on the establishment of a successful environmental management programme (Goudie, 2020; Pijl et al., 2018; Grill et al., 2019; Słowik, 2015; Brown et al., 2017). Additionally, contemporary scientific studies on the spatio-temporal

evolution of climate change and global warming impacts on river bank erosion trends in areas with accelerated anthropogenic activities could effectively contribute to the prediction of planform and fluvial landform deterioration trends in reaches where there is accelerated erosion (Rodrigo-Comino et al., 2019).

The Nzhelele River channel have experienced exceptional adjustment such as riverbed deterioration, variation in river flow pattern and river channel width declination as a result of land -use and land-cover changes caused by anthropogenic activities such as the Nzhelele dam construction, agriculture, sand mining and settlement expansion. The spatio-temporal variations in land-use and land-cover changes as observed from the study analysis are not unexpected in the study reach. The study area experienced a 36% decrease in dense forest cover between 2000 and 2020. The principal cause of the result is residential expansion that is associated with vegetation clearing. Between 2000 and 2020, the Nzhelele River channel was subjected to a number of anthropogenic impacts that were noted to have made adjustments to the attributes of the channel. It is very important to indicate that, the effectiveness of the observed anthropogenic impacts need much effort to assess because they are interconnected and overlap in a way that incorporates a combination of driving factors.

The Nzhelele river bed degraded in various parts of the study area such as near Maangani, Pfumember, Ha-Maphaila and Mphephu village. It must be noted that the present study did not make analysis on sediment size in the Nzhelele River, however, it was observed during field survey that the extent of the degradation of the riverbed incorporated a coarse-grained sediment with the visibility of bedrock outcrops (See Figure 5.2 below for the location of villages). This can be argued to be caused by the accelerated sand mining activities for the increasing local infrastructure development and a decline of sediment supply downstream as a result of the construction of the Nzhelele Dam. River bed destruction resulting from anthropogenic activities is widely acknowledged in the scientific literature (Gupta and Liew, 2007; Preciso et al., 2012; Wang et al., 2021).

The Nzhelele River channel narrowing from the observed analysis started in 2005. The Nzhelele River underwent significant changes in channel patterns. This is because it was observed that during the 2005 – 2010 period, the channel near Pfumembe Village changed its flow toward Maangani village, thus sediment reduction from the increasing sand mining, Nzhelele Dam construction and forest clearing caused by residential expansion were the

observed anthropogenic activities. These anthropogenic activities altered the river flow discharge, the transportation of sediment, and streambed deterioration. According to the analysis of the study, the current Nzhelele River channel situation can be schemed by a man affected river system model as advanced by Schumm (1977). This is because the river is no longer transporting and supplying sediments downstream as a result of Nzhelele Dam construction and sand mining activities. Additionally, there is no longer a natural balance between incoming and outgoing sediments. Furthermore, the sediment flux and stream flow discharge are altered because of the presence of the Nzhelele Dam, together with streambed mining activities that serves as the only source of coarse sediments in the area. This has resulted in accelerated river bank erosion and river channel degradation.

5.3 Nzhelele River channel morphology forecast

The Nzhelele River course is affected and altered by factor that are multisource. The sediment and hydraulic attributes of a river are related to the variation of the river course. the alteration of a river morphology is determined by the degree to which sediments are transported and the flow of the river course (Malik and Pal, 2019; Karki, et al., 2019; Suresh, et al., 2022). There is a significant relationship between the erosion, accretion, and sediment concentration, condition and transport in the Nzhelele River channel. Additionally, the significant relationship between the Nzhelele River channel, erosion and accretion may be argued to be attributed to the sediment reduction that determines the balance between erosion and accretion, thus, contributing to the deepening of the riverbed that causes the alteration of the river channel and consequently, causing erosion. Therefore, it can be observed from the analysis that the Nzhelele River is generally eroded, which may be argued to be caused by the accelerated sediment mining, flow regime alteration by the construction of Nzhelele Dam, and the decline of sediment supply to the river to replenish the mined sediment pits.

The time series forecast of the Nzhelele River morphology, the erosion forecasted to be 1.62 km³ and 1.90 km³ on the right bank for the year 2020 – 2025. Additionally, the accretion on the left bank was forecasted to be 0.88 km³ and 1.23 km³ on the right bank for the year 2020 – 2025 (see table 4.3 and Figure 4.6 A and B). The forecast of the overall erosion and accretion of the Nzhelele River and the accuracy of the forecast method and its difficulty is compromised by the choice of the forecast method. However, the clarity of the time series method, its cost effectiveness and the low performance impact were the main advantages in the present study.

On the other hand, the main disadvantage of river morphology forecast is attributed to the data availability of the river channel.

The present study experienced difficulties in obtaining historical morphological data of the Nzhelele River channel, thus, this was the gap the study identified. The more advanced execution and the clarity of the time series method in the present study, can bridge the gap in river channel with limited data availability, such as the Nzhelele River in the rural areas of South Africa. Further, there is paucity of technical modelling skills and the comprehension of the river channel and the dynamics of river sediments. Moreover, the forecast of the Nzhelele River morphology was based on previous morphological observations of erosion and accretion and the forecast was computed based on the past lead times from the beginning. Table 4.3 presents the forecasted erosion and accretion on both the left and right bank of the Nzhelele River. The highest forecasted erosion was 2.40 km³ at the right bank for 2020 - 2025. The forecasted values by the time series are higher as compared to the previous study period of 2015 – 2020. The forecast demonstrates that the erosion will dominate on the right bank and it will continue in the future. The forecasted results emphasize the importance of establishing local techniques to effectively manage erosion and accretion most especially the susceptible right bank of the Nzhelele River.

6 CONCLUSIONS AND RECOMMENDATIONS

The study is concluded in this chapter. The degree to which the study's aim and objectives were met determines the study's conclusion. This includes recommendations, a summary of the study's findings, and some ideas for further investigation.

6.1 Conclusions on the results of the study

The assessment of the spatio-temporal variation of Nzhelele River morphology such as erosion, accretion and lateral migration over two decades (2000 – 2020) provided the opportunity to understand the Nzhelele River system. The employment of Landsat images, GIS and RS technology to assess the spatio-temporal variation of the Nzhelele River were effective to map the eroded and accreted areas of the river as well as to assess the migration of the bankline and river channel from 2000 to 2020. Furthermore, the GIS and remote sensing technology facilitated effectively the assessment of the Nzhelele River sinuosity indices and the temporal scales of the river banks.

The study discovered a significant variation in Nzhelele River morphology, demonstrating a declining trend with regard to the width of the river, its channel sinuosity and a deterioration in river conditions from 2000 to 2020. Meander bends were extended, translated and rotated. Additionally, the hydrological conditions deteriorated while the anthropogenic activities present in the study area impacted the morphological processes. The Nzhelele River erosion and accretion, although they were high during the initial study period, their important function showed to decrease during the last study period of 2015 – 2020. The variation of Nzhelele River morphology were significant in the study. This is because the river was eroded and accreted from 2000 to 2020 with a total erosion of 8.8 km³ on the left bank and 9.41 km³ on the right bank. Accretion totaled 8.29 km³ on the left bank and 7.98 km³ on the right bank. Both river banks were eroded and accreted. However, erosion was high on the right bank than on the left bank, and accretion was high on the left bank than on the right bank.

The Nzhelele river water surface area decreased, and the bank of the river increased. The study considers the erosion and accretion processes as principal determinants that have an effect on the lateral migration of the Nzhelele River bankline and the river channel. The Nzhelele River is considered to be a meandering river a result of its flow structure and sinuosity index. According to sinuosity indices analysis in the present study, the Nzhelele River is meandering in nature, the sinuosity of the river was fluctuating, with the highest value of 1.68 found in 2010. This showed that there was high alteration on the course of the river.

The application of Landsat images to analyse channel migration further revealed the dynamics of the Nzhelele River course, thus, revealing the westward direction migration of the river bank. The erosion was exceptionally high during the 2000 – 2005 period, with 4.35 km³ noted on the right bank, and 3.17 km³ noted on the left bank during the 2010 – 2015 study period. This variation in erosion can have an effect on the land-use and land-cover of the study area such as the vegetation cover which may result in the accelerated erosion of the Nzhelele River bank. The present study has effectively recorded the morphological variation of the Nzhelele River through the application and analysis of Landsat images. The application of GIS and remote sensing to assess river morphology is widely acknowledged in the scientific literature. The analysis presented in this study has provided a significant revelation of the Nzhelele River spatio-temporal morphological variation that can be employed effectively for future research studies that will be aimed at assessing future river conditions. This is because erosion, accretion

and channel migration can have a significant impact on the livelihood of residents next to the Nzhelele River, including their agricultural lands and infrastructure.

The investigated land-use and land-cover change from the Landsat images produced six classes from 2000 to 2020 including water body, dense forest, sparse forest, grassland, residential/ bareland and agriculture using the unsupervised classification technique. Substantial classification accuracy was obtained with kappa coefficient ranging from 0.50 to 0.76. The land-use and land-cover analysis effectively facilitated the assessment of the anthropogenic impacts on the Nzhelele River morphology. The decline in dense forest and the increase in residential/ bareland based on the classification analysis revealed the expansion of settlement with the increase in demand of construction material such as sand. From 2000 to 2020, the dense forest, sparse forest and residential/ bareland are the cover classes that were increasingly changing in the study area.

Anthropogenic activities such as Nzhelele Dam construction, agriculture, residential expansion and sand mining were identified in this study to be the most contributing activities to changes in river morphology. The impacts of these activities on the Nzhelele River ecology are still unknown and can be the focus of future studies. The Nzhelele River has been a source of local water and sediment supply to the surrounding communities. The land-use of the study area changed from dense forest, sparse forest to residential/ bareland, thus exacerbating water extraction and sand mining, this caused a decline in the ability of the river to supply sediment and water as a result of the presence of the Nzhelele Dam. Additionally, the construction of the Nzhelele Dam was found to directly affect the Nzhelele River morphology as a result of sediment deposition upstream, channel narrowing, bush encroachment and increased slope due to the decline in water discharge and sediment load. The increase in illegal sand mining that does not consider environmental protection was also noted to affect the morphology of the river. This is due to the increasing infrastructural development and other developments such as the expansion of residential area that exacerbated the demand of sand in the surrounding Nzhelele communities.

The Nzhelele River channel width declined in a downstream flow of direction. Furthermore, a decline the river ability to re-fill the channel with water and sediments from upstream was noted during the study period. It is of great importance to demonstrate how the environment of the study area, Nzhelele River dynamics, ecosystem services and communities are impacted by

the variation in land-use and land-cover change driven by anthropogenic activities and the spatio-temporal variation of the Nzhelele River morphology impacts. The demonstration will play a significant role in the advancement of future planning and river management, thus, ensuring the sustainability of the Nzhelele River and the livelihood of communities in the area

The time series analysis was used to forecast the Nzhelele River erosion and accretion into the future. The forecasted erosion was 1.62 km³ on the left bank and 2.40 km³ on the right bank, the forecasted accretion was 0.88 km³ on the left bank and 1.23 km³ on the right bank. The forecasted results indicates that the time series analysis can reproduce the typical spatio-temporal morphological variation of the Nzhelele River channel by forecasting into the future. The method of assessing the spatio-temporal variation of river morphology and forecasting the river morphology can also be employed for other local rivers, most especially meandering rivers. The present study concludes that the forecasted of erosion and accretion of the Nzhelele River channel may not correspond exactly with the reality at the study area. The forecast of Nzhelele River erosion and accretion provides a significant forewarning that great awareness must be prioritized to the state of Nzhelele River channel erosion, accretion and migration. For this reason, the present study has broughtforth recommendations for the Nzhelele River channel. The assessment of the spatio-temporal evolution of the Nzhelele River morphology has provided a solid foundation for the future morphological variations and trends of the river.

6.2 Recommendations for Nzhelele River management

The following recommendations can be made in light of the information presented in the literature review in chapter two and the subsequent chapters.

- **Nzhelele River restoration and floodplain protection**

The present study recommends a river restoration and floodplain protection project to be undertaken by concerned local authorities such as the Department of Water and Sanitation, Department of Agriculture, Land Reform and Rural Development, and Department of Forestry, Fisheries and the Environment. River ecology restoration and floodplain protection project is essential in preventing the risks associated natural disasters such as floods, gullyng and mass wasting. Additionally, this will also prevent the ongoing river bank erosion and accretion in the river channel, therefore, ensuring effective floodplain management. Furthermore, the

geomorphic assessment of the river will facilitate and contribute significantly to the river restoration and floodplain management programmes. The time series analysis and the evolution trajectory of morphological variables and variation of the Nzhelele River channel will advance the effective description of the floodplain. This present study advocates for the environmental management strategies aimed at river restoration and the prevention of local river deterioration.

- **Sand mining impacts mitigation**

Local people around the Nzhelele River channel are ignorant of their detrimental effects on the river channel and the floodplain. The understanding of the anthropogenic and ecological processes could advance an effective development of the river restoration and floodplain protection objectives. Nzhelele River has been the source of sand for many years and has played a crucial role in the development of local infrastructure. Additionally, the mining of sand has provided job opportunities for local people. Sand mining needs to be sustainable, therefore, local authorities should enforce compliance with the environmental legislations governing all mining operations in South Africa. The significant mining regulations include the Mineral and Petroleum Resources Development Act 28 of 2000, National Water Act 36 of 1998, and the National Environmental Management Act 1998. These regulations, if effectively enforced, it will enable resource conservation, sand mining impacts mitigation and the issuance of sustainable sand mining permits. This will halt the accelerated sand mining activities in the Nzhelele River, thus, preventing further river bank erosion and river degradation.

6.3 The limitation of the study

The paucity of research data on the Nzhelele River morphological evolution has made it difficult to compare the present study finding with the past results. However, studies on river bank erosion, accretion and lateral channel migration have been conducted across the globe. Past studies employed field measurement (Wolman, 1959; Knighton, 2014), and topographical maps and aerial photographs (Lewin, 1972; Lawler et al., 1997) to study river bank erosion and accretion. The present study employed the freely available satellite images and GIS methods that at a large scale provided a detailed spatio-temporal assessment of the Nzhelele River Bank erosion and accretion processes. Studies that effectively employed satellite images and GIS methods exist in the scientific literature (Ibitoye, 2021; Li et al., 2021; Suresh et al., 2022). Globally, there is significant scientific evidence of the applicability and effectiveness of GIS

and remote sensing methodologies. However, locally there is a huge gap in knowledge of the application of GIS and remote sensing methodologies.

6.4 Aspects for future research

Following the completion of the current investigation, a knowledge gap was found in the evaluation of the morphological evolution of the Nzhelele River. The development of the Nzhelele River morphological evolution with provide a principal reference for theoretical support for the assessment of erosion, accretion and channel migration, thus, advancing river management strategies and projects aimed at ecological restoration of the Nzhelele River channel. The Nzhelele River needs ecological restoration with its current river conditions. Scientific research studies aimed at monitoring the Nzhelele River morphology and river ecology restoration post monitoring, needs to be at the forefront as a primary regulation for the ecological restoration of the Nzhelele River

An investigation is indispensable to assess the variation in the Nzhelele River natural hydrological condition and the topography of the riverbed. This will make it easier to obtain a thorough understanding of the Nzhelele River channel spatio-temporal evolution, thus, effectively facilitating the prevention of river channel deterioration and advance the river ecological restoration. Furthermore, investigation into the seasonal variability of Nzhelele River flow rates and the influence of riverbed topography in the meander bends and channel migration will help understand the Nzhelele River meander bends evolution that will facilitate the development of strategies aimed at preventing river bank erosion. The investigation carried out for this study will serve as the basis for a doctoral study in river morphology.

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APPENDICES

Appendix A: Land-use and land-cover classification of the study area

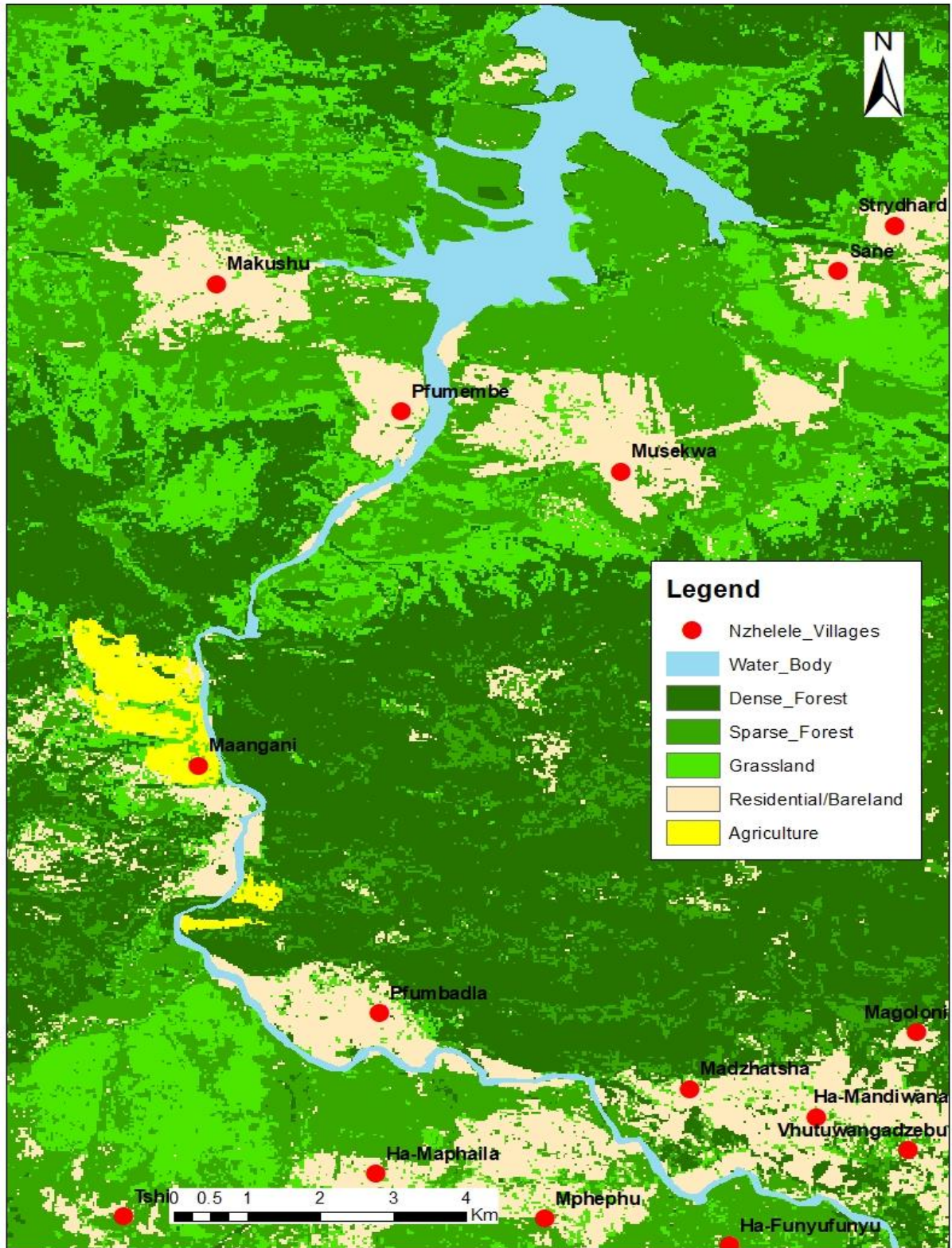


Figure A1: unsupervised classification of the study area 2000

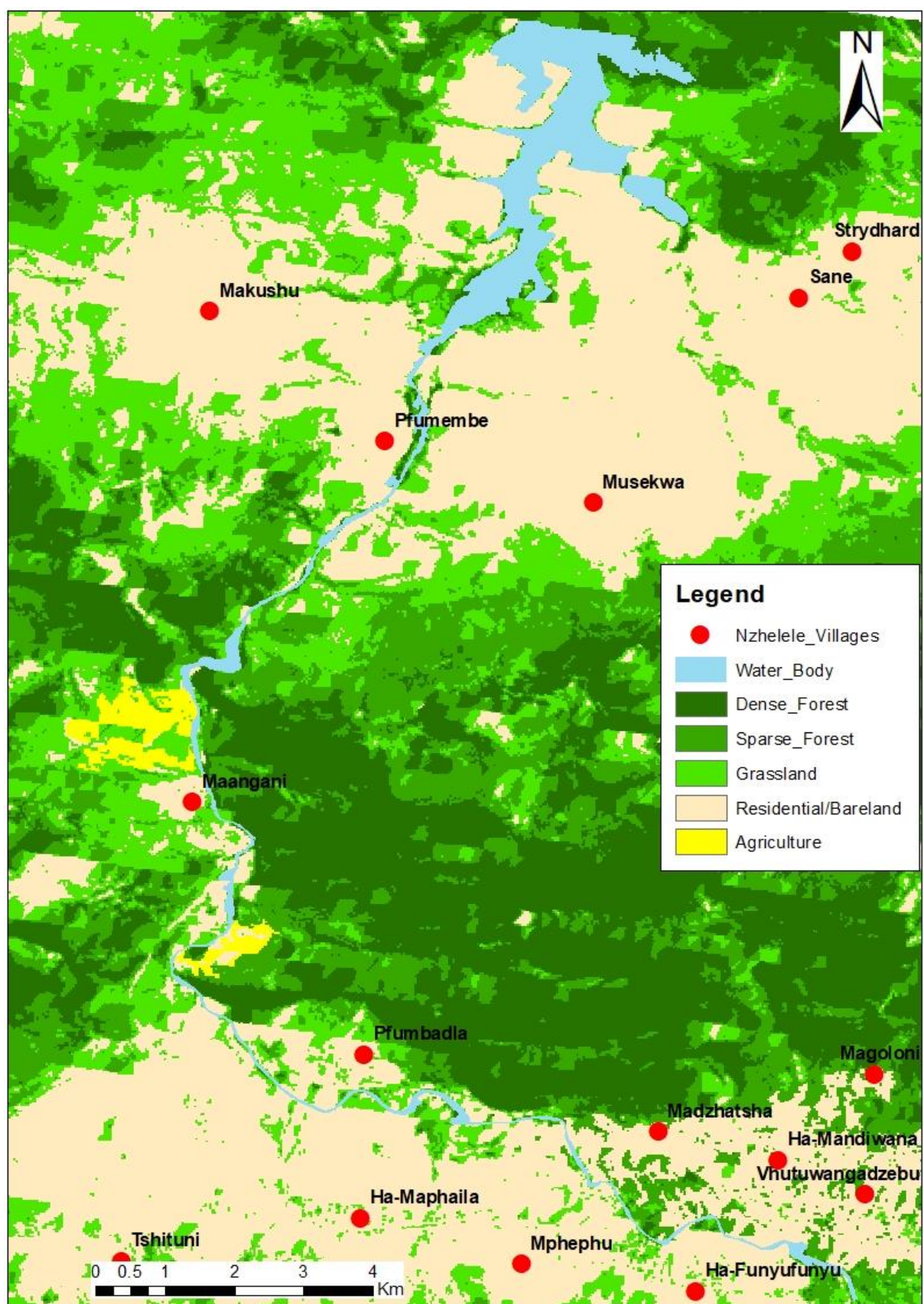


Figure A2: Unsupervised classification of the study area 2005

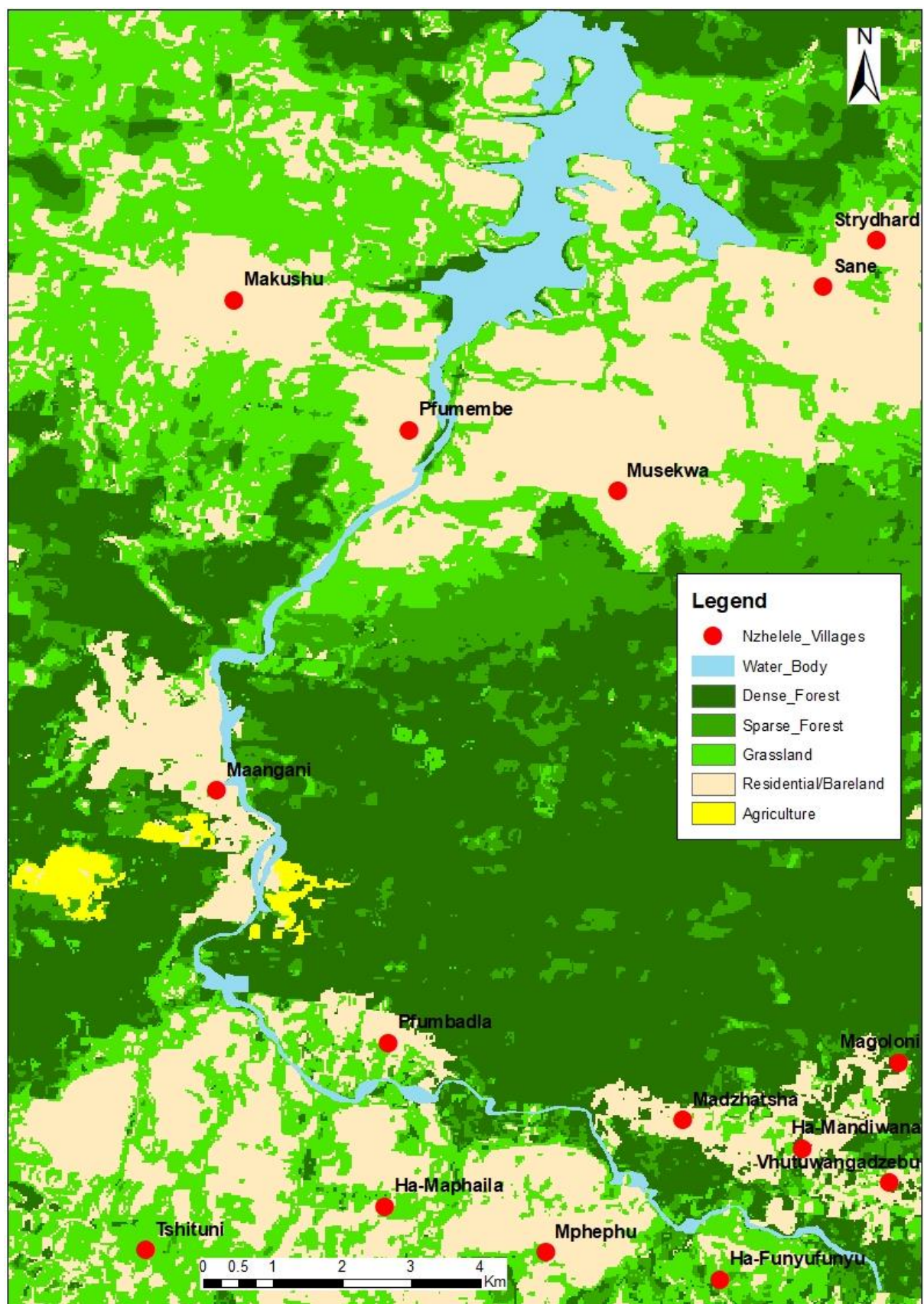


Figure A3: Unsupervised classification of the study area 2010

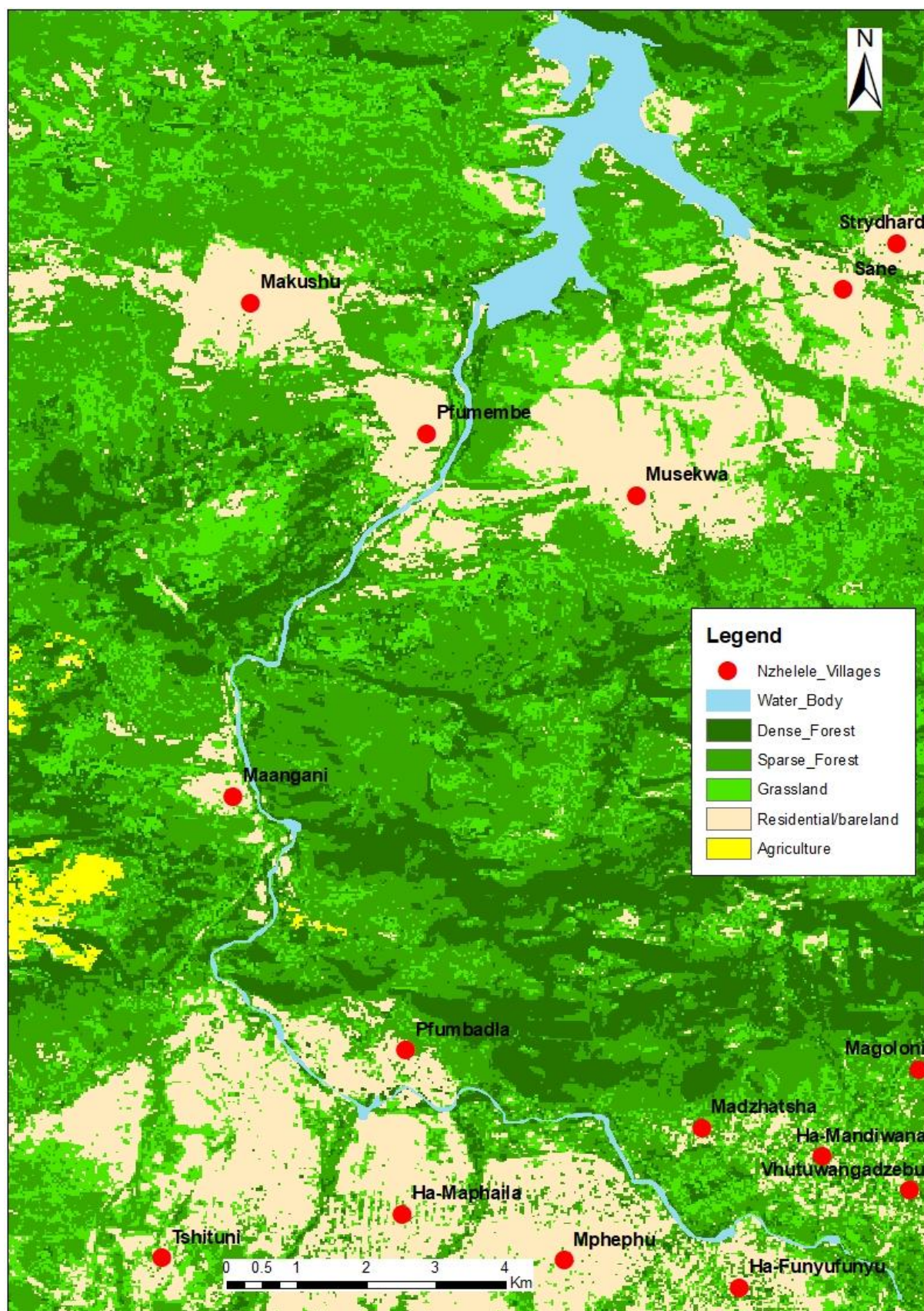


Figure A4: Unsupervised classification of the study area 2015

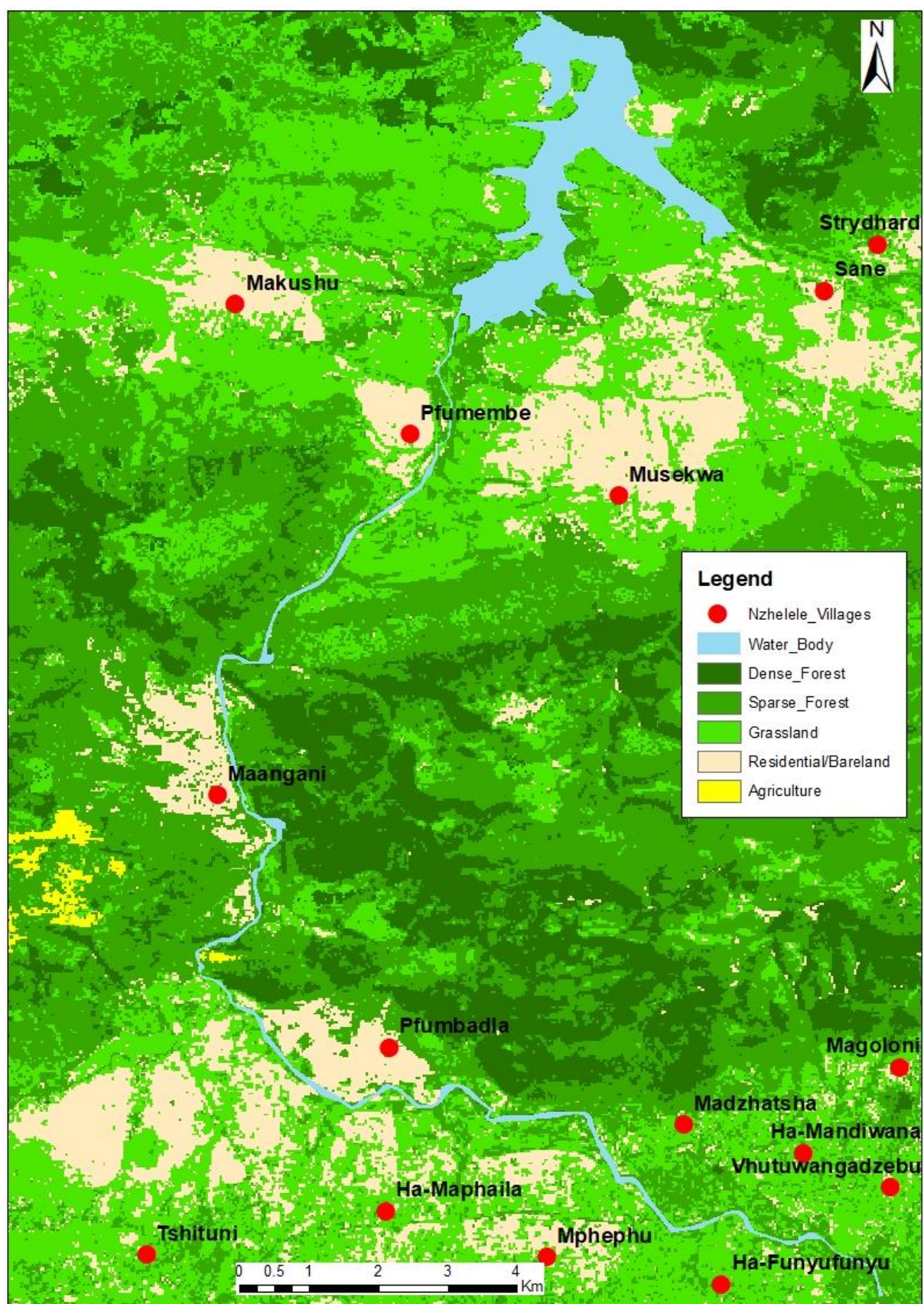


Figure A5: Unsupervised classification of the study area 2020

Table A1: Summary of the confusion matrix results.

Year	Land use/ Land cover	Error of omission (%)	Error of commission (%)	Producer's accuracy (%)	User's accuracy (%)	Kappa (K)	Average (K)
2000	Water Body	60.41	21.81	39.59	78.19	0.54	0.60
	Dense Forest	35.61	13.23	64.39	86.77	0.69	
	Spares Forest	33.53	15.44	66.47	84.56	0.64	
	Grassland	30.01	18.31	69.99	81.69	0.68	
	Residential/bareland	41.16	12.54	58.84	87.46	0.54	
	Agriculture	33.04	17.03	66.96	82.97	0.50	
2005	Water Body	35.11	29.14	64.89	70.86	0.61	0.58
	Dense Forest	29.40	17.12	70.06	82.88	0.55	
	Spares Forest	30.18	18.88	69.82	81.12	0.59	
	Grassland	35.16	21.13	64.84	78.87	0.55	
	Residential/bareland	48.59	16.43	51.41	83.57	0.50	
	Agriculture	37.22	25.69	62.78	74.31	0.66	
2010	Water Body	44.83	34.18	55.17	65.82	0.50	0.58
	Dense Forest	18.16	21.14	81.84	78.86	0.57	
	Spares Forest	34.88	27.13	65.12	72.87	0.63	
	Grassland	24.91	14.91	75.09	85.09	0.67	
	Residential/bareland	44.65	23.29	55.35	76.71	0.50	
	Agriculture	48.90	32.42	51.01	67.58	0.59	
2015	Water Body	29.57	25.32	70.43	74.68	0.61	0.64
	Dense Forest	40.26	26.13	59.74	73.87	0.65	
	Spares Forest	30.54	21.59	69.46	78.41	0.76	
	Grassland	20.39	18.07	79.61	81.93	0.64	
	Residential/bareland	47.13	33.09	52.87	66.91	0.61	
	Agriculture	40.01	37.01	59.99	62.99	0.54	
2020	Water Body	32.03	25.30	67.97	74.07	0.57	0.61
	Dense Forest	18.09	19.12	81.91	80.88	0.66	
	Spares Forest	26.04	19.59	73.96	80.41	0.75	
	Grassland	09.50	12.03	90.05	87.97	0.53	
	Residential/bareland	38.01	33.39	61.99	66.61	0.57	
	Agriculture	49.17	37.48	50.81	62.52	0.56	