Analysis of gully erosion as a hydro-geomorphological hazard in Thulamela Municipality, Limpopo Province, South Africa

By

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Declaration

This study is submitted in partial fulfilment of the requirements for the degree of Master of Environmental Science in Geography at the University of Venda. I hereby declare that this study was conducted and completed according to the guidelines of the faculty and the department. This dissertation is a work of my own and any work that was related to was acknowledged. This dissertation is copyrighted by the author, Asakundwi Makuya and may be used for any educational purposes only, when given proper credit to its author.

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Dedication

This study is dedicated to my beloved parents and grandmother, who never failed to give me financial and moral support throughout my entire life, especially for academic purposes, including this project. I again dedicate this study to my siblings, who are incredibly supportive and caring.

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Abstract

Gully erosion, a severe form of environmental process, poses significant global environmental and socio-economic challenges, worsened by deforestation, overgrazing and climate change. This study examines gully erosion as a hydro-geomorphological hazard in Thulamela Municipality, Limpopo Province, South Africa. The aim of this research was to investigate the occurrence and intensity of gully erosion in Thulamela Municipality. The study's first objective was to map gully distribution in Thulamela Municipality. The second objective was to map the severity of gullying. The third and last objective was to map factors contributing to gully erosion formation. This study investigated the three objectives across four temporal benchmarks (2008, 2013, 2018 and 2023) using GIS and Remote Sensing techniques. Distribution in gully occurrence was tracked through interpolation. Sampled gullies were overlaid to assess their size and shape transformation over time to determine the severity of gully erosion. Land use/cover changes were classified to track how they influenced gully development over the 15-year period. Topography was analysed based on elevation, terrain characteristics, flow accumulation and flow direction to determine areas that are more prone to gully development. Rainfall was assessed based on its intensity and distribution over the period of the study to determine how it contributes to gully erosion. Soil moisture was analysed to determine susceptibility to gully erosion. The results revealed a significant and exponential increase in gully development influenced by all the analysed factors. The findings highlight that Thulamela Municipality contains areas highly susceptible to gully erosion, presenting severe threats to land stability, safe habitation and sustainable development.

Keywords: Gully Erosion; Hydro-geomorphological Hazards; GIS and Remote Sensing; Land Use/Cover Change; Thulamela Municipality

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Chapter One

Background

1.1 Definition.

Gully erosion is the removal of soils along drainage lines by runoff, resulting in open, incised and unstable channels generally more than 30 cm deep (Harden, 2016). It is a significant hydro-geomorphological hazard currently posing significant environmental and socio-economic problems worldwide. It results from the interaction of many factors, including natural factors like intense rainfall and human activities such as improper land management and deforestation (Castillo and Gómez, 2016).

Hydro-geomorphological hazards are defined as natural processes that involve water and landforms that can cause environmental and human problems (Mandal and Ghosh, 2024). Recent studies have recognised gully erosion as a significant hydro-geomorphological hazard. With its intense nature, gully erosion contributes to issues like watershed sediment loads, making it a hydro-geomorphological hazard (Ciccolini *et al*., 2024). Gully erosion research has gained popularity and has become a growing interest for many researchers, but many knowledge gaps that need addressing still exist (Castillo & Gómez, 2016).

1.1.1 Overview of Gully Erosion and Hydro-Geomorphological Hazards

Gully erosion is a severe form of soil erosion that poses a significant environmental challenge globally (Lieskovský and Kenderessy, 2014; Gao et al., 2021). It results in soil loss, infrastructure damage, economic impacts, biodiversity loss and water pollution (Ionita et al., 2015; Bitikoro, 2024). The phenomenon has been established as one of the major drivers of landscape and soil degradation worldwide (Bennett and Wells, 2018).

Gully occurrence is often linked to factors such as intense precipitation, deforestation, overgrazing and climate change, which accelerate its spread and severity (Smith et al., 2023; Mukherjee et al., 2025). The impacts include environmental degradation, property

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damage, loss of livelihoods and disruption of socio-economic systems, with projections indicating greater risks under future climate scenarios (Poesen, 2018; Guerra et al., 2020).

To ensure sustainability, various methods have been developed to manage and control gully erosion, including mechanical structures, vegetation restoration, and modern monitoring tools. Remote sensing and GIS techniques, for example, use satellite imagery and Digital Elevation Models (DEM) to track gully formation and progression (Ehiorobo and Audu, 2012; Liu et al., 2019).

1.1.2 Regional and Global Perspectives on Gully Erosion

Gully erosion is a problem of both regional and global concern, affecting both developed and developing countries. Understanding gully erosion's global and regional dynamics is crucial for developing effective mitigation strategies. Globally, gully erosion is recognized as a major environmental challenge. The European Commission's European Soil Data Centre (ESDAC) reported that gully erosion results from concentrated water flow, forming and expanding the soil's erosional channels (Vanmaercke *et al*., 2021).

The combination of heavy rainfall, deforestation and overgrazing has led to severe gully formation. Efforts to combat gully erosion include reforestation projects, the construction of check dams and the implementation of sustainable agricultural practices (Nyssen *et al*., 2018). Countries like China and India face significant gully erosion issues in Asia. The Loess Plateau is particularly vulnerable in China due to its loose, easily erodible soil. The Chinese government has implemented large-scale soil conservation programs, including terracing and afforestation, to address this problem. In India, gully erosion is prevalent in the semi-arid regions, where overgrazing and deforestation are common (Li *et al*., 2019).

In Europe and North America, gully erosion is less widespread but still a concern in certain areas. In Europe, regions with intensive agriculture, such as the Mediterranean, are particularly susceptible. In North America, gully erosion is often associated with agricultural lands and areas with poor land management practices. Conservation tillage and the establishment of grass waterways are common strategies used to mitigate gully erosion in these regions (Boardman and Poesen, 2019).

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1.1.3 Factors affecting Gully Erosion

Understanding the causes of gully erosion is essential for developing effective prevention and mitigation strategies. These causes can either be natural or anthropogenic and their intensities may differ. Natural causes include fierce winds, heavy rains and flowing water (Natural Resources Defence Council, 2021). During intense rainfall, soil particles are carried away by runoff, leading to gully formation (Abdulfatai *et al*., 2014). Raindrop impact alone can result in significant soil displacement and when combined with surface runoff, it contributes to sheet, rill and gully erosion (Queensland., 2013).

Topographic relief, surface curvature and surface roughness also cause gully erosion (Fan *et al*., 2024). Topographic relief causes gully formation and expansion of gullies when steeper slopes accelerate surface runoff, increasing the water's erosive speed and force (Fan *et al*., 2024). Surface curvature is classified into concave and convex surfaces. Concave areas gather water, which heightens erosion risk by saturating the soil and diminishing its cohesion. In contrast, convex surfaces encourage water runoff, thus amplifying the potential for erosion (Fan *et al*., 2024; Valipour *et al*., 2021). Rough surfaces slow water flow, aiding sediment deposition and reducing erosion, while in contrast, smooth surfaces accelerate the flow, increasing erosion risk and thus causing gully formation (Fan *et al*., 2024).

Soil types also contribute to gully erosion, making it essential to understand to protect vulnerable soils (Department of Environment and Heritage., 2021). This is because different soil types have different soil characteristics that influence water infiltration, runoff and soil stability. Soils with high clay presence have lower infiltration rates, causing more surface runoff and are more prone to erosion compared to soils with less clay content (Mararakanye and Sumner, 2017).

Anthropogenic causes of erosion result from human activities that accelerate natural erosion processes. Transitioning from natural vegetation to agricultural use often disrupts the soil's structural integrity. Crops such as coffee, cotton, palm oil, soybean and wheat can significantly increase soil erosion beyond its natural capacity. (World Wildlife Fund., 2022). Poor ground cover, resulting from other activities like bush clearing and

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overgrazing, exposes soil to erosion, making it more vulnerable to water and wind (Brown, 2020). Agricultural practices, such as tilling and uncontrolled grazing, further increase runoff and reduce soil stability, promoting gully erosion (Abdulfatai *et al*., 2014). Additionally, poor land management accelerates erosion by channelling water into narrow, high-velocity flows that deepen gullies (Brown, 2020).

1.1.4 Impacts of Gully Erosion

The impacts of gully erosion extend beyond environmental degradation and socio-economic difficulties. When it comes to environmental degradation, the loss of vegetation cover encourages land degradation, thus contributing to habitat loss, fragmentation and biodiversity decline (Fan *et al*., 2024). Additionally, this leads to the displacement of populations as land becomes uninhabitable (Mararakanye and Sumner, 2017). This means that people and animals may leave a certain palace because the area no longer meets their environmental needs.

Water quality is also compromised as surface runoff carries sediments into rivers and lakes, increasing turbidity and reducing oxygen levels, which harms aquatic ecosystems and complicates water treatment (Miller *et al*., 2020). This leads to water scarcity and affects human consumption and ecosystem health (Phionah, 2024).

Erosion reduces agricultural productivity, threatening food security, especially in farming-dependent regions (Bennett, 2018), causing socio-economic problems. Agricultural production decreases because of degraded lands as they are less suitable for cultivation and vegetation growth. Communities that are dependent on agriculture experience economic challenges due to decreased crop yields and escalating soil erosion.

Furthermore, erosion leads to the destruction of infrastructure, particularly in areas with gully formations. Roads, bridges and buildings are often damaged, leading to costly repairs and posing safety risks (Johnson, 2017). These costly repairs can drain both the government and individuals, putting strain on the country’s development.

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1.2 Problem Statement

Gully erosion has lasting environmental, social and economic consequences, including livelihood loss, poverty and health issues from poor living conditions (Keiler and Fuchs, 2016). These hazards often damage infrastructure such as roads, bridges and buildings, leading to costly repairs and maintenance (Frankl *et al*., 2013). Gully erosion can hinder development and pose significant safety risks. It degrades land by stripping away fertile topsoil essential for plant growth, diminishing productivity and contributing to desertification (Kariminejad *et al*., 2023).

Hydro-geomorphological hazards have intensified with an increase in weather, climate and water-related hazards, according to the World Meteorological Organization (WMO) (2021). Studies indicate that gully erosion has become a critical environmental problem (Guo *et al*., 2019; Crowell., 2022), posing serious risks to development and safety. The locations of existing and potential gullies in Thulamela Municipality remain unclear. Without proper analysis and mapping, municipal developments may be hindered and the safety of residents, infrastructure and new projects could be compromised.

Gully erosion interferes with the United Nation's Sustainable Development Goals (SDGs) in various ways. Gullies directly threaten food security by reducing agricultural productivity, which aligns with the goal of Zero Hunger (SDG 2). The removal of nutrient-rich topsoil reduces soil fertility and lowers crop yields, making agricultural land unproductive (Belay and Bewket, 2012). In a region where many livelihoods depend on farming, the loss of arable land increases food insecurity and economic vulnerability.

The impact of gully erosion extends to water quality and availability, which is critical to achieving Clean Water and Sanitation (SDG 6). Soil erosion leads to increased sedimentation in rivers and reservoirs, reducing water quality and affecting aquatic ecosystems (Mekonnen *et al*., 2016). Sediment-laden water complicates water treatment processes and contributes to water scarcity, particularly in communities that rely on such water sources for domestic and agricultural use.

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Beyond agriculture and water resources, gully erosion significantly impacts infrastructure, posing challenges to sustainable development. This aligns with Industry, Innovation and Infrastructure (SDG 9), as erosion weakens roads, bridges and other structures, making them unsafe and costly to maintain (Addisu and Mekonnen, 2019). Unstable landscapes in Thulamela Municipality increase maintenance costs and limit access to essential services, which affects economic development and quality of life. Identifying high-risk areas through research will enable better planning and investment in resilient infrastructure, reducing future economic losses and ensuring community stability.

Gully erosion is also closely linked to broader environmental challenges, particularly those addressed in Climate Action (SDG 13) and Life on Land (SDG 15). Climate change has intensified extreme weather patterns, increased rainfall variability and exacerbated erosion processes (Borrelli *et al*., 2017). Unsustainable land use practices, such as deforestation and poor agricultural techniques, further accelerate land degradation and loss of biodiversity. Addressing gully erosion through sustainable land management will help mitigate climate change impacts and promote ecosystem conservation. Protecting land resources ensures the long-term stability of ecosystems, supporting biodiversity and preventing further environmental degradation.

1.3 Significance of the Study

Gully erosion is a significant environmental issue that threatens soil stability, agricultural productivity and infrastructure. It is essential to study gully erosion to develop effective soil conservation strategies, protect water quality and preserve infrastructure. Addressing this issue aligns with Sustainable Development Goals (SDGs) such as Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), Industry, Innovation and Infrastructure (SDG 9), Climate Action (SDG 13) and Life on Land (SDG 15). This study is important because it aims to understand the mechanisms of gully formation, identify vulnerable areas and develop sustainable mitigation strategies based on the mentioned SDGs.

One key reason to study gully erosion is to prevent soil degradation. Gully erosion removes nutrient-rich topsoil, which reduces agricultural productivity and threatens food security, particularly in farming-dependent regions (Bennett, 2018). Understanding the

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processes of gully formation develop techniques to mitigate erosion and ensure land productivity. Water carries sediments into rivers and lakes, increasing turbidity and reducing oxygen levels. The sedimentation harms aquatic ecosystems and complicates water treatment (Miller *et al*., 2020). Studying gully erosion helps in developing strategies to reduce sediment transport, protect water bodies and promote water quality for human use and ecosystem processes.

Gully erosion can also damage and destabilize roads, infrastructure, bridges and buildings, leading to costly repairs and safety risks (Johnson, 2017). Understanding the causes of gully erosion allows for the implementation of preventive measures to protect infrastructure. This also helps identify suitable development areas and decide appropriate materials and activities for each location.

Furthermore, studying gully erosion is crucial for sustainable land-use planning. Human activities such as deforestation and agriculture accelerate erosion processes. Understanding these factors enables the creation of policies that reduce environmental impact and promote land conservation. (Brown, 2020). The conversion of lands to built-up areas observed in Thulamela Municipality can be attributed to ineffective land use management practices (Lidzhegu and Kabanda, 2022). Early detection of gully formation can facilitate timely intervention to prevent further damage.

This study is important because it aims to investigate the occurrence and intensity of gully erosion in Thulamela Municipality. The findings will assist in planning mitigation practices to reduce the potential impacts of gully erosion in the region. It will provide crucial information for land-use planning, areas that need erosion control and those suitable for development or conservation (Ionita *et al*., 2015). The results will highlight South Africa's need to address gully erosion on both local and national scales

In short, studying gully erosion is vital for preventing soil loss, protecting water quality, safeguarding infrastructure and promoting sustainable land management. This research aligns with multiple SDGs, offering solutions to mitigate erosion impacts while contributing to a sustainable future.

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1.4 Aim

The overarching aim of this research is to investigate the occurrence and intensity of gully erosion in Thulamela Municipality.

1.5 Research Questions

This research sought to answer the following questions.

- What is the spatial distribution of gullies in Thulamela Municipality?
- What are the factors contributing to gully erosion?
- How severe is gully erosion in the study area?

1.6 Objectives

To achieve the main aim of this research project, three specific objectives were developed, and they were to:

- map the spatial distribution of gullies in Thulamela Municipality.
- analyse factors contributing to gully formation.
- establish the severity of gully erosion.

1.7 Geographical and Environmental Setting of the Study Area

This study was conducted in Thulamela Municipality, within Limpopo Province, South Africa. It is located in the eastern subtropical region of Limpopo province (Musyoki *et al*., 2016). Thulamela Municipality covers over 162 villages and towns. As part of a developing country, the Municipality is also classified as a developing Municipality. This study area's common land uses and cover include subsistence farming, small scale farming, urbanization, built-up areas, pastoral farming, forestry and conservation areas (Lidzhegu and Kabanda, 2022).

The study area is characterised by a subtropical climate, receiving the majority of its rainfall during summer between October and March (Louw and Flandorp, 2017). It has annual rainfall ranging between 400mm and 1 000 mm, with an average of 800mm (Louw and Flandorp, 2017). The study area is generally hot and humid (Musyoki *et al*., 2016)

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and experiences long-term minimum average temperatures in July with from 5°c in the west to 12°c in the north-east (Louw and Flandorp, 2017). The long-term maximum average temperatures are experienced in January from 26°c in the southwest to 34°c in the northeast (Louw and Flandorp, 2017).

Thulamela's topography features gently rolling landscapes with notable mountains like the Soutpansberg, diverse elevations and drainage patterns. Populations are higher on gradual slopes, while steep slopes are less suitable for agriculture (Louw and Flandorp, 2017). The geology and soil type of the study area Flandorp, 2017). Economic changes within the Municipality come with extensive land use necessitating terrain analysis. Terrain analysis is important for identifying areas that are prone to hydro-geomorphological hazards important for planning purposes. Figure 1 shows Thulamela Municipality.

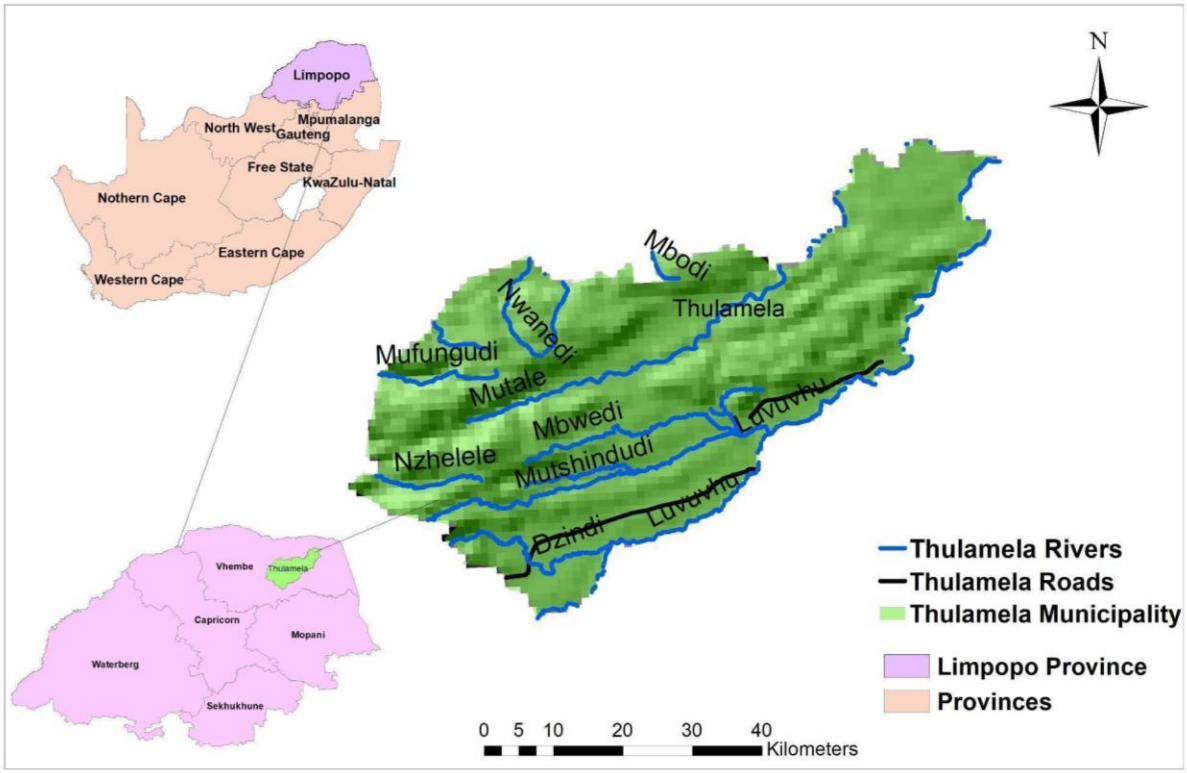

Figure 3.1. Study area map, Thulamela Municipality

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1.8 Chapter Summary

Gully erosion is a significant hydro-geomorphological hazard caused by the removal of soil along drainage lines by runoff. It poses socio-economic and environmental challenges due to factors like intense rainfall and human activities like deforestation and improper land management. This process is recognised globally as a major cause of landscape and soil degradation, impacting on biodiversity, agriculture and infrastructure. This research highlights the need for effective mitigation strategies, including remote sensing and GIS techniques, to monitor and address gully erosion. To deal with this issue, worldwide efforts concentrate on reforestation, sustainable agricultural practices and large-scale soil conservation programs.

Gully erosion poses serious environmental, social and economic challenges, including livelihood loss, infrastructure damage and decreased agricultural productivity, which contribute to poverty and poor living conditions. This issue is exacerbated by both natural factors such as intense rainfall and human activities like deforestation and improper land management. Gully erosion significantly impacts Sustainable Development Goals (SDGs) by threatening food security (SDG 2), water quality (SDG 6) and infrastructure (SDG 9). This research aims to map gullies in Thulamela Municipality, assess their severity and analyse contributing factors to develop effective mitigation strategies and promote sustainable land management.

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Chapter Two

Literature Review

2.1. Defining Literature Review

A literature review is important to academic research because it offers context, reveals gaps in current knowledge and guides to new findings. It situates the research within the wider context of known knowledge and highlights its significance. (Snyder, 2019). By systematically analysing previously done studies, researchers can pinpoint areas that require further exploration, contributing to the advancement of the field (Tranfield *et al*., 2021).

In addition, literature reviews assist in refining research questions and methodologies by presenting best practices and highlighting potential obstacles (Boote and Beile, 2016). They help prevent the duplication of efforts by identifying areas that have already been thoroughly studied, ensuring resources focus on generating novel insights (Torraco, 2016). Reviewing existing literature also encourages academic dialogue and collaboration, fostering innovative and interdisciplinary research approaches (Snyder, 2019).

A literature review surveys sources such as scholarly articles and books related to a specific issue or research area, providing descriptions, summaries and critical evaluations of these works (Ramdhani *et al*., 2014). For example, this literature review focuses on analysing gully erosion as a hydro-geomorphological hazard. Numerous studies have been conducted regarding the analysis and mapping of this hazard. Such a review is valuable for documenting existing knowledge about the phenomenon of interest and builds on information validated by other authors.

The purpose of this literature review is to identify gaps in existing studies and address these gaps where possible. Research on gully erosion processes and their modelling is limited. This is partly because gully erosion is influenced not only by extreme weather

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events and land-use changes but also by a long history of antecedent conditions that are often overlooked due to their complexity and cost of analysis (Valentin *et al*., 2005; Majhi, 2022).

2.2 Hydro-Geomorphological Hazards

Hydro-geomorphology is an evolving interdisciplinary scientific field that studies the relationships between geomorphology and hydrology (Teixeira et al., 2013). This relationship forms the basis for analysing hydro-geomorphological hazards, which comprise hydrological and geomorphological hazards. Hydrological hazards are defined as extreme events associated with the occurrence, movement and distribution of water (Trajkovic et al., 2016).

Gully erosion is classified as a hydro-geomorphological hazard because it occurs when water flow interacts with geomorphological factors such as soil type, slope and land use. Intense rainfall, limited ground cover and specific soil conditions contribute to the formation of deep channels in the landscape (Osman, 2014). Geomorphological hazards, on the other hand, are extreme events resulting from natural phenomena (Alcántara-Ayala, 2010). Examples include soil erosion (including gully erosion), soil deposition and rain erosivity. These hazards arise when natural landscape processes conflict with human activities, leading to catastrophic events (Alcántara and Goudie, 2010).

Geo-hydrological risk policies related to hydro-geomorphological hazards are becoming a significant challenge for environmental sustainability at both national and international levels (Paliaga et al., 2020). Two major factors contribute to this challenge: the increased intensity and frequency of rainfall due to climate change and greater exposure to these hazards from unchecked urban expansion (Paliaga et al., 2020). Hazards such as floods, landslides and gully erosion are often triggered by heightened rainfall intensity and volume (Fon and Mbella, 2015; Osman, 2014).

Floods and droughts can accelerate the formation and deepening of gullies (Ionita et al., 2015). While these events are primarily classified as hydrological hazards, they can also have geomorphological impacts. Hazards are not classified as such merely because of

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their occurrence but because they pose significant risks or cause damage to people, livelihoods and properties (Glago, 2021).

Based on these definitions of hydro-geomorphological hazards, various types are experienced in real-world scenarios. Gully erosion is one such hazard and is the focus of this study. It arises when water flow interacts with landform processes, causing significant landscape changes (Ionita et al., 2015). It is a form of soil erosion where surface runoff cuts into drainage lines, forming large channels or gullies. This interaction between water (hydro) and landform processes (geomorphological) underscores the classification of soil erosion as a hydro-geomorphological hazard, with the potential to cause major landscape transformations (Goudie and Boardman, 2010).

2.3 Soil Erosion as a Hydro-Geomorphological Hazards

Soil erosion is defined as a process whereby topsoil wears away through transportation of the surface particles by agent or physical processes such as wind and water (Arrington, 2022). It was again stated that it is a constant process which is occurring either slowly or at an alarming rate (Arrington, 2022) (Balasubramanian, 2017). Fast paced erosion is however a result or consequences of human activities. The rate of erosion can also be increased by other activities that are not human related such as fire (Balasubramanian, 2017) and drought. Thus, it leads to a continuous loss of the top layer of soil, potentially forming gullies.

Soil erosion is also a land degradation problem that results in economic, social and environmental implications due to on-site and offsite effects (Parwada and Van Tol, 2016). If prolonged, it leads to irreversible soil loss over time thus reducing ecological and hydrological functions of soil, becoming a hazard (Le Roux and Smith, 2014). It impacts on land development and human habitation by affecting human activities.

The impacts include the destruction of structures such as buildings and bridges as their foundations get weakened, hindering land development (MWAIKUSA, 2020). Other infrastructures such as dams, embankments and drainage get negatively impacted on when they experience sediment accumulation thus reducing their efficiency (Arrington,

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2022). Agricultural activities are also impacted on when erosion causes the productive topsoil to loosen up, lowering the land's agricultural potential (MWAIKUSA, 2020).

Soil erosion takes place through different types and this literature focused gully erosion. This type of soil erosion is believed to be more severe than other types of soil erosion, such as sheet or rill erosion, as it results in the permanent loss of productive topsoil and can render land unsuitable for agriculture or development (Poesen *et al*., 2018; Valentin *et al*., 2020).

2.4 Gully Erosion as a Hydro-Geomorphological Hazards

There are various types of soil erosion namely: water, splash, sheet, rill, gully, tunnel, wind erosion and mass movement (Arrington, 2022). This study focuses on gully erosion as the main soil erosion hazard. Gully erosion has become an environmental and land degradation most recognised problem (Olivier *et al*., 2023c). It has also been directly linked to unsustainable land management in many cases (Castillo and Gómez, 2016). The rate of soil erosion due to gullies and is not too much, but it is noticeable, ranging between 30 and 123 t ha^{-1} yr^{-1} in prominent areas (Olivier *et al*., 2023c).

As per literature, Gullies are described by morphology, formation processes, development stage, landscape position, drainage basin location, soil type, vegetation and climate (Thwaites *et al*., 2022). Gullies can range from simple extensions of rills to the distinctly unconventional 'badass' gullies described by (Marden *et al*., 2018). As such, they come in different sizes and they are divided into ephemeral (EG) and permanent gullies (PG) (Liu *et al*., 2021). They always start as ephemeral gullies and become permanent gullies when they increase. Gully development represents a unique kind of natural hazard (Saksa and Minár, 2012).

During the last few decades, especially the mid-20th century, great progress has been made in understanding gully erosion, associated processes and its controlling factors (Ionita *et al*., 2015; Ionita *et al*., 2015). During the process of gully erosion formation, topsoil and underlying loose rocks are washed by runoff within a short period of time (Radoane and Rădoane, 2017). Globally, this type of process poses a significant

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environmental threat, impacting soil health and land functionality (Ionita *et al*., 2015). It has also been recognised throughout history as a major process of land degradation (Dotterweich *et al*., 2012).

With respect to sheet and rill erosion, gully erosion is more dangerous and destructive (Saksa and Minár, 2012). This is because the soil displaced by sheet and rill erosion is deposited close to its original source, whereas the soil displaced by gully erosion is carried much farther away (Saksa and Minár, 2012). There is enough physical evidence of intense gully occurrence in the past in different parts of the world at various times (Ionita *et al*., 2015). Figure 2 shows some of the gullies that have been identified in a study about gully morphology in different biomes and land uses in South Africa (Olivier *et al*., 2023).

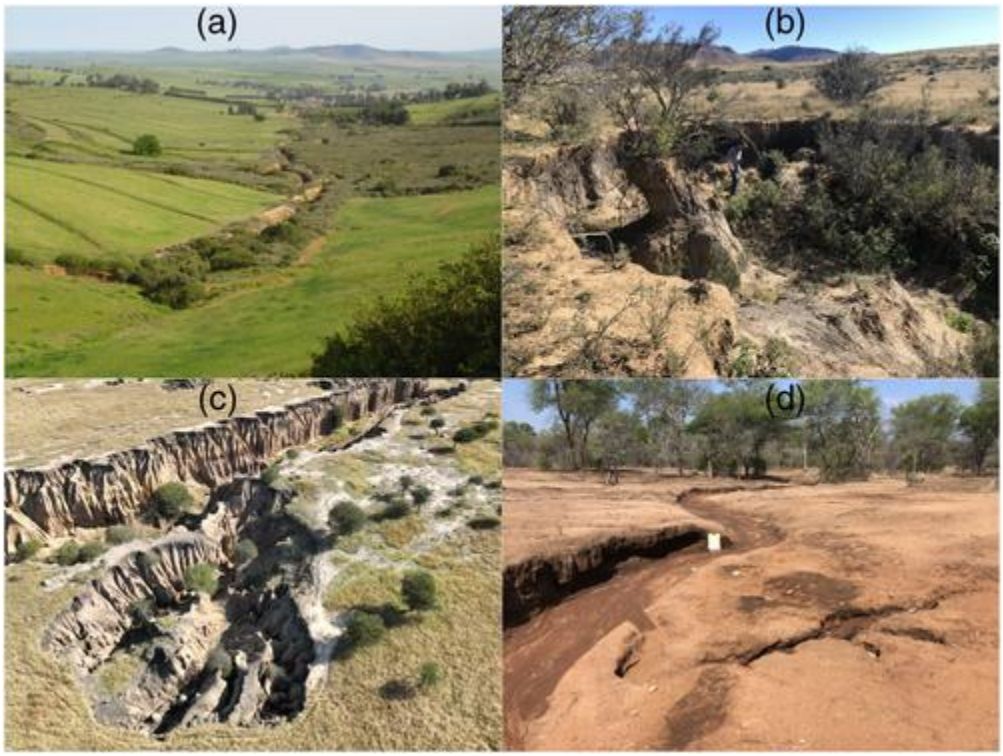

Figure 1. Examples of gully morphology in different biomes and land-uses in South Africa (Olivier et al., 2023)

2.5 Gully Erosion in South Africa

Gully erosion in South Africa is driven by climatic, geological and human factors, such as intense rainfall, deforestation, overgrazing and poor soil conservation practices

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(Kakembo *et al*., 2015; Hoffman *et al*., 2018; Shongwe *et al*., 2020). This erosion leads to the loss of topsoil, reducing agricultural productivity and threatening food security (Mashimbye *et al*., 2019). It also contributes to sedimentation in rivers and reservoirs, decreasing water quality and storage capacity (Mandal *et al*., 2021). Moreover, gully expansion damages infrastructure, increasing maintenance costs and safety risks (Hughes and Mantel, 2020).

Recent studies in show that gully erosion has affected hundreds of thousands of land in hectares particularly, Eastern Cape, KwaZulu-Natal, Free State, Mpumalanga and parts of Limpopo . They have been affected because of local geology, steep slopes, land use and rainfall intensity (Mararakanye & Sumner, 2017; Le Roux et al., 2010; Bernini et al., 2021). Case studies in the Free State and Eastern Cape reported rapid gully expansion rates that threaten villages and farms when not addressed early (Mararakanye & Sumner, 2017; Joseph & Van der Westhuizen, 2021).

To mitigate these impacts, both low-cost and engineered measures are being practiced. Successful techniques in South Africa include reshaping gully heads and banks, installing check dams, using soil-filled tyres and sandbags, revegetation, runoff retention structures, and community-based labour for early treatment of nascent gullies (Joseph & Van der Westhuizen, 2021; Bernini et al., 2021; Olivier et al., 2023). At a national and regional level, researchers have developed susceptibility mapping and monitoring tools to prioritise areas at high-risk zones (Le Roux & Sumner, 2012; Olivier et al., 2023). Early detection and locally appropriate, low-cost measures are emphasised as the most cost-effective way to reduce long-term damages and livelihood losses.

2.6 Hydro-Geomorphological Hazards in South Africa

Hydro-geomorphological hazards, including floods, landslides and soil erosion, present significant challenges in South Africa. Flooding, intensified by heavy rainfall associated with climate change, leads to considerable economic losses, displacement of communities and infrastructure damage (Bopape *et al*., 2021). A study in South Africa stated that urbanization and insufficient drainage systems further elevate the risk of these events (Mudau *et al*., 2017). Remote sensing and GIS technologies are critical for

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mapping flood-prone areas, supporting early warning systems and conducting risk assessments (Ngwenya and Abiodun, 2020).

Landslides are a significant hydro-geomorphological hazard in South Africa, especially in areas with steep terrain and high rainfall, such as the Drakensberg Mountains (Knight and Grab, 2015). Landslides, typically triggered by intense rainfall and exacerbated by human activities such as deforestation and mining, are another serious hazard (Mwaniki *et al*., 2018). Geomorphological mapping and predictive modelling are essential for identifying vulnerable areas and implementing preventive measures (Chelli *et al*., 2021).

Climate change exacerbates these hazards by increasing the frequency of extreme weather events and accelerating erosion (Ziervogel *et al*., 2016). Mitigation and adaptation strategies must incorporate climate projections and combine structural measures like flood barriers and slope stabilisation with non-structural approaches such as sustainable land-use planning and reforestation (Bhattacharya *et al*., 2020). Advances in remote sensing and GIS technologies enhance hazard monitoring, enabling more precise interventions and resource allocation (Rahmati *et al*., 2021).

2.7 Causes of Gully Occurrence

Human activities are known to be the catalyst of gully erosion and consequently enough, the type of soil material affected is usually fertile and fit for agricultural purposes (Saksa and Minár, 2012). Gully erosion has generally been increased by human activities such as deforestation, agricultural activities and improper land use and their population pressure. However, it is important to look at the factors that are influencing the formation and impacts of this hazard phenomenon. The main factors influencing this problem are Climate, land cover change (Badasa et al., 2021), Land use change and soil characteristics (Bogale, 2020) and topography.

2.7.1 Land Use and Land Cover Change

It is widely recognised that there has been significant change in land use and land cover over the past few decades (Sajikumar and Remya, 2015). Erosion severity is influenced by the type of land use and land cover (LULC) as well as the cumulative effects of land

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use and management practices (Moisa *et al*., 2021). Land use and cover change (LUCC) is one of the key drivers of soil erosion, with human activities being the primary forces behind these changes (Guo *et al*., 2024). Land Use and Land cover changes have significantly and consistently disrupted the hydrological cycle and altered land and soil conditions, contributing to gully formation (Frankl *et al*., 2021).

Land use and land cover changes significantly influence runoff characteristics in a drainage basin, negatively impacting both surface and groundwater levels (Sajikumar and Remya, 2015). Gullies primarily form during periods of high runoff and during these peak times (Frankl *et al*., 2021), land use practices play a significant role in shaping the topographic conditions that lead to gully head development (Torri and Poesen, 2014). As land use changes, it often becomes dominated by human activities, which can lead to increased soil erosion compared to areas with other types of land use (Moisa *et al*., 2021). This is because these activities negatively alter the original land use and cover patterns, thereby impacting the soil erosion process (Guo *et al*., 2024), which may result in gully formation.

Other human activities, such as improper agricultural practices like improper ploughing, monoculture and overgrazing, intensify gully erosion possibilities. Likewise, ploughing along the slope instead of contour ploughing creates channels that allow water to flow more quickly, raising the risk of gully formation. Monoculture can deplete soil nutrients and reduce soil structure, making it more prone to erosion (Bogale, 2020). Overgrazing by livestock removes the vegetation cover, leaving the soil exposed. Therefore, areas with reduced vegetation cover experience higher rates of gully erosion due to increased surface runoff and soil detachment (Badasa *et al*., 2021).

2.7.2 Climate

When it comes to climate, there are three factors that play a significant role, namely wind, precipitation and temperature. Climate plays a significant role in the formation and progression of gully erosion through its influence on precipitation patterns, temperature fluctuations, extreme weather events and wind direction. Understanding the relationship

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between climate and soil erosion is essential because it helps when developing effective land management and soil conservation strategies (Nearing *et al*., 2024; Liu *et al*., 2024).

When it comes to precipitation, a study in southern China adopted the Boruta algorithm to identify key factors in gully distribution, precipitation and rainfall erosivity were highlighted as critical (Liu *et al*., 2024). Heavy, prolonged rainfall can saturate the soil, reducing its cohesion and making it more prone to erosion. Intense rainfall boosts surface runoff, which can quickly erode soil and lead to gully formation (Wang *et al*., 2023). Recent research indicates that areas experiencing high rainfall intensity are more susceptible to gully formation because of intensified runoff and soil displacement (Liu *et al*., 2024).

Temperature can lead to gully formation because of its variations. This is often called temperature variation and it occurs due to factors such as geographic location, time of day and seasonal changes (Smith, 2022). Temperature fluctuations, especially freeze-thaw cycles, can weaken soil structure and make soil more vulnerable to erosion. This process contributes to gully formation and their expansion, particularly in areas with significant temperature variations (Barnes and Luffman, 2016). Knowing these temperature-driven changes in soil moisture and structure is also a key to understanding gully erosion dynamics (Gelete *et al*., 2024).

Wind causes gully erosion indirectly by affecting rainfall. Wind affects rainfall characteristics, influencing raindrop trajectory, splash angle and erosivity force. Wind direction significantly affects runoff, sediment yield and nitrogen loss in both runoff and sediment (An *et al*., 2022). With intensified and prolonged rainfall, wind influence on the rainfall trajectory plays a huge role in gully formation, especially if the rainfall is trajected to one direction.

2.7.3 Topography

Topography is often defined using terrain analysis. The terrain is described as the vertical and horizontal characteristics of the land surface (Omondi, 2018). Terrain analysis involves the interpretation of topographic features using geographic information systems (Our Planet Today, 2022). These features include slope, aspect, viewshed and elevation. Terrain analysis is often regarded as synonymous with geomorphometry (Wilson, 2022).

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Geomorphometry and terrain analysis provide essential tools for the study of geomorphology, hydrology, soil science and geographic information systems (GIS) (Florinsky, 2017).

Topography examines the land surface, providing the foundation for landscapes, including mountains, valleys, rivers and craters (GIS Geography, 2024). It is essential for various fields like geography, environmental sciences, geology and engineering. This research will explore the impacts of topography on gully erosion, focusing on slope gradient, slope length and catchment area. This is because these factors are the ones that influence gully erosion the most (Zare *et al*., 2022). Furthermore, these factors affect the flow velocity and volume of water runoff, thus influencing the water's erosive power and most likely forming gullies (Zare *et al*., 2022).

When it comes to slope gradient, the steepness of the area is a primary influencer. This is because steeper slopes facilitate faster water flow, increasing the runoff (Valipour *et al*., 2021). For example, in some areas, slopes with a gradient greater than 8 degrees are much more susceptible to gully erosion (Wang and Fan, 2019) than those less than 8 degrees. This impact mostly occurs during heavy rainfalls due to the increased runoff (Gelete *et al*., 2024). Also, the more the slope gradient increases, the more gravitational force on the water worsens, increasing runoff velocity (Johnson *et al*., 2023). This is also influenced by inadequate vegetation cover as it increases runoff and soil detachment, thus forming gullies (Badasa *et al*., 2021).

Slope length is the horizontal distance from the top of the slope to where it decreases or levels. It is a key factor in the process of gully formation, with longer slopes being the most influential since they result in more extensive gully networks (Li *et al*., 2017). Understanding the impact of slope length on water erosion comes in handy during the prediction of soil loss and enhances soil and water conservation measures as a result (Fu and Zhang, 2014). Results from a study carried out in China indicated that slope length alongside rainfall intensity, plays critical roles on runoff formation and soil erosion (Fu and Zhang, 2014).

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2.7.4 Soil Characteristics

Soil characteristics play a particularly significant role in the development and progression of gully erosion. Soil texture, cohesion, moisture content and organic matter forms part of factors that greatly affect soil's vulnerability to erosion and gully formation (Gelete *et al*., 2024). Furthermore, a thorough understanding of these properties enables land managers to apply targeted soil conservation methods to reduce gully erosion and maintain soil health (Gelete *et al*., 2024). Soil texture and structure; soil cohesion and compaction; soil moisture content; and soil organic matter are the soil characteristics that influence erosion.

Soil texture and structure both determine the soil's ability to hold and drain water, as well as its aeration root penetration (Moorberg and Crouse, 2021). As soil texture refers to the proportions of the mix of sand, silt and clay, it affects nutrient retention, water holding, workability and fertility (Moorberg and Crouse, 2021). Furthermore High-clay soils have low permeability, increasing surface runoff during heavy rains (Moorberg and Crouse, 2021). In contrast, sandy soils are more permeable but less cohesive, making them more vulnerable to detachment and transport by water flow (Gelete *et al*., 2024). Furthermore, heavy rainfall drives gully erosion by increasing surface runoff, which intensifies soil erosion and promotes gully formation and expansion (Vanmaercke *et al*., 2016).

Soil cohesion is the molecular attraction between soil particles, mostly strong in clay soil due to fine particles and high surface area, helping soil resist erosion and shear (Britannica, 2024). This means that the highly cohesive soils are less likely to be eroded during the runoff period. However, when these soils erode, they develop deep and narrow gullies (Barnes and Luffman, 2016). Soil compaction compresses particles, reducing pore space and increasing density, often through methods like rolling, tamping, or vibration. It enhances soil strength and stability but can lower permeability and aeration (UMN Extension, 2024). As soil compaction reduces infiltration rate, runoff increases resulting in gully erosion process (Barnes and Luffman, 2016).

Soil moisture content is the amount of water in soil, including both liquid and vapor forms (Drought.gov, 2024). The more the soils are saturated, the more susceptible to erosion

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that soil is. This is because the water reduces the cohesive forces between soil particles making them easier to dislodge (Gelete *et al*., 2024). Furthermore, the weight of water can cause soil slumping and gully formation, particularly on slopes (Gelete *et al*., 2024).

Soil organic matter is another soil property which is essential for soil health and fertility, enhancing soil structure, water retention and nutrient availability (Magdoff and van Es, 2021). The organic matter improves the soil structure by binding soil particles together, increasing soil resistance to erosion (Jones *et al*., 2021). This means that the soil with high organic matter content absorbs more water than experience runoff. In contrast to that, soil with less organic matter content is prone to runoff and therefore leads to erosion (Jones *et al*., 2021).

2.8 Impacts of Gully Erosion/Gullying

Effectively tackling this issue necessitates adopting integrated strategies centered on sustainable land management, soil conservation practices and active community involvement to minimize its impacts and halt further deterioration (Kariminejad *et al*., 2023). Gully erosion, an advanced form of soil erosion, presents severe threats to human livelihoods, ecosystems and infrastructure, particularly under conditions conducive to its rapid development (Majhi, 2022). Its extensive effects span environmental, agricultural, infrastructural and socio-economic sectors, making it a pressing challenge for sustainable development.

A primary consequence of gully erosion is land degradation. By removing the fertile topsoil essential for vegetation growth, it renders the land infertile and unproductive (Kariminejad *et al*., 2023). This degradation disrupts ecological systems and leads to the formation of Badlands areas unsuitable for agricultural or residential use (Saksa and Minár, 2012). As a result, the land is degraded and cannot function to its fullest capacity.

The erosion of fertile soil and the formation of deep gullies drastically diminish agricultural output. This results in a decrease in the land area suitable for farming (Kariminejad *et al*., 2023). The affected land becomes unfit for farming, leading to decreased crop yields and exacerbating food insecurity (Fan *et al*., 2024). In areas where agriculture serves as the primary livelihood, this loss threatens community welfare and amplifies poverty.

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Gully expansion significantly alters natural drainage systems, disrupting the hydrological cycle. These changes exacerbate soil erosion, contribute to sediment accumulation in water bodies and heighten flood risks in downstream regions (Phionah and Extension, 2024; Kariminejad *et al*., 2023). Such disruptions impact ecosystems and increase risks to human settlements and infrastructure.

Gully erosion significantly degrades water quality by contaminating nearby water bodies with sediment, increasing turbidity and reducing light penetration, which harms aquatic habitats and disrupts ecosystems (Hassen and Bantider, 2020). The eroded soil often carries nutrients like nitrogen and phosphorus, leading to eutrophication, which promotes excessive algal growth, depletes oxygen levels and threatens aquatic life (Kariminejad *et al*., 2023). Additionally, gully erosion facilitates the transport of pollutants such as pesticides and heavy metals into water systems, posing risks to both aquatic ecosystems and human health (Fan *et al*., 2024). The formation of gullies also alters natural water flow patterns, increasing runoff and reducing infiltration, further exacerbating the movement of sediments and pollutants into water bodies (Ocheli *et al*., 2021).

The destructive nature of gully erosion extends to infrastructure, undermining roads, bridges and buildings. These damages result in costly repairs and maintenance, especially in rural regions where infrastructure is limited and essential for economic activities and communication (Ocheli *et al*., 2021). Such disruptions further isolate affected communities, impeding their development.

Economic losses are also experienced as an aftermath of gully erosion. Communities in affected areas often experience displacement, loss of livelihoods and worsening poverty. The financial burden of addressing erosion damage, implementing control measures and mitigating long-term effects is significant (Ocheli *et al*., 2021). Reduced agricultural output and compromised infrastructure exacerbate these challenges, trapping communities in a cycle of vulnerability.

When it comes to biodiversity impacts, Gully erosion severely disrupts ecosystems, leading to habitat destruction, biodiversity loss and ecosystem instability. It displaces species, including rare or endangered ones and erodes nutrient-rich topsoil, reducing

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plant growth and species diversity (Fan *et al*., 2024; Kariminejad *et al*., 2023). Altered water flow patterns increase runoff, harm aquatic ecosystems and degrade water quality through sedimentation (Hassen and Bantider, 2020; Ocheli *et al*., 2021). Furthermore, disturbed soils encourage invasive species, further threatening native biodiversity (Fan *et al*., 2024).

2.9 Impacts of Hydro-Geomorphological Hazards – A General Perspective

The most exposed elements to these hazards are the resident population, structure (both private and public properties) and the economic activities (Paliaga *et al*., 2020). Hydrological hazards cause significant destruction to human lives, their properties and environment and occur with varied scales across the globe every year (Glago, 2021). Flood events cause community disruption, displacement, property loss, deaths, injuries and economic losses (Glago, 2021). In addition to this, agricultural endeavours, historical and cultural sites also get negatively affected (Glago, 2021).

Like floods, droughts also pose threats and there have been negative impacts that are related to droughts. Related drought disasters have gone as far as causing deaths, suffering and economic damages (Panagoulia, 1998). Beside the direct aftermath of droughts, they have been followed by secondary and indirect impacts such as famine, epidemics and fire (Panagoulia, 1998). These indirect impacts also pose great threats of deaths, of not only humans but all living things. More impacts include desertification, drying up of water bodies, reduction in crop yields, migration and deaths of animals, monetary loss, waterborne diseases spread, malnutrition and deaths (Meenakshi, 2018). Each of these impacts can be categorised into different types of droughts as there are four types namely, Agricultural, meteorological, hydrological and socioeconomic droughts.

2.10 Remote Sensing and GIS in Gully Erosion Studies

2.10.1 Mapping and Monitoring Gully Erosion

Understanding gully erosion mechanisms and effects is crucial for implementing effective land management and conservation measures (Doe, 2021). Managing gully erosion

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effectively requires a comprehensive understanding of the hydro-geomorphological processes involved. This includes analysis of rainfall intensity, runoff, soil characteristics, land use and topography (Poesen, 2018). Advances in GIS and remote sensing have significantly enhanced erosion mapping, providing valuable insights for developing targeted mitigation strategies (Wilson *et al*., 2018).

Remote sensing techniques, including satellite imagery, Unmanned Aerial Vehicles (UAVs) and Light Detection and Ranging (LiDAR), capture detailed gully morphology and expansion data. High-resolution imagery provides a cost-effective way to monitor changes over time, identifying areas with significant soil loss (Ali and Ahmed, 2019). LiDAR is particularly valued for generating accurate Digital Elevation Models (DEMs), which are essential for analysing terrain characteristics and detecting subtle topographic changes linked to gully formation (Thomas *et al*., 2020). Recent advancements in remote sensing and geospatial technologies have facilitated the development of global gully head density maps, enabling researchers to assess the prevalence and intensity of gully erosion across different landscapes (Vanmaercke *et al*., 2020).

In the broader context of hydrological hazards, geomorphological mapping has also proven useful for evaluating related risks. Systematic geomorphological mapping, adopted in both academic and field communities, allows the representation of hazards and contributes to risk assessment (Chelli *et al*., 2021). Gully erosion inventory maps, which detail spatial locations of gullies, are particularly useful for training predictive models to clarify the distribution of susceptible areas (Arabameri *et al*., 2018).

2.10.2 Integration of Remote Sensing and GIS

Remote sensing and GIS technologies have improved the monitoring of gully erosion, using tools like high-resolution satellite imagery, UAVs and Digital Elevation Models (DEMs) to map gully morphology and predict vulnerable areas (Ali and Ahmed, 2019; Kumar *et al*., 2018; Thomas *et al*., 2020). Effective management involves structural measures, such as checking dams and retaining walls and non-structural strategies, like reforestation and sustainable land-use practices (Bhattacharya *et al*., 2020; Mashimbye

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et al., 2019). Community involvement is key to ensuring the success and sustainability of these interventions (Hughes and Mantel, 2020).

Challenges include the high cost of acquiring detailed data, limiting its use in small-scale studies and the lack of comprehensive policies to prevent unsustainable land practices (Chowdhury *et al*., 2019). Future research should focus on enhancing erosion risk models using machine learning and integrating socio-economic studies to improve interventions (Rahmati *et al*., 2021).

GIS complements remote sensing by offering powerful tools for spatial analysis and modelling. Inputs such as slope, rainfall and soil type are combined in GIS-based models to assess gully erosion susceptibility (Mandal *et al*., 2021). These models, enhanced by machine learning and data integration techniques, provide accurate predictions that inform targeted interventions (Pradhan *et al*., 2017). Furthermore, the integration of remote sensing and geospatial technologies has enhanced the ability to predict gully erosion susceptibility on a regional and national scale (Le Roux and Sumner, 2021). For instance, a novel method has been introduced to predict gully erosion susceptibility across South Africa by synthesizing literature directives and utilizing advanced geospatial analyses (Olivier *et al*., 2023).

GIS is also integral to broader hydrological hazard studies. Spatial analysis enables the assessment of relationships among built surfaces, hydrographical networks, floodplains and landslides, providing insights into hazard-prone areas (Paliaga *et al*., 2020). The use of data interpolation further aids in analysing spatial data, supporting comprehensive hazard evaluations.

2.10.3 Applications in Land Management

Remote sensing and GIS facilitate sustainable land management by identifying erosion-prone areas and supporting decision-making processes. For gully erosion, these technologies have been applied to design effective soil conservation measures, such as reforestation and improved drainage systems, reducing the risk of soil loss (Bhattacharya *et al*., 2020). Similarly, historical datasets integrated with contemporary remote sensing

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data enable the study of long-term erosion patterns, aiding in sustainable land-use planning (Kumar *et al*., 2018).

In the context of hydrological hazards, GIS and remote sensing support the development of early warning systems and decision-support frameworks for flood management (Glago, 2021). By identifying hazard-prone areas, these tools help allocate resources effectively and mitigate risks.

2.10.4 Methodological Standards and Cartographic Approaches

The cartographic approach has been widely adopted for assessing geomorphological hazards, involving methodologies for input creation and WebGIS outputs (Lazzari *et al*., 2018). This approach is essential for defining methodological standards and guidelines, ensuring comprehensive hazard representation through geomorphological cartography. When combined with remotely sensed data and statistical or physically based 27odelling, these methods enable detailed hazard and risk assessments (Chelli *et al*., 2021).

2.10.5 Limitations and Future Directions

Despite their advantages, the application of remote sensing and GIS faces challenges such as the high costs of acquiring high-resolution data and the technical expertise required for processing and analysis. Advances in open-access satellite platforms and user-friendly GIS tools are addressing these challenges, improving accessibility for researchers and practitioners (Chowdhury *et al*., 2019).

Future research should emphasize the integration of advanced machine learning algorithms and cloud-based platforms to enhance the precision and scalability of gully erosion studies. This focus could further improve the efficiency of monitoring and prediction systems, supporting proactive hazard management strategies (Rahmati *et al*., 2021).

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2.11 Gully Controls

Since gullies cause significant harm to the environment, infrastructure, livelihoods and communities, control methods are necessary to mitigate these impacts. The severity of the gully erosion problem has reached a point where there is a lack of proper evaluation of the effectiveness of control strategies and practices (Zimale *et al*., 2017). However, gully processes have been widely studied and numerous control practices have been implemented globally to mitigate their impacts (Asmamaw and Yosef, 2015; Ayele *et al*., 2015).

Information on techniques to prevent and control gully erosion is scattered and inadequate, particularly concerning failure rates and effectiveness (Frankl *et al*., 2021). Many gully control schemes have been implemented, but their success has been limited and often controversial (Frankl *et al*., 2021). This is because techniques that can be successful in certain areas may not be best applicable in other areas because of their different environmental settings (Rebai *et al*., 2013); (Zimale *et al*., 2017). Failures of these techniques are also influenced by runoff and sediment characteristics, cross-sectional stability and the gully's micro-environment (Frankl *et al*., 2021).

Even with many techniques not being successful and with insufficient information on them, prevention methods can still work. Many regions have implemented large-scale land rehabilitation (Frankl *et al*., 2021) to stabilise gully erosion. The application of these practices to mitigate or control gully erosion depends on topography, gully size and local economy (Liu *et al*., 2019). Land use change, applying soil and water conservation techniques would be great ways to prevent or reduce gully formation (Frankl *et al*., 2021). Moreover, increasing vegetation cover through reforestation and cover cropping can further stabilize soils and reduce the effects of runoff (Moorberg and Crouse, 2021; Guerra *et al*., 2016; Frankl *et al*., 2021).

2.12 Critique of Literature

Hydro-geomorphology is an evolving interdisciplinary field that examines the interplay between geomorphology and hydrology (Teixeira *et al*., 2013). This relationship forms the basis for analysing hydro-geomorphological hazards, encompassing both hydrological

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and geomorphological hazards. Gully erosion, classified as a hydro-geomorphological hazard, occurs when hydro-geomorphological factors such as runoff, soil type, slope and land use interact (Osman, 2014). This means that it is important to consider hydro-geomorphological factors when addressing gully erosion. Even though previously done studies used for this literature consider the interaction between hydrological and geomorphological factors in gully erosion, there is a need for more empirical studies to quantify the specific contributions of each factor.

Intense rainfall and specific soil conditions are recognised as contributors to gully formation, but there is limited data on how these factors vary across different regions and climates (Ionita *et al*., 2015). The role of human activities like deforestation and poor land management practices in encouraging gully erosion is well-documented (Hoffman *et al*., 2018). However, there is not enough research based on evaluating the effectiveness of various mitigation strategies for gully erosion. When natural landscape processes conflict with human activities, they cause catastrophic events (Alcántara and Goudie, 2010) such as soil erosion, soil deposition and rain erosivity (Alcántara-Ayala, 2010). The literature provided a comprehensive overview of the associated risks of these hazards. However, the lack of enough studies examining the long-term impacts of hydro-geomorphological hazards on ecosystems and human communities is evident.

Gully erosion in South Africa is primarily driven by climatic, geological and human factors such as intense rainfall, deforestation, overgrazing and poor soil conservation practices (Kakembo *et al*., 2015; Hoffman *et al*., 2018; Shongwe *et al*., 2020). This erosion results in the loss of topsoil, which reduces agricultural productivity and threatens food security (Mashimbye *et al*., 2019). It contributes to sedimentation in rivers and reservoirs, decreasing water quality and storage capacity (Mandal *et al*., 2021). Additionally, gully expansion damages infrastructure, increasing maintenance costs and safety risks (Hughes and Mantel, 2020). This interferes with the achievement of sustainable development goals SDGs).

Most studies do not highlight the difficulty of acquiring detailed data for gully erosion-based studies. Also, historical data is highly required but either expensive or rare to acquire. This puts a strain on researchers to produce more detailed results that can be

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useful in developing mitigation measures. Another challenge noted by other studies is the lack of comprehensive policies to prevent unsustainable land practices further exacerbates the issue (Chowdhury *et al*., 2019). Future research must focus on improving erosion risk models using and integrating socio-economic studies to improve interventions in gully erosion.

The literature highlighted why it is necessary to understand the relationship between climate and soil erosion to develop effective land management and soil conservation strategies. Studies have shown that heavy, prolonged rainfall and high rainfall intensity increase gully formation due to intensified runoff and soil displacement. Temperature variations, particularly freeze-thaw cycles, can weaken soil structure, contributing to gully formation and expansion. However, not enough detailed regional studies examine the specific climatic conditions most conducive to gully erosion in different areas.

Soil characteristics play a crucial role in the development and progression of gully erosion. Key factors such as soil texture, cohesion, moisture content and organic matter significantly influence soil vulnerability to erosion and gully formation. Soil texture and structure determine the soil's ability to retain and drain water, impacting root penetration and overall soil health. Due to low permeability, high-clay soils increase chances for surface runoff during intensified rainfalls, whereas sandy soils, despite being more permeable, are less cohesive and thus more prone to detachment and transport by water flow. However, this is not highlighted in most of the regional studies.

Topography, defined using terrain analysis, is recognised as a significant factor influencing gully erosion by most studies. The literature effectively discusses the role of slope gradient, slope length and catchment area in gully formation. Steeper slopes increase runoff and they increase the velocity of water flow on the surface, making low lying areas adjacent to them easily erodible. Similarly, longer slopes result in more extensive gully networks. While these findings are well-supported, further research is needed to explore the interaction between topography and other factors, such as soil characteristics and vegetation cover, in influencing gully erosion dynamics. Understanding these interactions will be critical for developing more accurate predictive models and effective conservation measures.

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To address gully erosion, there is a need to develop frameworks that will help with mitigation measures, the introduction of GIS and remote sensing is essential. Remote sensing and GIS technologies have enhanced the monitoring of gully erosion, with tools like high-resolution satellite imagery and Digital Elevation Models (DEMs) that are useful for gully morphology mapping and predicting vulnerable areas (Ali and Ahmed, 2019; Kumar *et al*., 2018; Thomas *et al*., 2020). Alongside these approaches, more effective management measures should incorporate both structural measures, such as check dams and retaining walls and non-structural strategies, like reforestation and sustainable land-use practices (Bhattacharya *et al*., 2020; Mashimbye *et al*., 2019).

Advances in GIS and remote sensing have significantly enhanced the understanding and management of gully erosion. These technologies provide valuable insights into the hydro-geomorphological processes involved, including rainfall intensity, runoff, soil characteristics, land use and topography. Remote sensing techniques, such as high-resolution satellite imagery and LiDAR, have proven effective in capturing detailed data on gully morphology and expansion. The development of global gully head density maps has further enabled researchers to assess the prevalence and intensity of gully erosion across different landscapes.

Systematic geomorphological mapping, which allows the representation of hazards and contributes to risk assessment, has also proven useful in this context. However, while these advancements are significant, there is a need for more studies to evaluate the long-term effectiveness and accuracy of these technologies in different environmental settings. Researchers must consider involving communities for their Indigenous knowledge to ensure the success and sustainability of these interventions as individuals are experiencing the impacts firsthand.

The integration of remote sensing and GIS has enhanced the ability to predict gully erosion susceptibility on regional and national scales. GIS-based models, which combine inputs such as slope, rainfall and soil type, offer powerful tools for spatial analysis and modelling. These models, enhanced by machine learning and data integration techniques, provide accurate predictions that inform targeted interventions. Remote sensing and GIS also play a crucial role in sustainable land management by identifying

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erosion-prone areas and supporting decision-making processes for designing effective soil conservation measures.

Future research should focus on integrating advanced machine learning algorithms and cloud-based platforms to enhance the precision and scalability of gully erosion studies, ultimately improving the efficiency of monitoring and prediction systems. Effectively addressing gully erosion requires integrated strategies focused on sustainable land management, soil conservation practices and active community involvement to minimise its impacts and halt further deterioration. Gully erosion poses severe threats to human livelihoods, ecosystems and infrastructure, leading to land degradation.

2.13 Summary

Gully erosion in South Africa is driven by climatic, geological and human factors, such as intense rainfall, deforestation, overgrazing and poor soil conservation practices. This erosion leads to the loss of topsoil and reduces agricultural productivity. This threatens food security and contributes to sedimentation in rivers decreasing water quality and storage capacity. Gully expansion damages infrastructure, increasing maintenance costs and safety risks. Factors influencing gully formation are land use/cover, climate, topography and soil characteristics. These factors not only act independently but also cause gully formation when they interact with one another.

Changes in land use/cover disrupt hydrological cycles, increasing runoff and gully formation. Improper agricultural practices exacerbate soil erosion, while climate factors like heavy rainfall and temperature fluctuations weaken soil structure, promoting erosion. Topographic features such as slope gradient and length impact water flow and runoff velocity, enhancing gully formation. Soil characteristics like texture, cohesion, moisture content and organic matter significantly affect erosion. High-clay and compacted soils increase runoff, whereas soils with high organic matter resist erosion. Understanding these factors helps apply targeted soil conservation methods to mitigate gully erosion.

Gully erosion is a severe form of soil erosion that leads to significant land degradation, reducing agricultural productivity and threatening food security. It disrupts natural

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drainage systems, degrades water quality and damages infrastructure, resulting in costly repairs and maintenance. The erosion of fertile topsoil diminishes crop yields, exacerbating food insecurity and poverty, particularly in farming-dependent communities. Gully erosion also negatively impacts ecosystems, causing habitat destruction and biodiversity loss. Effective management requires sustainable land practices, soil conservation and active community involvement to mitigate these extensive environmental, agricultural, infrastructural and socio-economic impacts.

Remote sensing and GIS play a crucial role in studying gully erosion, enhancing mapping and monitoring capabilities to inform effective land management and conservation measures. Techniques such as satellite imagery, UAVs and LiDAR capture detailed gully morphology and expansion data, aiding in erosion mapping and the development of mitigation strategies. GIS-based models combine inputs like slope, rainfall and soil type to assess erosion susceptibility and support sustainable land management. Despite challenges like high data acquisition costs, advancements in machine learning and cloud-based platforms are improving precision and scalability. Effective gully erosion control methods include land rehabilitation, reforestation and improved soil conservation practices.

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CHAPTER THREE

Materials and Methods

3.1 Introduction

Gully erosion is a significant environmental concern, leading to severe land degradation and impacting both ecological balance and socio-economic activities. Understanding the patterns and drivers of gully erosion is crucial for the sustainable land management and agricultural productivity of Thulamela Municipality. Gully erosion also affects infrastructure, posing challenges to sustainable development. Studying gully erosion is significant because it helps develop effective soil conservation strategies, protect water quality and preserve infrastructure, aligning with SDGs. The SDGs covered in this study are SDG 2, SDG 6, SDG 9, SDG 13 and SDG 15.

Gully erosion weakens roads, bridges and other structures, making them unsafe and costly to maintain (Addisu Mekonnen, 2019). This research aimed to investigate the occurrence and intensity of gully erosion within Thulamela Municipality. This aim was investigated by dissecting it into three objectives. These objectives were to map the spatial distribution of gullies in Thulamela Municipality, analyse factors contributing to gully erosion formation and establish the severity of gully erosion.

Literature states that gully erosion occurs when hydro-geomorphological factors like runoff, soil type, slope and land use/cover interact (Osman, 2014). Gully erosion, driven by these factors, negatively affects agricultural productivity and water quality (Bennett *et al*., 2018; Mandal *et al*., 2021). People's safety and infrastructures are impacted on. Researchers indicate that remote sensing and GIS technologies effectively monitor gully expansion and aid soil conservation efforts (Ali and Ahmed, 2019).

3.2. Research Design

The research design refers to the overall strategy used to integrate different components of the study in a coherent and logical way (Harris, 2021). It, therefore, ensures the

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research will effectively address the research problem. It constitutes the blueprint for the collection, measurement and analysis of data (Harris, 2021), detailing all the steps the study plans to undertake to conduct the data collection process and their analysis.

This study is evaluative and descriptive and it used quantitative data to achieve the set of objectives. The study consisted of both secondary and primary data and relied on a desktop study. This entails the analysis of maps of areas vulnerable to hydro-geomorphological hazards consisting of people, buildings, infrastructure, livelihood sources and unused lands.

3.3 Sampling technique and Data Collection

Prior to data collection, this study conducted sampling for each objective to effectively guide the data collection process. Researchers often face limitations in terms of time and resources, making analysing an entire population difficult. To address this problem, different sampling techniques are used to ensure a representative and manageable dataset (Noor *et al*., 2022). In this study, sampling was necessary for all objectives, allowing for a more efficient and manageable approach of data collection and analysis.

The first objective of this study was to map the spatial distribution of gullies in Thulamela Municipality. The data needed to achieve this objective were coordinates of areas used for collection and the quantity of gullies identified. The random sampling method was used to select 49 areas out of the 162 to represent the total population (162 areas). This sampling method was used because it allows researchers to randomly select participants for a study, without bias (Noor *et al*., 2022).

The rule of thumb was adopted as it recommends 20 – 30% of the population for sampling. In agreement with this claim, the Central Limit Theorem (CLT) also states that a sample size of 30% is sufficient (Ganti, 2024). The reason for using this rule was because if the total number of areas is small, the evaluation needs a larger sample (Rogers, 2018). Equation 3.1 below was used to calculate the sampling size.

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$$N = \frac{30}{100} \times 162$$
$$= 48.6$$
$$= 49$$

3.1 Sample Percentage equation

After the sampling, *in-situ* data of gullies (location and their quantity) were collected from the 49 areas (villages and towns) sampled and this was done in Google Earth Pro software. The data were collected for the years 2008, 2013, 2018 and 2023. Each year was treated as an experiment. The *in-situ* data collected were the coordinates of the sampled areas and the number of gullies per each of the 49 areas. Four Google Earth Pro images of the north side of the study area were captured and used for the aid of the four experiments. This was done to clarify the abrupt disappearance of gullies observed in the 2013 image, which were present in the 2008 image, as well as their subsequent reappearance in the 2018 and 2023 images.

The second objective was to analyse factors contributing to gully erosion formation. Three different datasets were needed to address this objective. Four Landsat 7 etm+ images for the years 2008, 2013, 2018 and 2023 were downloaded from USGS. Rainfall data were collected from South African Weather Services. Lastly, a digital elevation model (DEM) was sourced from USGS. A brief description of the different datasets is provided below.

Landsat 7ETM+ was launched on the 15th of April 1999. This satellite mission is equipped with Enhanced Thematic Mapper Plus (ETM+), which is the successor of Landsat TM. All 8 bands of Landsat 7 etm+ were downloaded, Band 1 (Blue), Band 2 (Green), Band 3 (Red), Band 4 (Near-Infrared), Band 5 (Short-wave Infrared), Band 7 (Mid-Infrared) with a spatial resolution of 30m, Band 6 (Thermal) with a spatial resolution of 60m and the newly added Band 8 (Panchromatic) with a higher resolution of 15m. This dataset required sampling to create representative samples of each land use/cover type to train the classification algorithm. Five classes, water bodies, agricultural activities, bare land, vegetation and built-up areas, were used for the image classification. The four images

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were utilized in ArcGIS to identify and select representative areas for each land use/cover class.

Ground truth data for this land use/cover was gathered by selecting representative areas with high-resolution satellite imagery in ArcGIS, verifying land cover types through field surveys and then dividing the data into 70% for training, 20% for validation and 10% for testing to ensure precise classification and evaluation.

The South African Weather Services (SAWS) and Agricultural Research Council (ARC) offer extensive precipitation datasets, which include daily, monthly and historical rainfall records. The datasets are crucial for hydrological modelling, geomorphological studies and spatial analysis of weather patterns and climate trends within a GIS framework. Rainfall data were collected in a Microsoft Excel spreadsheet for the years 2008, 2013, 2018 and 2023. The data consisted of monthly precipitation recorded at the following weather stations of Thohoyandou, Vondo, Tshivhase tea, Tshanowa, Phiphidi, Palmryville, Mutale, Mara, Punda Maria and Sumbana.

The United States Geological Survey (USGS) provides Digital Elevation Models (DEMs) that accurately represent the Earth's natural topography by excluding vegetation, buildings and other surface features. These DEMs are widely used for terrain analysis, hydrological modelling and environmental research. In this study, the DEM obtained from USGS had a cell size of 1000 × 1000, ensuring a detailed representation of elevation variations across the study area.

The third and last objective of the study was to establish the severity of gully erosion. The data needed were five gullies sampled from all the gullies identified from the 49 areas in the form of polygons. Analysing all 49 gullies was impractical due to extensive data collection and processing demands, thus opting for five gullies as representatives. A systematic sampling method was used to sample the gullies needed. The sampling was done using the year 2023 and the same set of sampled gullies collected in this year were used for 2008, 2013 and 2018. This method entails choosing every kk-th element from a list or population, with kk representing a fixed interval.

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The total number of gullies identified in the starting point (year 2023) were 25 and the desired sample size was 5 gullies. Equation 3.2 below was used for the calculation of the interval.

$$k = \frac{N\ (Population\ size)}{n\ (Sample\ size)}$$

$$= \frac{59}{5}$$

$$= 11.8$$

$$k = 12$$

(3.2) Sampling Interval equation.

Starting at the desired starting point (1), an interval (12) was added to get to each subsequent sample point. The sample points were calculated as follows:

Starting from 1, add the sampling interval (k=12k = 12k=12) repeatedly until 5 samples were selected:

- 1st sample: 1 (starting point)
- 2nd sample: 1+12=13
- 3rd sample: 13+12=25
- 4th sample: 25+12=37
- 5th sample: 37+12=49

Therefore, the systematic sample was gully 1, 13, 25, 37 and 49.

As a result, gullies 1, 13, 25, 37 and 49 were drawn and extracted in polygon form from Google Earth Pro. The data were acquired in KML files and they were for years 2008, 2013, 2018 and 2023.

3.4 Data Analysis

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Data analysis systematically involves collecting, cleaning and modelling data to uncover insights, support decision-making and solve problems (Encyclopaedia Britannica, 2024). This study objectives, guided by one aim. The data was analysed to produce gully spatial distribution maps for Thulamela Municipality. Data was also analysed to establish the severity of gully erosion. The last objective was to analyse factors influencing gully formation.

Data preprocessing was required to clean the datasets before the final analysis. This involves removing unwanted data, which includes duplicates, missing values, noise, inconsistencies and outliers in the data sets (Hu *et al*., 2023). Its main purpose is to extract useful and salient information from the collected raw data in such a way that it preserves the relevant information for better predictions (Raschka *et al*., 2020).

3.4.1 Data Analysis and Spatial Mapping

This study utilised Microsoft Excel, Quantum GIS (QGIS) 3.36.3 and ArcGIS 10.7.1 for data recording, conversion and spatial analysis. Microsoft Excel was used to record the 49 sampled areas, including their coordinates and the number of gullies per area. To facilitate spatial analysis, the dataset was exported in Comma-Separated Values (CSV) format and imported into QGIS 3.36.3, where it was converted into an Esri Shapefile format. This conversion was essential for enabling further processing and analysis in ArcGIS 10.7.1.

In ArcGIS 10.7.1, the ordinary kriging interpolation technique was applied to analyse gully occurrence and distribution across the study area. Ordinary kriging is a geostatistical method used to estimate unknown values based on known data of neighbouring points, making it effective for spatial prediction. Interpolation, a statistical technique that uses existing values to estimate unknown ones (Kenton, 2022), was generated to generate a gully distribution map for the years of 2008, 2013, 2018 and 2023. Interpolation was used because gullies exhibit spatial variability and often occur in patterns influenced by terrain, soil, and land use. It enabled the estimation of gully presence in unsampled areas, generating a continuous surface from discrete point data.

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The use of the mentioned datasets and analysis tools allowed for the assessment of changes in gully distribution over time, providing valuable insights into erosion patterns. The final output data was classified into five distribution categories: very low, low, moderate, high and very high gully distribution. These classifications helped in understanding the severity and spatial extent of gully formation within the study area.

3.4.2 Analysis of Factors Contributing to Gully Erosion

The selection process of the four factors analysed began with a literature review on gully erosion, which identified these factors as key contributors. Data availability played a crucial role in the selection process of these factors. Land use/cover change was included to assess the impact of human activities on gully formation, while rainfall data provided insights into climate-driven erosion. The topography factor was selected because of its direct influence on gully erosion through surface runoff and sediment transport. While soil characteristics include various properties, only soil moisture was analysed due to data limitations.

Four experiments were undertaken in ArcGIS 10.7.1 to assess land use/cover change for 2008, 2013, 2018 and 2023 to track the change. The Landsat 7 ETM+ images were preprocessed through pansharpening. The 15m resolution panchromatic band was used for pansharpening to enhance the resolution of bands 1, 2, 3, 4 and 5 before classification and Moisture Stress Index (MSI) analysis.

MSI is a remote sensing index that evaluates moisture content by analysing the shortwave infrared (SWIR) ratio to near-infrared (NIR) reflectance. MSI was essential as it acted as an indicator of soil moisture levels, compensating for the lack of direct soil moisture measurement data. Low MSI values indicate areas with low soil moisture stress, also indicating high water retention. Areas with high MSI values indicate high soil moisture stress, also indicating poor water retention.

A supervised classification method was used in ArcGIS 10.7.1 to study land use and land cover (LULC) changes by assigning training points to specific categories. This process involved manually selecting sample areas based on high-quality satellite images to

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represent different land types such as vegetation, bare land, water bodies, urban areas and farmland. The software then analysed the unique characteristics of these samples to create patterns for each category, helping to distinguish them from one another.

The rainfall data were preprocessed as they were in a Comma-Separated Values (CSV) format and contained data for 15 years, from 2008 to 2023. Only 2008, 2013, 2018 and 2023 were extracted for the analysis and the rest of the years were filtered out. These data were then imported to QGIS for their conversion to Esri shapefiles. The rainfall data in shapefile format were analysed with ArcGIS 10.7.1 through the kriging tool to achieve interpolation with the idea of showing the spatial distribution of rainfall.

The Digital Elevation Model (DEM) initially had a cell size of 1000 × 1000 and was preprocessed by resampling to a cell size of 100 × 100 using ArcGIS 10.7.1 software, employing bilinear interpolation as the resampling technique. The DEM was used for the topographic analysis of Thulamela Municipality and it was also used for calculating the Topographic wetness index (TWI). This was done to assess how water moves on the landscape and to identify areas with the potential for water accumulation. The analysis tools used include Flow Direction Tool, Flow Accumulation Tool, Slope Tool, Raster Calculator and Map Algebra (Spatial Analyst Extension). This was done in ArcGIS 10.7.1 software.

3.4.3 Establishment of Gully Erosion Severity

Google Earth Pro, QGIS 3.36.3 and ArcGIS 10.7.1 were employed for extracting, converting and analysing gully changes over time. The five sampled gullies were digitized and extracted as polygon features from Google Earth Pro. These polygons were initially saved in KML format and then converted into an Esri Shapefile using QGIS 3.36.3 to facilitate further spatial analysis.

To track gully changes over time, overlay analysis was conducted in ArcGIS 10.7.1, allowing for the assessment of variations in area size and length. This involved calculating the area and length of each gully across different time periods, ensuring a comprehensive evaluation of their growth and transformation. The calculated measurements were then

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exported to Microsoft Excel, where a table was generated to document the changes in area and length over time.

Additionally, transparency was set at 30% in ArcGIS 10.7.1 to improve visualization. This adjustment was particularly necessary for distinguishing smaller gullies that were overlapped by larger ones, ensuring that all gully changes were clearly observed and analysed. It was also to make sure all the gullies were clearly visible to interpret and compare. The methodology is condensed in a research matrix shown in Table 3 below.

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3.5. Research Matrix

Table 3 Research Matrix

Objectives	Research Questions	Key Variables	Data Sources	Analytical Tool	Key Deliverables
1. To map the spatial distribution of gullies in Thulamela Municipality.	How is the distribution of gullies in Thulamela Municipality?	Coordinates of gullies from four different years with five-year intervals.	Google Earth Pro.	Microsoft Excel; QGIS 3.36.3 and kriging tools in ArcGIS10.7.1 softwares.	Gully distribution changes over-time maps.
2. To analyse factors contributing to gully erosion formation.	Which factors are influencing gully formation?	Landsat 7 images; rainfall data; DEM.	SAWS; USGS and ARC	Kriging in ArcGIS 10.7.1, Microsoft Excel and raster calculator in ArcGIS10.7.1 software. QGIS 3.36.3, Overlay through ArcGIS 10.7.1 and Microsoft Excel softwares	Maps of influencing factors and their spatial distribution. Bar graph of total rainfall of years used for the study.
3. To establish the severity of gully erosion.	How much impact does gully erosion have on the study area?	Polygons of gullies drawn on google earth pro.	Google Earth Pro.		Gully erosion severity maps.

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3.6 Chapter Summary

The study investigates gully erosion through a structured research design, employing both primary and secondary data. Sampling was conducted before data collection to guide the process, using random and systematic sampling methods. Spatial distribution mapping involved collecting gully coordinates from 49 sampled areas using Google Earth Pro, with interpolation techniques applied in ArcGIS. Factors contributing to gully erosion were analysed using Landsat images, rainfall data and a Digital Elevation Model (DEM). Severity assessment utilized overlay analysis on five systematically sampled gullies across different years. Data preprocessing was done to clean the data off unwanted data. Pansharpening the Landsat 7 ETM+ images and resampling the DEM ensured a clear resolution for analysis. Microsoft Excel and ArcGIS were used for statistical and spatial analyses to derive meaningful insights on erosion trends.

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CHAPTER FOUR

Results and Discussion

4.1 Introduction

Gully erosion is a severe hydro-geomorphological hazard driven by both natural and human-induced factors, leading to significant environmental, social, and economic challenges like intense rainfall, deforestation, improper land management and overgrazing accelerate gully formation. This results in soil degradation, sedimentation in water bodies and costly infrastructure damage. Gully formation depletes fertile soil, threatens development and compromises the safety of residents.

Without proper mapping and analysis, the risks to infrastructure, food security and water resources will continue unnoticed. Gully erosion affects both developed and developing regions globally, which is a call for mitigation strategies such as reforestation, conservation tillage and remote sensing-based monitoring. Addressing this issue aligns with Sustainable Development Goals. This research aimed to investigate the occurrence and intensity of gully erosion in Thulamela Municipality by mapping its spatial distribution, analysing contributing factors and assessing severity. The tools used in the analysis were Kriging, Flow Direction Tool, Flow Accumulation Tool, Slope Tool, Raster Calculator and Map Algebra (Spatial Analyst Extension).

4.2 Results

After thorough data analysis, the next part to complete is to present the results. The results are reported while referring to the presentations or visuals. This study used maps, tables and graphs to present the results. All the objectives results are presented and reported in the following sections.

4.1 Spatial Distribution of Gullies in Thulamela Municipality

The results of the four (4) experiments conducted to address the first objective of mapping the spatial distribution of gullies in Thulamela Municipality are present in Figure 4.1. The experiments were conducted to investigate and indicate the occurrence of gullies over time in the study area. The majority of the study area shows very low occurrence of gullies

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throughout the four experiments. Based on the results, the lowest gully occurrence was recorded in 2013 and highest was recorded in 2018.

Gully occurred in the North and North-Eastern parts in 2008 but disappeared in 2013. The gullies in the northern part reappeared again in 2018, with a slight decrease in 2023. The western and central areas of Thulamela Local Municipality have remained gully-free throughout the time period of the study, with only low occurrence in the centre in 2013 and 2023. The southern part has not experienced much of this hazard but did experience a low and moderate occurrence during in image 2018 and 2023. Overall, Thulamela Local Municipality was found to be most prone to gully erosion on its north and north-eastern sides and gully erosion free on most of its areas.

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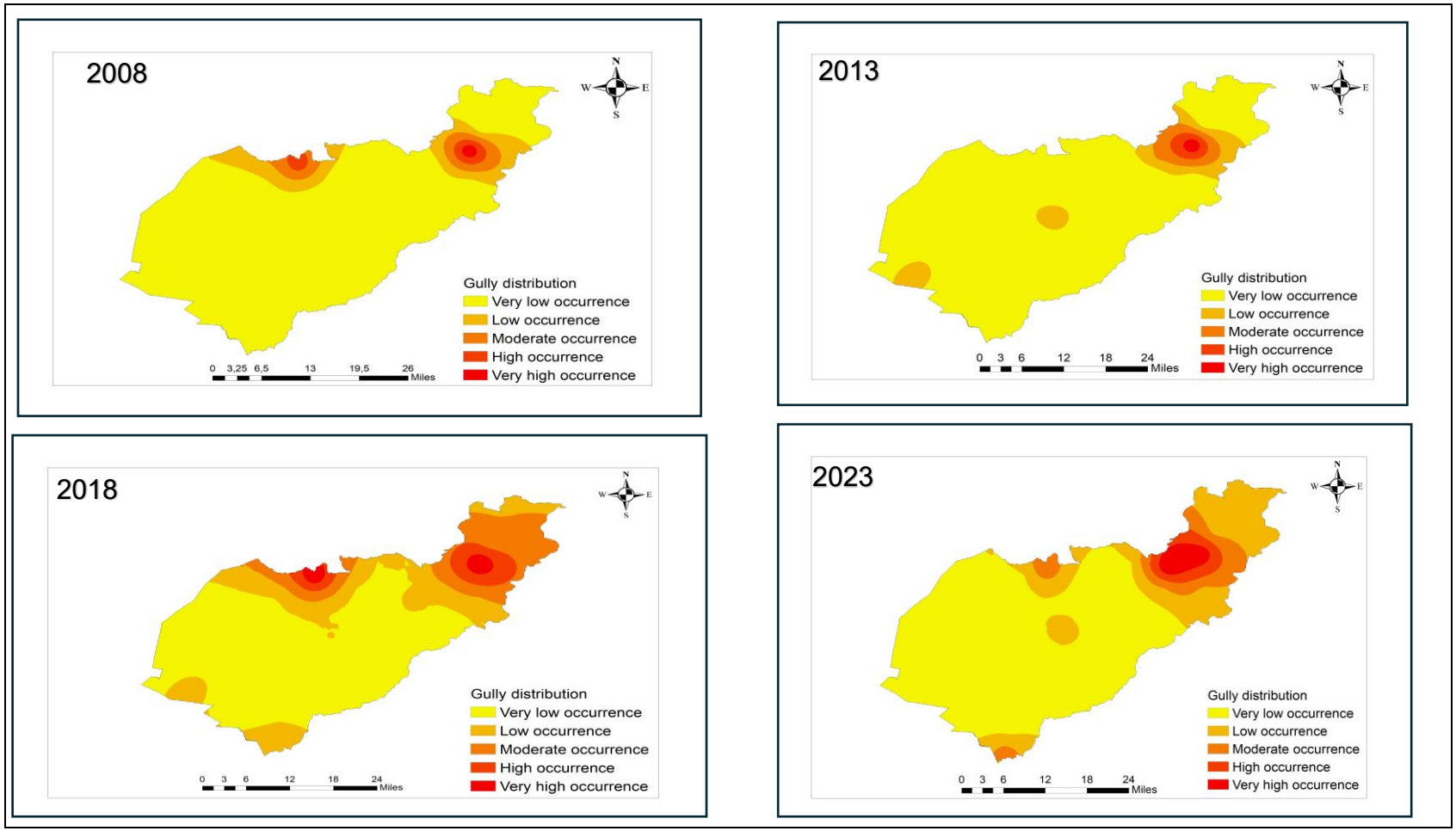

Figure 4.1. Gully distribution over the years (2008; 2013; 2018; 2023)

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4.2.2 Factors Contributing to Gully Erosion

Several factors contribute to gully formation, with land use/cover change through vegetation removal. Land use (human activities), like deforestation and overgrazing can accelerate erosion, making land use practices a key determinant in gully development. Climate factors such as rainfall intensity, frequency and temperature further shape gully formation. Topography influences gully erosion through slope steepness, aspect and elevation. Soil characteristics, including soil moisture, type, texture and erodibility, also contribute to gully erosion.

4.2.2.1 Land Use/Cover Change

Five classes, including water body, built-up areas, agricultural areas, bare land and vegetation were used to analyse and understand the influence of land use/land cover on gully formation. Water bodies remained constant throughout the 15 years of the study, with no significant change in the locations and their quantity. Built-up areas were present throughout the study period, with a notable change occurring in 2023, with substantial expansion towards the North side, indicating new urban centres or residential developments.

Agricultural activities went through a lot of changes, from being less common in 2008 and becoming dominant in 2013, 2018 and 2023. The agricultural areas showed substantial expansion in the North-Eastern side of Thulamela Municipality in 2023. Bare land areas remained almost the same throughout the study period, with substantial changes only on the North-Eastern side of the study area caused by the presence of agricultural activities. The vegetation class started more dominant in 2008 and decreased in 2013 when agricultural activities became more dominant. Vegetation recovered in 2018 and remained like that until 2023.

Overall, bare land remained constant and slight change occurred throughout the study period. Built-up areas, agriculture and vegetation went under more changes and dominated all the years considered for this study. Figure 4.2 below presents all the reported results.

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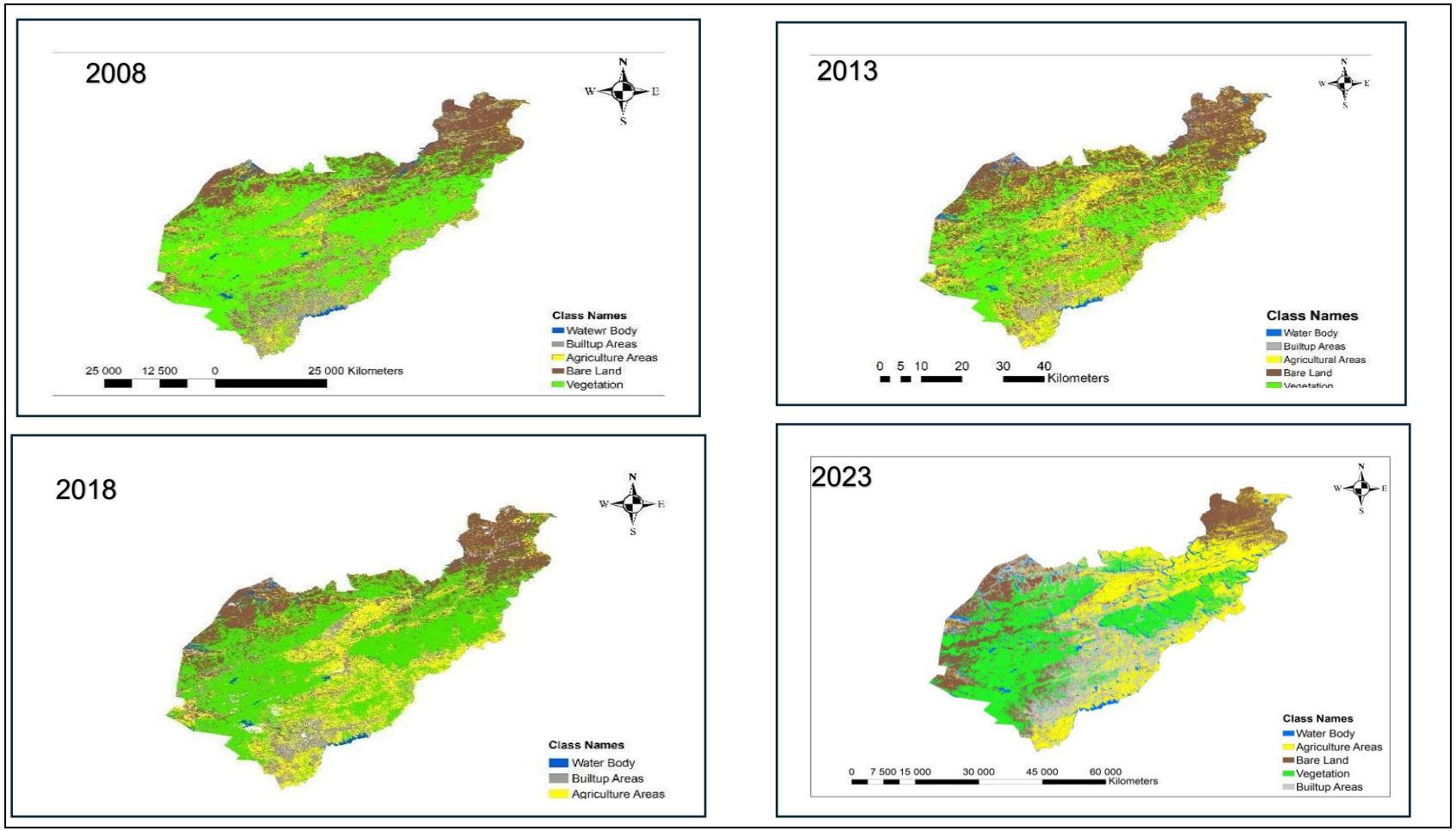

Figure 2.2. Land use/cover change over time (2008; 2013; 2018; 2023).

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4.2.2.2 Rainfall

Four (4) experiments were conducted to analyse and address the influence of rainfall distribution on gully erosion. Five categories were used to distinguish the distribution of rainfall across the study areas. The categories were Very low rainfall, Low rainfall, Moderate rainfall, High rainfall and Very high rainfall. These categories were applied to all the four experiments.

Results showed that rainfall distribution did not remain constant throughout the study period and was also not distributed evenly in all four experiments. Rainfall occurrence in 2008 was very low across the majority of the study areas, with low, moderate, high and very high rainfall only being experienced Western side of Thulamela Municipality. The highest rain rainfall received was in 2013, with very high and high rainfall being dominant and were recorded in the North and North-Eastern part of the study area. Rainfall distribution was even at most of the areas in 2018, showing low rainfall distribution in the majority of study area. In 2023, the study area was dominated by very low rainfall distribution, low rainfall came second. Moderate and high rainfall were experienced on experienced on the far South-Western of Thulamela Municipality. The reported results are displayed in Figure 4.3 below.

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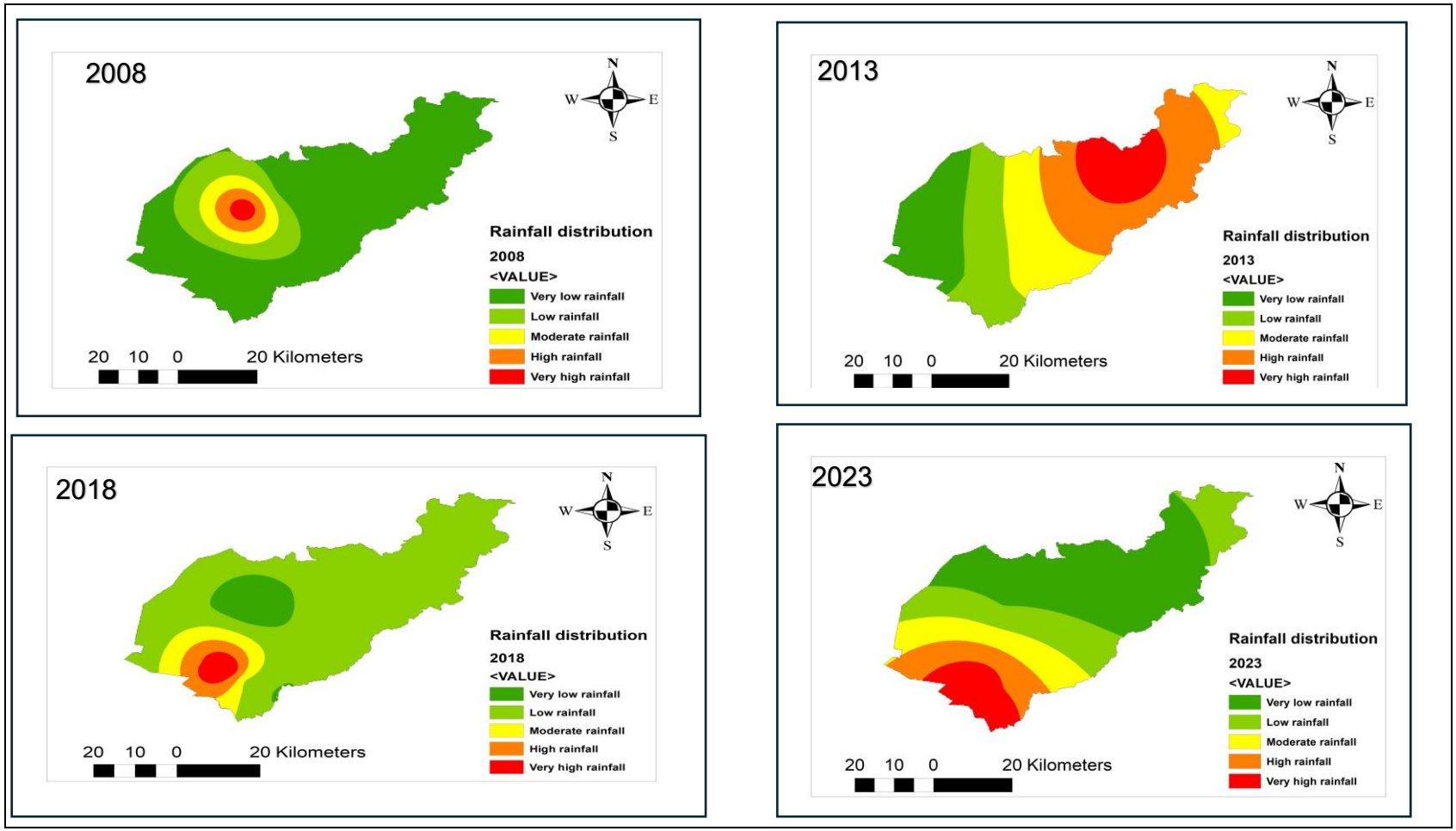

Figure 4.3. Thulamela total rainfall variability throughout the study period

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4.2.2.3 Topography -Slope and Topographic Wetness

The slope was analysed as it has primary topographic influence on gully erosion. Slopes between 0º - 6.2º indicate flat areas, while 6.2º - 12º represents gently sloping terrain. These two categories are dominant across Thulamela Municipality. Areas that have a slope of 12º – 19º are considered moderate and they are not as dominant as flat areas. Areas of slope with 19º - 25º are steep and were found to be present but not too common. Areas of slope 25º - 31º are very steep and were also found to be less common compared to flat areas. Overall, Thulamela Municipality mostly has flat to gentle slopes. However, there are also areas with very steep and moderately steep slopes. Figure 4.4 below indicates the results.

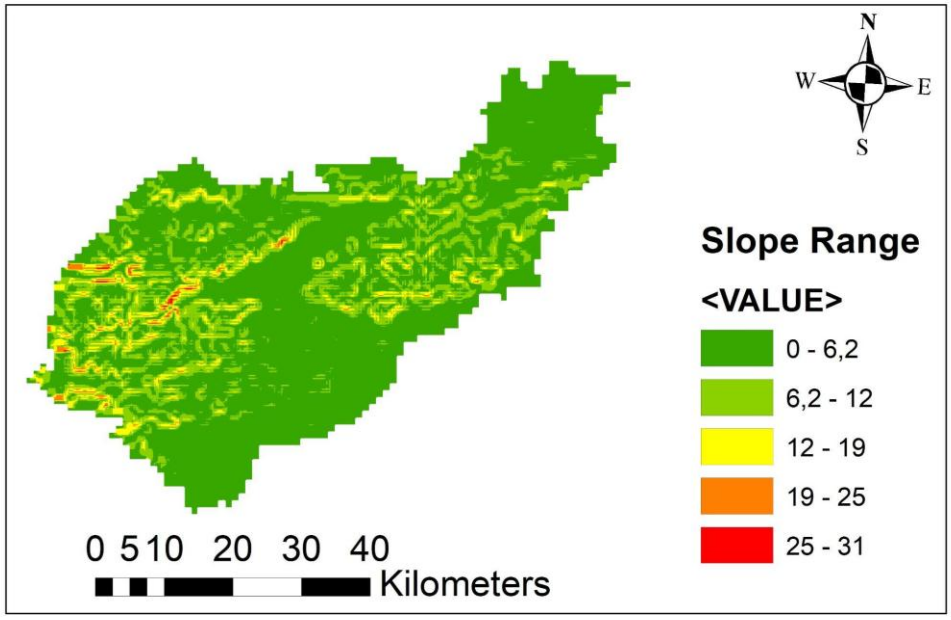

Figure 4.4 Thulamela Slope ranges

Lower TWI values between 5 - 7 represent areas with very little wetness where water is less likely to accumulate. Values between 7 - 9 indicate low wetness, while those between 9 - 12 show moderate wetness. Higher values from 12 - 15 correspond to areas with significant wetness and the highest values from 15 - 20 indicate zones with very high wetness where water accumulates the most. Generally, areas with lower TWI values are

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drier and less prone to water accumulation, while higher values suggest wetter areas that are more likely to be saturated. This is shown in Figure 4.5 below.

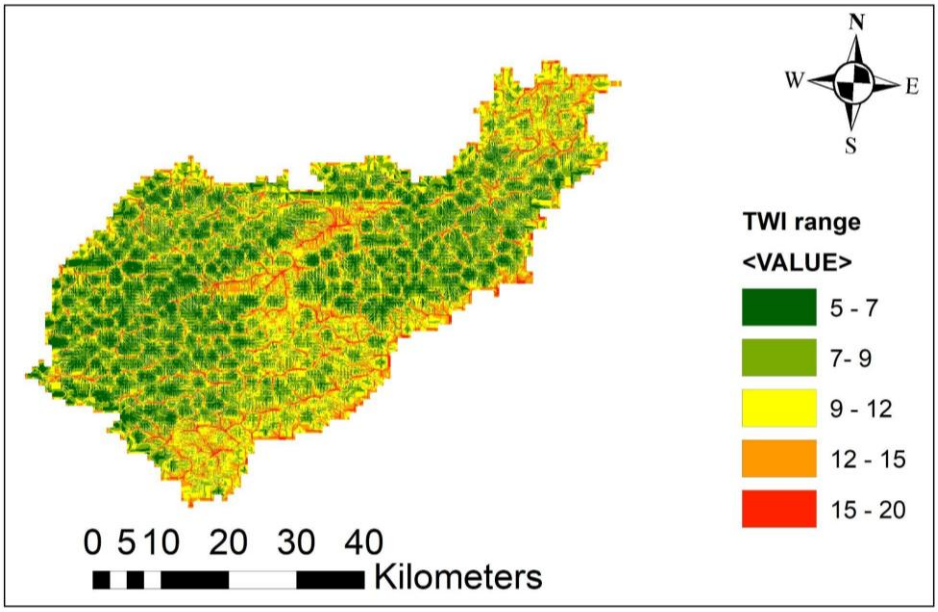

Figure 4.5 Thulamela Topographic wetness index ranges

4.2.2.4 Soil Moisture

The Moisture Stress Index (MSI) was used to analyse the soil moisture of Thulamela Municipality. Low MSI values indicate areas with low soil moisture stress, also indicating high water retention. Areas with high MSI values indicate high soil moisture stress, also indicating poor water retention. There are also mid-range MSI values indicating normal soil moisture stress.

The 2008 image shows that the highest MSI value was 3.07. However, this was not the most dominant. However, it is fairly common in the study area. The North and North-eastern sides of the study area, where gullies were common, experienced high MSI values. Low and mid-range MSI values dominated the rest and most parts of the study area, with the lowest MSI values reaching 0.27.

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The 2013 image shows that the difference between the highest and lowest MSI values was not big. The highest MSI value was 1.89 and these values were only more common in the North-eastern part of the study area where gullies were common. Low and mid-range MSI values dominated the rest of the areas and most of the study area, with the lowest MSI values reaching 0.32.

The 2018 image shows that the highest MSI value was 2.6. However, the values were not the most dominant, although they were fairly common in the study area. The North and North-Eastern sides of the study area, where gullies were common, experienced high MSI values. Low and mid-range MSI values dominated the rest of the areas and most parts of the study area, with the lowest MSI values reaching 0.14.

The 2023 image shows that the highest MSI value of the year 2023 reached 3.88, but these values were not the most dominant. However, they were also fairly common in the study area. The North and North-eastern side of the study area where gullies were common, also experienced high MSI values. Low and mid-range MSI values dominated the rest of the areas and most parts of the study area, with the lowest MSI values reaching 0.42.

According to these results, High MSI value areas influence gully erosion formation by the presence of high moisture stress in the soil's water content. Figure 4.6 below shows the reported results.

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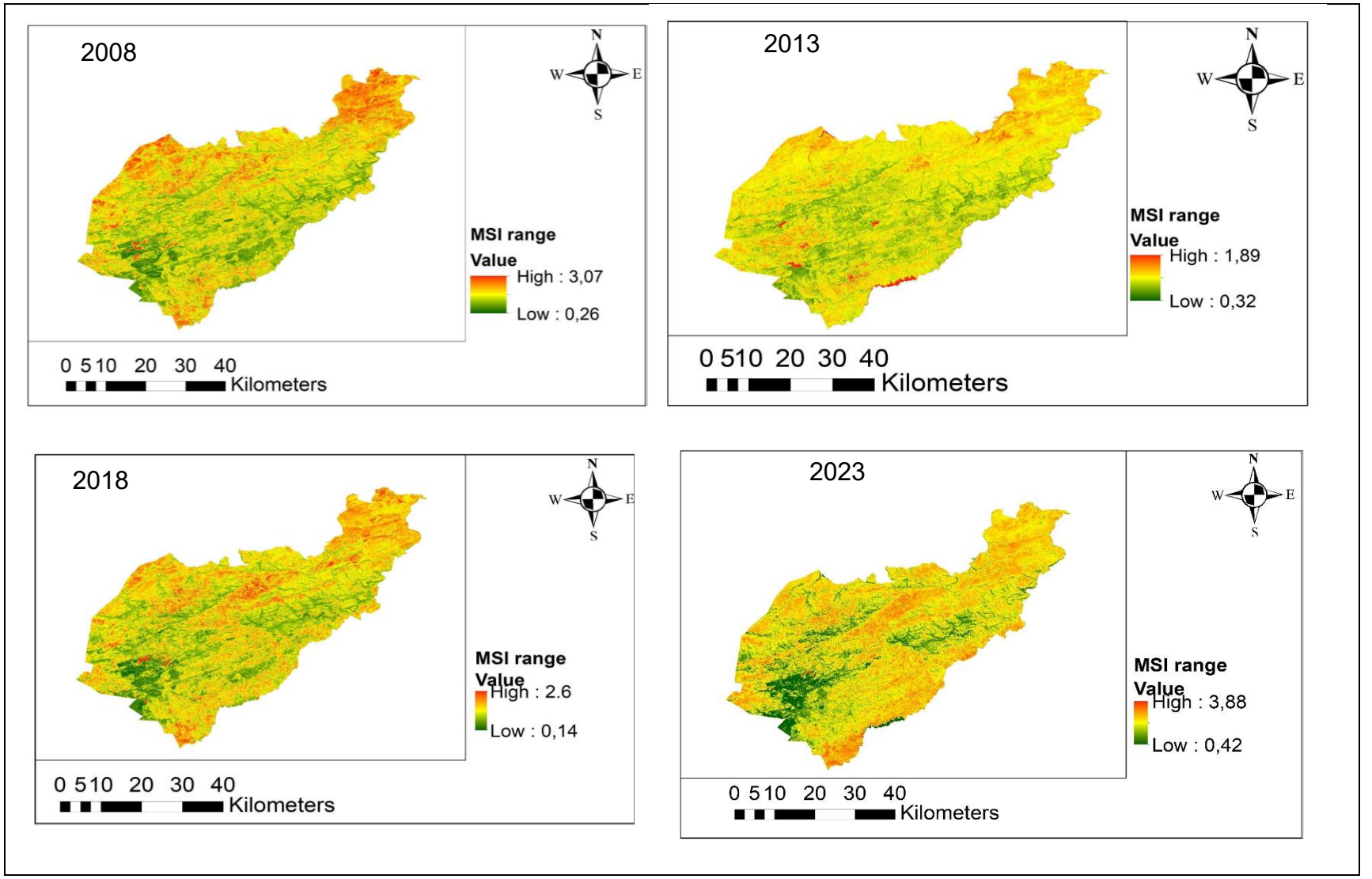

Figure 4.6 Thulamela soil moisture ranges (2008; 2013; 2018; 2023)

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4.2.3 Gully Erosion Severity

For each of the five sampled and analysed gullies, each of the four years used for this experiment is represented in a different colour. The satellite images are for context and for referrals. The images show the exact location of the gullies used for this objectives analysis

Gully 1 was present in 2023 only. Although the gully only appeared in 2023, it developed at a fast pace, occupying an area of 43.18 m² and grew to a length of 29.12 m. This is presented in Figure 4.7 and Table 4.1 below.

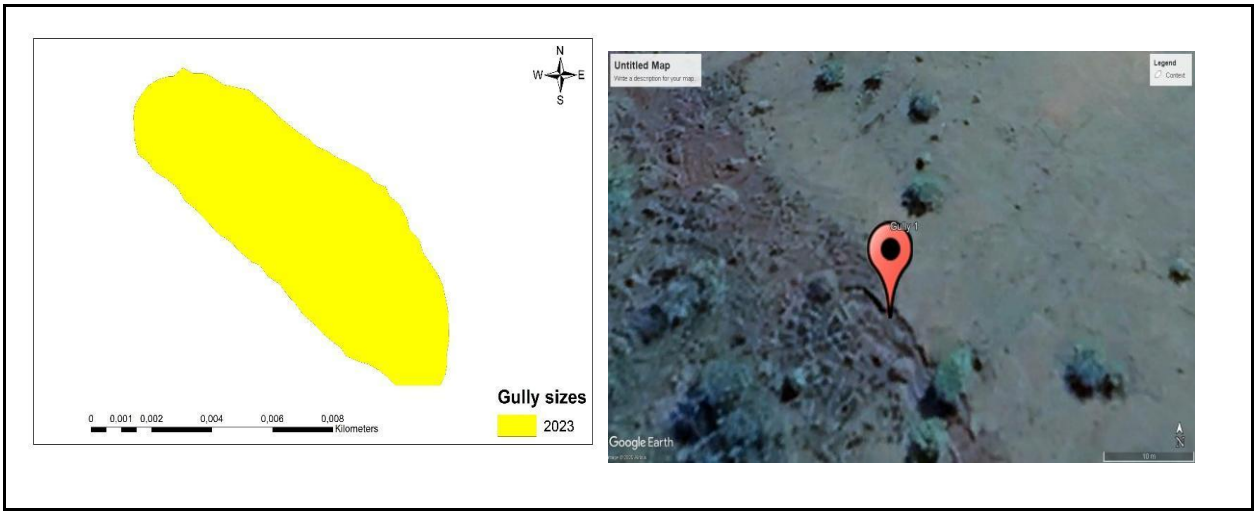

Figure 4.7 Gully 1 change over time (22°47'13.92"S, 30°48'13.01"E)

Table 4.1 Gully 1 sizes calculated

Year	Gully Length (m)	Gully Area (m²)
2023	29,12	43,18

Gully 13 appeared in three of the four years 2013, 2018 and 2023, but not in 2008. However, the gully's shape and size kept changing throughout the years. The gully was elongated in 2013. Gully 13 had an area of 164.25 m² in 2013, making it the largest area occupied in the three years it appeared. It decreased by -45,3% to 89.91 m² in 2018. It again increased by 82,4% to 163.94 m² in 2023. In terms of length, gully 13 was at its longest in 2013 at 131.13 m and decreased by -29,4% to its shortest in 2018 at 92.58 m.

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In 2023, it increased by 10,8% to 102.59 m. Figure 4.8 and Table 4.2 displays the above reported changes.

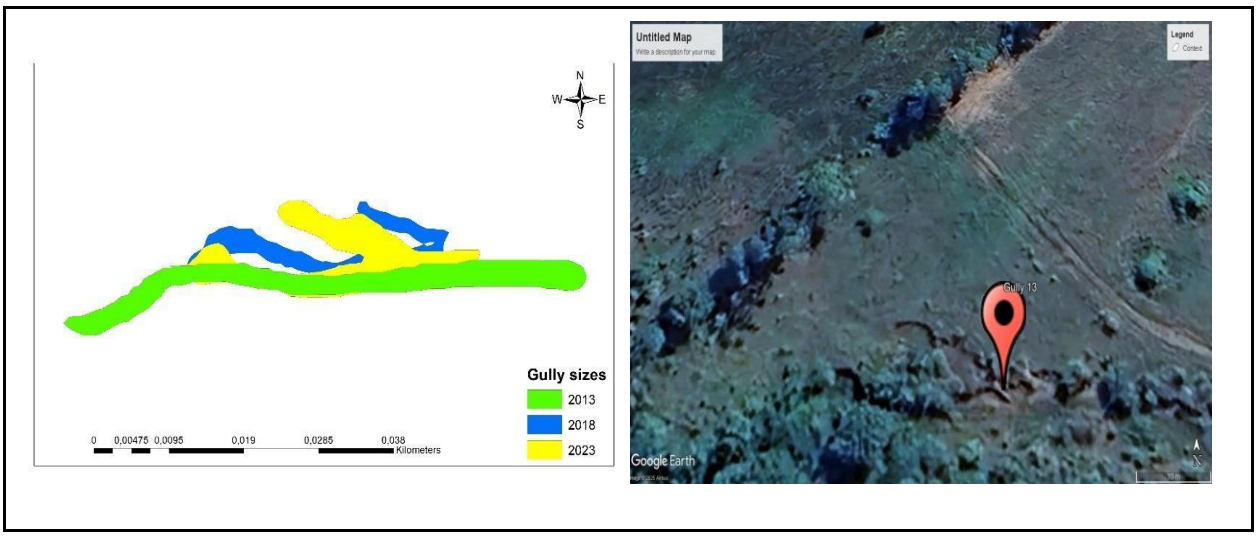

Figure 4.8 Gully 13 change over time (22°48'11.75"S, 30°47'40.42"E)

Table 4.2 Gully 13 sizes calculated

Year	Gully Length (m)	Gully Area (m²)	Change in Percentage	
			Gully Length	Gully Area
2013	131,13	164,25		
2018	92,58	89,91	-29,4	-45,3
2023	102,59	163,94	10,8	82,4

Gully 25 appeared in all four years (2008, 2013, 2018 and 2023). However, the gully's shape and size changed throughout the years. It was large in 2013 but became smaller in 2018, then increased again in 2018 and continued to do so until 2023, as shown in Figure 4.9. In 2008, gully 25 was at its largest, occupying an area of 100.68 m². However, it decreased by -71,2% to an area of 28.98 m² in 2013, indicating less erosion. The size increased again by 41,9% from an area of 28.98 m² to an area of 41,12 m² in 2018. It further increased by 143,2% from an area 41,12 m² to an area of 100,03 m² in 2023. In terms of length, this gully was at 46,99 m in 2008, but decreased by -23,47% to its shortest at 35.96 m in 2013. The length slightly increased in 2018 by 2,97% to 37,03 m and it

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increased again by 38,4% in 2023 to its longest at 51,24 m. Table 4.3 below shows the changes reported above.

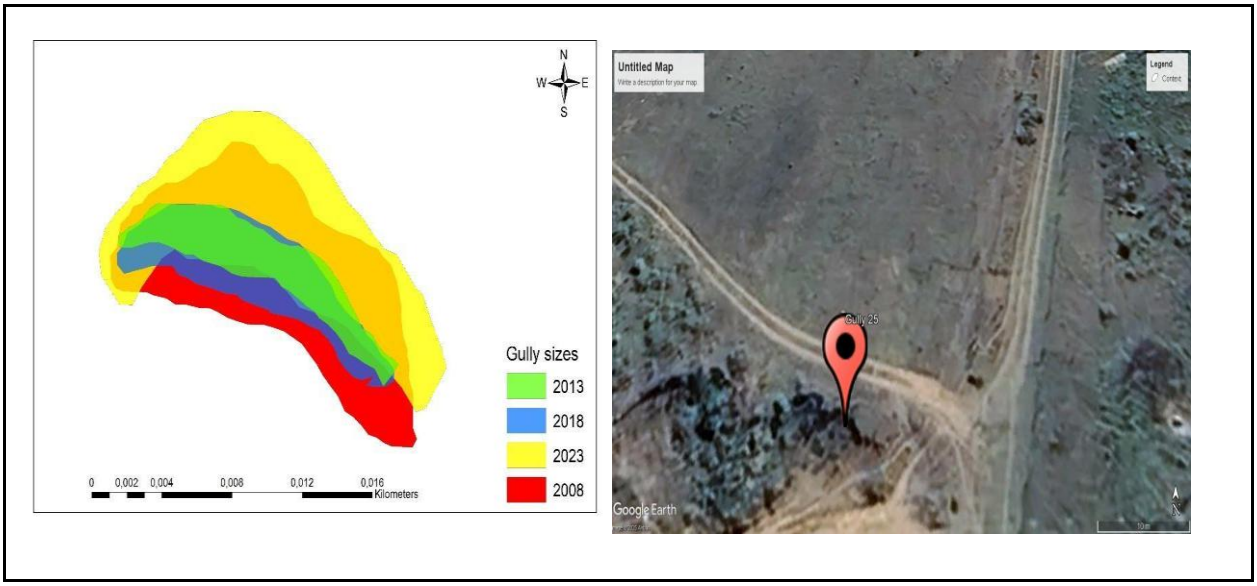

Figure 4.9 Gully 25 change over time (22°47'53.23"S, 30°32'53.22"E)

Table 4.3 Gully 25 sizes calculated

Gully years	Gully Length (m)	Gully Area (m²)	Change in Percentage	
			Gully Length	Gully Area
2008	46,99	100,68		
2013	35,96	28,98	-23,47	-71,2
2018	37,03	41,12	2,97	41,9
2023	51,24	100,03	38,4	143,2

Gully 37 only existed in 2008 but disappeared before 2013. This gully covered an area of up to 242.61 m² and had a length of 83.23 m. This is shown in figure 4.10 and table 4.4 below.

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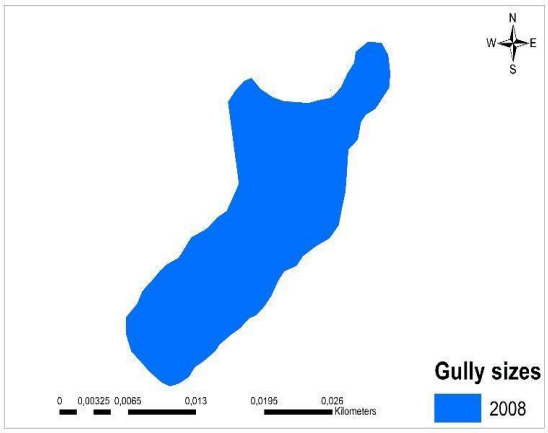

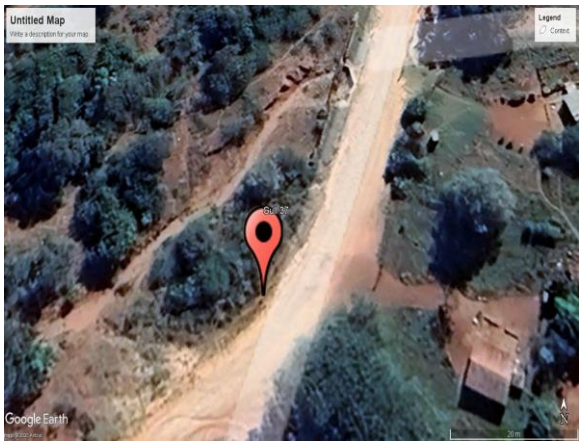

Figure 4.10 Gully 37 change over time (22°40'15.47"S, 30°30'28.28"E)

Table 4.4 Gully 37 sizes calculated

Gully years	Gully Length (m)	Gully Area (m²)
2008	83,23	242,61

Gully 49 was only present in 2023. This gully covered an area of up to 197.17 m² and has a length of 86.40 m. This is shown in figure 4.11 and table 4.5 below.

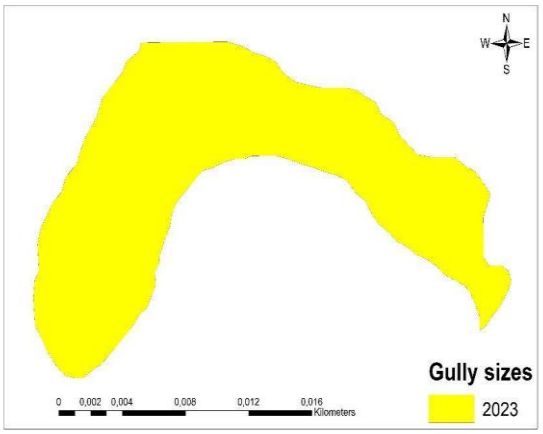



Figure 4.11 Gully 49 change over time (22°40'59.27"S, 30°37'57.23"E)

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Table 4.5 Gully 49 sizes calculated

Gully years	Gully Length (m)	Gully Area (m²)
2023	86,40	197,17

4.3. Discussion

Gully erosion is a persistent environmental challenge in Thulamela Local Municipality, showing a significant increase over the period under review. While the change between 2008 and 2013 was minimal, the overall trend indicates a substantial expansion of gullies, particularly in the northern and northeastern regions. The areas have consistently been erosion hotspots, with a noticeable increase in occurrence in 2018 and 2023. The western and central parts of the Municipality have remained largely gully-free throughout the study period, while the southern region has been experiencing gully erosion throughout the study period of 15 years from 2008 to 2023.

The observed variation in gully distribution, particularly the absence of gullies in the 2013 dataset, can be attributed to differences in data collection conditions. Figure 4.1 illustrates that gullies observed in 2008 disappeared in 2013 but reappeared in 2018 and 2023. This discrepancy is likely due to seasonal variations during data collection. Figure 4.12 shows that the 2013 image had dense vegetation cover and cloud interference, making it difficult to identify gullies. Conversely, the 2008, 2018 and 2023 images had less vegetation cover, making gully identification easier. The differences highlight the importance of using consistent methodologies and considering seasonal variations when analysing gully erosion patterns.

Gullies can evolve in size and shape over time due to both environmental and anthropogenic factors. Monitoring these changes is crucial for effective land management and soil conservation. Figures 4.7 (gully 1) and 4.11 (gully 49) demonstrate that gullies can form and expand rapidly. For example, gully 1 was absent in 2008, 2013 and 2018 but appeared rapidly in 2023, while gully 49 also developed at a fast rate. The findings align with research conducted in Ethiopia, where gullies expanded by an average of 21 meters in length, 0.275 meters in width and 0.28 meters in depth annually (Woldearegay

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et al., 2019). Similarly, studies in China reported annual gully growth of 0.23 meters in length, 0.25 meters in width and 0.09 meters in depth between 2014 and 2021 (Zhang *et al*., 2023). The rapid expansion of gullies in Thulamela indicates a worsening erosion problem, necessitating immediate intervention.

The dynamic nature of gully erosion is further evidenced by changes in gully morphology. Gully13 in figure 4.8 transformed from an elongated shape to a Y-shape, while gully 25 in figure 4.9 exhibited fluctuations in size between 2013 and 2023. Similarly, Table 4.4 indicates that gully 37, which covered the largest area (242.61 m²) in 2008, disappeared in later years. This could be due to soil stabilization through vegetation regrowth or sediment deposition. In 2023 gully 49 was the largest, covering 197.17 m², making it the most severe erosion by the end of this study's period. This is consistent with findings from Wang *et al*. (2021) on the Chinese Loess Plateau, where gullies exhibited varying growth rates, averaging 5.66 m² per year over 41 years. The continued expansion of large gullies like gully 49 poses significant environmental threats, including land degradation and increased vulnerability to further erosion.

Land use and land cover (LULC) changes play a crucial role in gully formation and expansion. Research has consistently shown that bare land is highly susceptible to gully erosion due to the absence of protective vegetation. In Northeast China, cultivated lands experienced significant gully erosion over 50 years, demonstrating the vulnerability of disturbed soils (Li *et al*., 2021). Similarly, human activities such as urbanization and agricultural expansion contribute significantly to soil erosion by removing vegetation and disturbing the soil. A study in Ethiopia confirmed that LULC changes exacerbate gully formation, particularly when combined with increasing rainfall intensity (Setargie *et al*., 2023). However, improved land management practices can help mitigate these effects (Setargie *et al*., 2023).

The inverse relationship between vegetation cover and gully erosion is well-documented. In Nanka, Nigeria, areas with dense vegetation cover experienced minimal erosion, highlighting the role of vegetation in soil conservation (Nwaogu *et al*., 2018). With that said, Thulamela experienced more gully erosion on the northeast where the area was

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bare land and had little to no vegetation cover throughout the 15 years of the study. Research by (Li et al., 2021) confirmed that land use changes like cultivating on slopes and the act of deforestation by converting forest to farmland intensifies gully formation. These findings emphasize the importance of maintaining vegetation cover to mitigate gully erosion in Thulamela.

Rainfall is another critical factor influencing gully erosion. The finding showed that Thulamela experience very low rainfall in three of the four experiments. Lack of rainfall causes soil to dry out, causing vegetation to struggle to obtain enough moisture and begin to dry out as well (Cairoli, 2017). The lack of vegetation laves soil exposed and easier to erode, leading to gully erosion. This could have influenced gully formation in 2008, 2018 and 2023 as they experienced low rainfall but suffered from gully erosion.

Heavy rainfalls also cause gully erosion by increasing the volume and speed of surface runoff. Research in Thulamela on the R523 road found that extreme rainfall events contribute to slope instability and erosion, further accelerating gully formation (Sengani and Mulenga, 2020). Similarly, research in the Guadalquivir Basin, southern Spain, found that extreme rainfall events, combined with land use changes, exacerbate gully erosion (Hayas *et al*., 2025). This supports the results of higher rainfall and gully erosion in the North-Eastern side of the study area in 2013. These findings reinforce the need for sustainable land management practices to mitigate the effects of extreme rainfall on soil erosion.

Topography significantly influences gully formation, as evidenced by Figures 4.4 and 4.5. Areas in low-lying areas adjacent to high elevations experience more runoff and water saturation. This means that areas in Thulamela in these conditions as shown in figures 4.4 and 4.5 experience more gully erosion. Studies in Nigeria and Ethiopia confirm that steep areas experience high erosion levels, while low-lying areas adjacent to higher elevations accumulate runoff, increasing susceptibility to gully formation (Nwaogu *et al*., 2018; Setargie *et al*., 2023). The Topographic Wetness Index (TWI) supports these findings, indicating that low-lying areas in Thulamela experience higher water accumulation, making them more prone to gully erosion.

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Soil moisture content also plays a crucial role in gully formation. Figure 4.6 indicates that areas with high moisture stress are more prone to erosion due to reduced water retention and increased surface runoff. The Moisture Stress Index (MSI) analysis confirms that areas with elevated soil moisture stress are more vulnerable to gully development. Research by (Welikhe *et al.,* 2017) found that MSI is a reliable indicator of soil moisture conditions, supporting the conclusion that soil moisture significantly influences gully erosion by weakening soil structure and increasing susceptibility to erosive forces.

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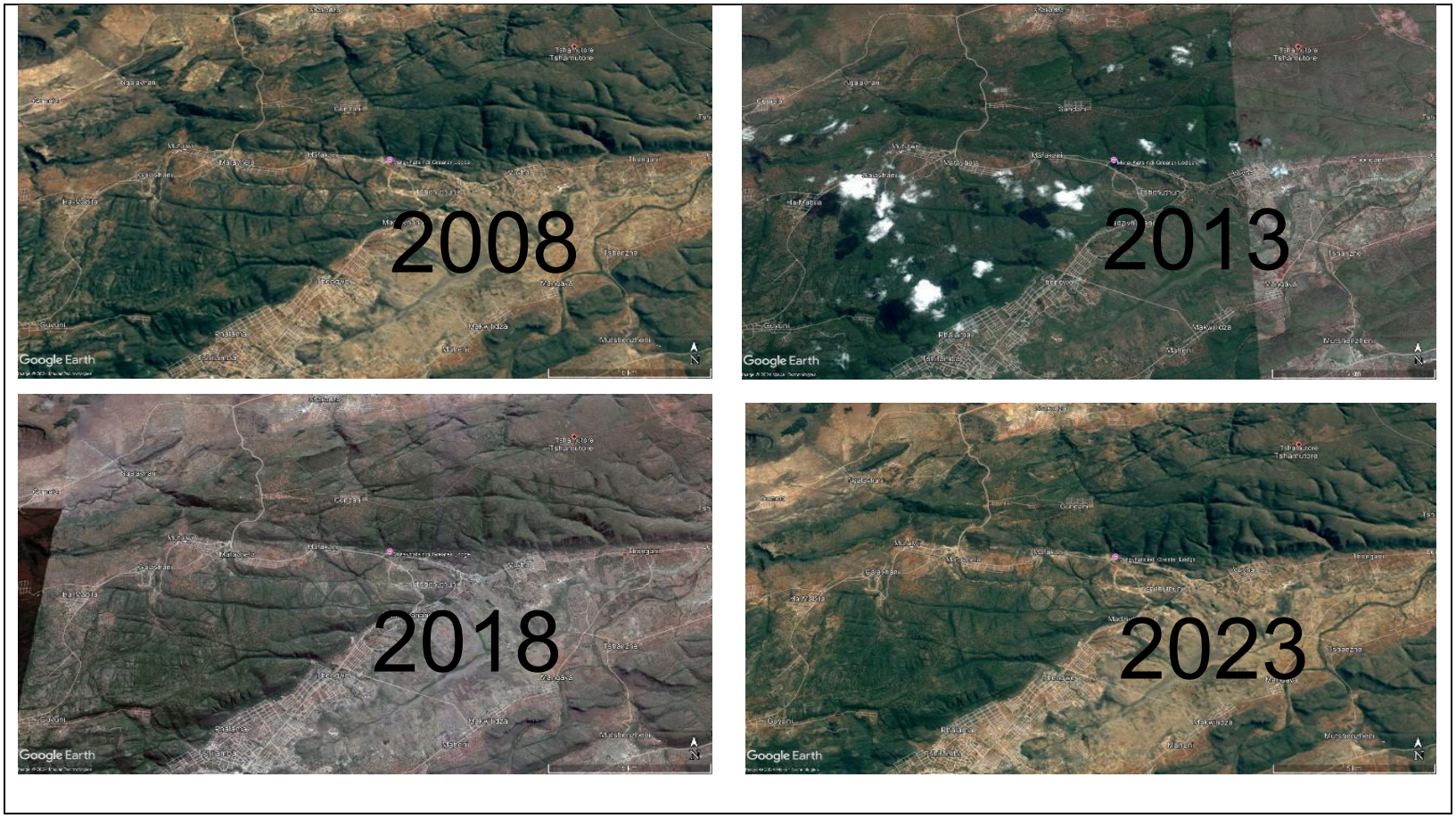

Figure 4.12. Land cover of the Eastern-north part of Thulamela (A - 2008; B - 2013; C -2018; D - 2023)

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4.4 Chapter Summary

The study was carried out based on three objectives, created from the aim of the study. Mapping the spatial distribution of gullies showed that gully erosion has been common during the course of the study period. The results showed that gully erosion is not common everywhere but is still a problem because its presence proves it is an ongoing problem. Assessing the severity of gully erosion gave results that determined their impacts as significant. The results showed the change in gully sizes, further detailing the areas and lengths covered by sampled gullies.

Four factors contributing to gully erosion were analysed and their results showed that all four factors influence gully erosion differently. These factors included land use/cover change, rainfall, topography and soil properties (soil moisture). The results of each factor showed that gully erosion is a product of many factors, acting both together and independently. The change in land cover by land use poses greater opportunity for gully erosion. Rainfall distribution at favourable conditions and places makes the formation of gullies highly possible. Topography showed that in the right elevation, rainfall-runoff could cause gullies due to the increased high speed of runoff caused by increased elevation. Soil moisture analysis showed that gullies form in areas with high water saturated soil.

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CHAPTER FIVE

Summary, Conclusion and Recommendations

5.1. Summary

Gully erosion, a severe hydro-geomorphological hazard, results from both natural factors, such as intense rainfall and soil characteristics and human activities like deforestation, agriculture and poor land management. It leads to significant environmental and socio-economic challenges, including soil degradation, loss of agricultural productivity, water pollution and infrastructure damage. Globally, regions like Ethiopia, China's Loess Plateau and parts of North America face severe gully erosion due to climatic and land-use factors. In South Africa, particularly in Thulamela Municipality, gully erosion threatens development and livelihood making it crucial to analyse its distribution, severity and contributing factors using remote sensing and GIS technologies for effective mitigation.

This study aimed to assess gully erosion in Thulamela Municipality to identify safe areas for habitation and land use. This study focused on mapping gully distribution, assessing the severity of gully erosion and analysing factors contributing to gully formation in Thulamela Municipality. These objectives were developed based on the main aim of the study to achieve it. Addressing gully erosion through preventive and remedial strategies, such as vegetation cover maintenance, sustainable land practices and erosion control structures, helps mitigate its impacts.

The literature review examined gully erosion as a hydro-geomorphological hazard, emphasizing its environmental and socio-economic impacts. Gully erosion, driven by factors like intense rainfall, soil composition and land-use practices, is particularly severe due to its lasting effects on landscapes, agriculture and infrastructure. In South Africa, climatic, geological and human influences accelerate land degradation, reducing agricultural productivity and increasing erosion risks. Remote sensing and GIS technologies are crucial for monitoring and managing these risks, though challenges such as data costs and policy limitations remain.

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Additionally, the review addressed factors influencing gully formation. The factors were land use/cover change, climate in terms of rainfall, topography and soil in terms of soil moisture.

A qualitative and quantitative research design was employed, using both primary and secondary data. Sampling was necessary due to resource constraints, with 49 out of 162 areas selected using a random sampling method for objective 1, while systematic sampling was applied to identify five representative gullies for objective 2. Data collection involved Google Earth Pro for visual interpretation, Landsat 7 images from USGS, rainfall data from South African Weather Services and DEM data for topographic analysis. Preprocessing steps included pan-sharpening for enhanced satellite imagery, filtering rainfall data in Excel and resampling the DEM using bilinear interpolation in ArcGIS.

Data analysis was conducted using GIS-based techniques. For objective 1, gully distribution was mapped using the kriging interpolation method in ArcGIS. Objective 2 involved overlay analysis to track gully size and shape changes over time, with area and length calculations exported to Excel. For objective 3, land use/cover classification was performed for different years and rainfall data was analysed through bar graphs. The DEM was utilized for topographic analysis, including the calculation of the Topographic Wetness Index (TWI) and Moisture Stress Index (MSI) to assess water accumulation and soil moisture levels.

The study found that gully occurrence in Thulamela Municipality fluctuated over the years, with the north-eastern region being the hotspot for gully erosion. While some areas remained free of gully erosion, others experienced moderate levels of erosion. Notably, gully formation increased from 2008 to 2023, with a slight decline between 2018 and 2023. The appearance and growth of specific gullies, such as Gully 1, Gully 13, Gully 25, Gully 37 and Gully 49, were observed across different years, each exhibiting unique patterns of size and shape changes.

Land use changes, particularly agricultural expansion and vegetation loss, were found to increase the susceptibility of areas to gully formation, with the highest gully occurrences in the north-eastern region. Rainfall played a role, with lower rainfall causing lack of

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vegetation, leaving soil exposed for erosion while extreme rainfalls increase surface runoff speed and volume, causing erosion. Furthermore, topographic factors such as slope and wetness index values indicated that flatter areas were more prone to water accumulation and gully formation, while steep areas contributed to runoff. This runoff, enhanced by steep areas, increases runoff and causes erosion. Soil moisture analysis revealed that areas with high moisture levels were more prone to gully erosion.

5.2. Conclusion

Based on the findings that the spatial distribution of gully erosion is common, the aim of the study was achieved. This is because the occurrence of gully erosion was tracked and gully inventory maps were produced to show areas that are prone to gully erosion formation. It was concluded that gully erosion is present in many of Thulamela Municipality areas. The results also indicated where these gullies are most common and need intervention.

Based on the findings that the severity of gully erosion is significant as gully sizes and shapes fluctuated over the years, the aim of the study was achieved. The size and shape of the gullies fluctuated during the study, indicating that the situation is severe and requires drastic measures. It was concluded that gully erosion in the study area is a constant hazard because it keeps on appearing and gullies vary in size, thus causing different impacts of different magnitude.

Based on the findings that all the factors analysed to study their influence on gully erosion formation, it was found that each of the factors influence gully formation differently. Factors analysed were land use/cover change, rainfall, topography and soil moisture content. Land use like agricultural activities, built-up areas and land cover like Bare-land areas revealed that they influence gully erosion, because most gullies appeared where these activities and land cover occupied. It was concluded that lack of vegetation cover and human activities cause susceptibility to gully erosion. It was also revealed that Rainfall influences gully erosion because of its impacts on vegetation cover and surface runoff.

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Topography was found to cause gully formation by how it increases the velocity of runoffs and also causes water accumulation in low-lying areas. According to TWI, gullies occurred where there are higher TWI values, indicating the presence of water and water accumulation areas. Soil moisture as a soil property was found to influence gully erosion, as results showed that gullies took place in areas with higher soil moisture stress.

It is then concluded that these results show that gully formation is an ongoing concern, particularly in the North and North-East of Thulamela Municipality, where environmental factors such as land use changes, rainfall, topography and soil moisture contribute significantly to erosion.

5.3. Recommendations

To effectively address gully erosion as a hydro-geomorphological hazard in Thulamela Municipality, future research should focus on integrating advanced machine learning algorithms and cloud-based platforms. These technologies can enhance the precision and scalability of gully erosion studies, thereby improving monitoring and prediction systems for proactive hazard management strategies (Rahmati *et al*., 2021).

Given the significant environmental and socio-economic impacts of gully erosion, it is essential to implement effective control measures. However, there is a lack of comprehensive evaluation of the success rates of existing control strategies (Zimale *et al*., 2017). While numerous gully control practices have been implemented globally, their effectiveness varies depending on environmental conditions, runoff dynamics and sediment characteristics (Frankl *et al*., 2021; Rebai *et al*., 2013). Therefore, it is important to prioritize site-specific approaches tailored to local topography, gully size and economic conditions (Liu *et al*., 2019).

Large-scale land rehabilitation programs have shown potential in stabilizing gully-prone areas (Frankl *et al*., 2021). Implementing land-use changes, soil and water conservation techniques and sustainable agricultural practices can help mitigate gully formation (Frankl *et al*., 2021). Additionally, increasing vegetation cover through reforestation and cover cropping can reinforce soil stability and reduce surface runoff, thus preventing further gully expansion (Moorberg and Crouse, 2021; Guerra *et al*., 2016; Frankl *et al*., 2021).

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Addressing gully erosion requires an integrated approach that combines scientific advancements, sustainable land management and active community participation. Without proactive intervention, the escalating effects of gully erosion will continue to threaten land productivity, infrastructure and environmental sustainability in Thulamela Municipality.

5.4. Limitations of the Study

The limitations and challenges faced during the study included the unavailability of rainfall data covering the entire Thulamela Municipality. Unavailability of historic soil type data and current soil type data due to lack of funding for site visits for soil samples collection. Lack of funding made it difficult to get high resolution satellites and DEM that are not freely available. The resolution of remote sensing imagery and Digital Elevation Models (DEMs) may have influenced the precision of gully mapping and analysis. Limited historical records on gully erosion in Thulamela Municipality could have impacted trend analysis. No access to campus during school holidays made it difficult to get a better working environment and internet to run some softwares.

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