



# **Utilising GIS as a tool for anticipatory governance: Mapping current and future flood risk in the eThekweni Metropolitan Municipality**

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## **ABSTRACT**

Flooding poses a significant disaster risk to inhabitants of the eThekweni Metropolitan Municipality in South Africa. The rapid growth of informal settlements and climatic changes have led to increased vulnerability to flooding events, as evidenced by the floods of April 2022 in the eThekweni Metropolitan Municipality. Arguably, the lack of proactive identification and mapping of flood-vulnerable areas have hindered effective disaster preparedness and mitigation efforts in the city. Given this research gap, this study integrates geographic information systems (GIS) with anticipatory governance (AG) principles to map current and future flood risks, focusing on identifying vulnerable informal settlements in the eThekweni Metropolitan Municipality. The research employs a multi-criteria decision analysis (MCDA) approach, incorporating seven key factors: land slope, elevation, rainfall patterns, drainage density, soil type, land use, and distance from rivers. The methodology combines current flood risk mapping with future scenarios based on different shared socioeconomic pathways (SSPs), projecting potential changes in precipitation and informal settlement growth by 2050. The study applies a pluralistic futures approach to AG to develop multiple flood risk scenarios. Key findings reveal that 289 informal settlements, housing approximately 163 000 households and covering 34.7 km<sup>2</sup>, currently face extremely high flood risk. The study's cross-scenario analysis identified 230 informal settlements, spanning 29.2 km<sup>2</sup>, that consistently show extremely high flood risk across the current as well as all the future scenarios. Future projections indicate potential increases in at-risk areas, with up to 69.9 km<sup>2</sup> of informal settlements facing extremely high flood risk by 2050 in the most severe scenario (SSP5).

The research demonstrates the effectiveness of integrating GIS and AG principles for flood risk assessment and management. The research further provides a robust framework for prioritising interventions and developing adaptive strategies for flood risk mitigation in informal settlements. The multi-scenario approach offers valuable insights to decision makers, enabling them to make more informed decisions in the face of climate change and ongoing urban growth challenges in the eThekweni Metropolitan Municipality. Combining GIS capabilities with AG principles offers a replicable methodology for other cities facing similar challenges. The findings of this study highlight the need for proactive urban planning and targeted interventions to enhance the resilience of informal settlements against flood risks.

### **Key terms**

Flood risk mapping, informal settlements, anticipatory governance, geographic information systems, the eThekweni Metropolitan Municipality

## LIST OF ABBREVIATIONS

|        |                                               |
|--------|-----------------------------------------------|
| AG     | Anticipatory governance                       |
| AHP    | Analytic hierarchy process                    |
| BZ     | Belousov-Zhabotinsky                          |
| CA     | Cellular automata                             |
| CBA    | Cost-benefit analysis                         |
| CGIS   | Canada Geographic Information System          |
| CHIME  | COVID-19 Hospital Impact Model for Epidemics  |
| CI     | Consistency Index                             |
| CMIP6  | Coupled Model Intercomparison Project Phase 6 |
| CoBRA  | Community-based resilience assessment         |
| CPU    | Central processing unit                       |
| CR     | Consistency ratio                             |
| Dd     | Drainage density                              |
| DEM    | Digital elevation model                       |
| D'MOSS | Durban Metropolitan Open Space System         |
| EFAS   | European Flood Awareness System               |
| EPA    | United States Environmental Protection Agency |
| ERP    | Emergency response planning                   |
| ESA    | European Space Agency                         |
| ESRI   | Environmental Systems Research Institute      |
| EU     | European Union                                |
| EU ETS | European Union Emissions Trading System       |
| EWS    | Early warning systems                         |
| FbF    | Forecast-based financing                      |
| FCA    | Financial Conduct Authority                   |
| FEM    | Finite element method                         |



|         |                                                          |
|---------|----------------------------------------------------------|
| FEMA    | Federal Emergency Management Agency                      |
| FIRM    | Flood insurance rate map                                 |
| FSCA    | Financial Sector Conduct Authority                       |
| GDPR    | General data protection regulation                       |
| GIS     | Geographic information systems                           |
| GMO     | Genetically modified organism                            |
| GNSS    | Global navigation satellite system                       |
| GPS     | Global positioning system                                |
| GPU     | Graphics processing unit                                 |
| HEC     | Hydrologic Engineering Center                            |
| HEC-RAS | Hydrologic Engineering Center - River Analysis System    |
| ICIMOD  | International Centre for Integrated Mountain Development |
| ICT     | Information and communication technology                 |
| IVR     | Integrated virtual reality                               |
| JATWC   | Joint Australian Tsunami Warning Centre                  |
| LiDAR   | Light detection and ranging                              |
| MAOUDC  | Metropolitan Area Outer Underground Discharge Channel    |
| MCDA    | Multi-criteria decision analysis                         |
| MIDAS   | Mapping and integrated data analysis system              |
| MRC     | Mekong River Commission                                  |
| NbS     | Nature-based solutions                                   |
| NDC     | Nationally determined contribution                       |
| NGI     | National Geo-spatial Information                         |
| NICD    | National Institute for Communicable Diseases             |
| NOAA    | National Oceanic and Atmospheric Administration          |
| RAM     | Random-access memory                                     |
| RCP     | Rotterdam Climate Proof                                  |
| RDP     | Reconstruction and Development Programme                 |

|         |                                                                                       |
|---------|---------------------------------------------------------------------------------------|
| RFC     | River Forecast Center                                                                 |
| RI      | Random index                                                                          |
| RMSE    | Root mean square error                                                                |
| Rv      | Runoff coefficient                                                                    |
| SaaS    | Software as a service                                                                 |
| SADC    | Southern African Development Community                                                |
| SAWS    | South African Weather Service                                                         |
| SENAMHI | National Service of Meteorology and Hydrology of Peru                                 |
| SLEUTH  | Slope, land cover, excluded regions, urban land cover, transportation, and hill shade |
| SOTER   | Soil and Terrain Database                                                             |
| SSP     | Shared socioeconomic pathway                                                          |
| UN      | United Nations                                                                        |
| UNDP    | United Nations Development Programme                                                  |
| UNDRR   | United Nations Office for Disaster Risk Reduction                                     |
| UNOSAT  | United Nations Satellite Centre                                                       |
| USGS    | United States Geological Survey                                                       |
| WfW     | Working for Water                                                                     |
| WR2012  | Water Resources of South Africa, 2012 Study                                           |
| WRF     | Weather research and forecasting                                                      |
| WW2     | World War II                                                                          |
| WRMA    | Water Resources Management Authority                                                  |

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# CHAPTER 1 INTRODUCTION

## 1.1 Introduction

In South Africa, the topic of informal housing and the occupants' exposure to disaster risks is a multidimensional issue (Barry & Rüther, 2005; Huchzermeyer & Karam, 2006; Hunter & Posel, 2012; Marutlulle, 2017). Previously, the apartheid government applied laws that ordered black Africans to relocate to peripheral areas of settlement and limited their free movement (Hunter & Posel, 2012; Iliffe, 1987). Given the economic development in the 1970s, racial segregation caused an influx of black Africans, which led to more informal housing settlements (Barry & Rüther, 2005). Rural-urban relocation population increase and the arrival of both documented and undocumented migrants from bordering countries, along with people migrating between provinces, have all led to the expansion of informal settlements in South Africa (Barry, 2003; Marutlulle, 2017).

The number of families living in informal housing settlements has also grown. In 2021, South Africa had approximately 1 300 000 families, representing over five million people living in informal settlements, rising from 1 170 902 people in 1995 (Nkonki-Mandleni *et al.*, 2021; Stats SA, 2016). Informal settlements housed approximately 13.1% of the people living in KwaZulu-Natal, and this is the second highest prevalence in the country, second only to the Eastern Cape (GCIS, 2021). Over time, these settlements have become more overcrowded and have grown in both quantity and size (Jeffery, 2010). The number of informal settlements, for example, surged from 1 176 in 2004 to more than 2 600 in 2020. (GCIS, 2021). The majority of informal settlements in South Africa are situated in susceptible and vulnerable surroundings like steep slopes, wetlands, flood plains, and poorly drained land, making them vulnerable to hydro-meteorological hazards (Barry, 2003; Musungu *et al.*, 2016; Le Quéré *et al.*, 2020; Williams *et al.*, 2019).

This rapid growth of informal settlements, particularly in KwaZulu-Natal, has led to increased vulnerability to flooding events, as evidenced by the floods of April 2022 in KwaZulu-Natal (Dlamini *et al.*, 2024). The lack of proper identification and mapping of flood-vulnerable areas hinders effective disaster preparedness and mitigation efforts. Key aspects of this problem include the increasing populations of informal settlements, their location in flood-prone areas, intensifying rainfall patterns due to climate change, inadequate identification of at-risk areas, and challenges in preparing for and mitigating flood events. There is a critical need to develop a systematic approach to identify and map flood-vulnerable informal settlements using geographic information systems (GIS). This information can then be used in conjunction with anticipatory governance

(AG) approaches to improve disaster preparedness and minimise the impact of future flooding events on informal settlements.

In an effort to improve the flood risk of informal settlements, this study focuses on the informal settlements of the eThekweni Metropolitan Municipality. This area serves as an ideal case study for several reasons. First, it has a significant number of informal settlements, with close to 600 informal settlements. For the purposes of this study, each informal settlement is defined and identified by its unique name as officially designated by the eThekweni Metropolitan Municipality. Each informal settlement within the municipality's jurisdiction has been assigned a specific name by municipal authorities, which serves as the primary identifier in this research. The eThekweni Metropolitan Municipality's geographical characteristics, including the coastal topography, numerous river systems, and a history of flood events, make it particularly vulnerable to flooding. Finally, the recent floods of April 2022 in this region highlight the urgent need for improved flood risk management in informal settlements. The study aims to develop a methodology for flood risk mapping that can be applied in the eThekweni Metropolitan Municipality.

This chapter next addresses the research problem, followed by a clearly defined aim and objectives that guide this study. The methodology section provides a comprehensive framework, beginning with a detailed study area description that examines the eThekweni Metropolitan Municipality's flooding history and urbanisation patterns, particularly focusing on the informal settlements of the eThekweni Metropolitan Municipality. The research design, tools, and sampling strategies are then discussed, followed by data analysis and validity measures. Finally, ethical considerations are outlined, ensuring research integrity throughout this study.

## **1.2 Research problem**

Flooding has become a critical global issue, with climate change exacerbating the frequency and severity of extreme weather events worldwide (Tellman *et al.*, 2021; Tabari, 2020; Jongman, 2018). As sea levels rise and precipitation patterns become more unpredictable, coastal and inland communities alike face growing risks of flood-related disasters (Brunner *et al.*, 2021; Kirezci *et al.*, 2020). This global trend highlights the need for effective flood risk management strategies, particularly in vulnerable regions such as informal settlements in developing countries (Kablan *et al.*, 2017). Within this global context, South Africa presents a compelling case study for examining flood risk and developing innovative approaches to mitigate the effects of floods.

South Africa experienced larger than average amounts of rainfall in 2022 as a result of La Niña (Thoithi *et al.*, 2023). Numerous areas witnessed the heaviest precipitation since accurate record keeping started in 1921 (Cele & Njini, 2022). Downpours began on April 8 in KwaZulu-Natal

(Erasmus, 2022). By April 11, the South African Weather Service (SAWS) released a level 5 alert for the shore and neighbouring interior of KwaZulu-Natal. The alert level was eventually upgraded to a level 8 and then to a level 9 alert as the consequences and magnitude of the storms became clearer. A level 8 or 9 alert represents a severe impact on humans (SAWS, 2022b). The heaviest rain fell in the municipalities of the eThekweni Metropolitan Municipality, iLembe District Municipality, and Ugu District Municipality (SAWS, 2022a). From April 8 to 12, most of KwaZulu-Natal received well over 50 mm of downpours, with coastal parts receiving upwards of 200 mm. Virginia Airport reported 304 mm of rainfall over 24 hours from April 11–12 (SAWS, 2022a). Rainfall totalled 450 mm along the coast of KwaZulu-Natal (McKenzie *et al.*, 2022).

The heavy rains destroyed scores of homes, wiped out roads, and caused mudslides. On April 13, 59 people were killed in KwaZulu-Natal, with 45 killed in the eThekweni Metropolitan Municipality and 14 in iLembe District Municipality (CNA, 2022; Kumwenda-Mtambo & Mukherjee, 2022). By April 21, the total of confirmed flooding fatalities was revised to 435 (Reuters, 2022). According to KwaZulu-Natal Premier Sihle Zikalala, at least 2 000 houses and 4 000 informal houses were destroyed or damaged (CNA, 2022). Additionally, it was also that flooding damaged infrastructure totalling R17 billion (Grab & Nash, 2023). Future flooding events are set to worsen, with climate change anticipated to make rainfall more unpredictable and lead to increases in the incidence of severe weather events and the risk of flooding. Consequently, identifying and estimating which areas could be at risk of flooding in the future is becoming increasingly important (Allen & Ingram, 2002; Ingram, 2016; Trenberth *et al.*, 2003).

GIS can be used to identify and map areas vulnerable to flooding. GIS can aid in mapping flood risk in specific geographic locations (Hambati & Yengoh, 2018; Li *et al.*, 2011; Musungu *et al.*, 2012). It is notable for its capacity to integrate data from multiple sources, analyse it, and generate spatial overlay maps. GIS techniques have been extensively used to map flood risk worldwide, not just in South Africa (Musungu *et al.*, 2012; Roy & Blaschke, 2015; Yahaya *et al.*, 2010). In addressing the challenge of mapping flood risk, the integration of GIS-based flood vulnerability mapping with the concept of AG presents a potential solution. AG, as defined by Fuerth (2009), uses foresight to mitigate and reduce risk, enabling disaster response to occur in the early stages of a disaster event. By combining GIS techniques with AG principles, a more proactive and effective approach to flood risk management in informal settlements may be developed. By conducting GIS mapping of flooding through an AG lens, multiple possible future scenarios and their implications can be mapped rather than trying to predict a single, most likely future. Following this approach recognises the inherent uncertainty in future flood events and their impacts and develops multiple scenarios of how flooding might affect different informal settlements.



The AG framework adopted in this study will guide the consideration of multiple future scenarios in developing flood management strategies for the eThekweni Metropolitan Municipality. This approach allows for the examination of how informal settlements might evolve and expand in the future, and how changing climate patterns might alter flood risks over time. Subsequently, the research aims to produce both current flood risk maps and identify existing informal settlements at risk of flooding. It will also develop future flood risk maps based on multiple scenarios, identifying possible future informal settlements that may be at risk of flooding.

### **1.3 Research aim and objectives**

In an effort to address the research problem outlined above, a dedicated research aim and research objectives have been formulated.

#### **1.3.1 Research aim**

This study aims to map informal settlements of the eThekweni Metropolitan Municipality vulnerable to current and future flooding events using GIS mapping techniques, framed within the lens of AG. This aim is informed by the following objectives:

#### **1.3.2 Research objectives**

- To create a theoretical background of urban flood risk trends on a regional and local scale;
- To investigate the theoretical tenets of AG and its relevance for the management of urban flood risk in eThekweni Metropolitan Municipality;
- To discuss the use of and utility of GIS in mapping urban flood risk;
- To map the current and potential future areas of the eThekweni Metropolitan Municipality that are vulnerable to flooding events; and
- To make recommendations for future disaster risk reduction measures and AG principles to be implemented by the municipality.

### **1.4 Research methodology**

This section outlines the methodological approach adopted for this study on flood risk in the eThekweni Metropolitan Municipality. It details the research design, tools, sampling techniques, data analysis methods, measures to ensure reliability and validity, and ethical considerations. Each component has been carefully selected and implemented to ensure a rigorous, systematic, and ethically sound investigation into potential future flooding locations in the eThekweni Metropolitan Municipality, to contribute to more effective flood risk management in this critical

urban area. As a point of departure, the section that follows describes the eThekweni Metropolitan Municipality as the study area.

### 1.4.1 Study area description

The eThekweni Metropolitan Municipality is situated on South Africa's east coast in the province of KwaZulu-Natal. It covers approximately 2 555 km<sup>2</sup> and borders three districts: Ugu to the south, iLembe to the north, and uMgungundlovu to the west. It can be accessed via the N2, N3, and King Shaka International Airport (see Figure 1.1) (eThekweni Municipality, 2023).

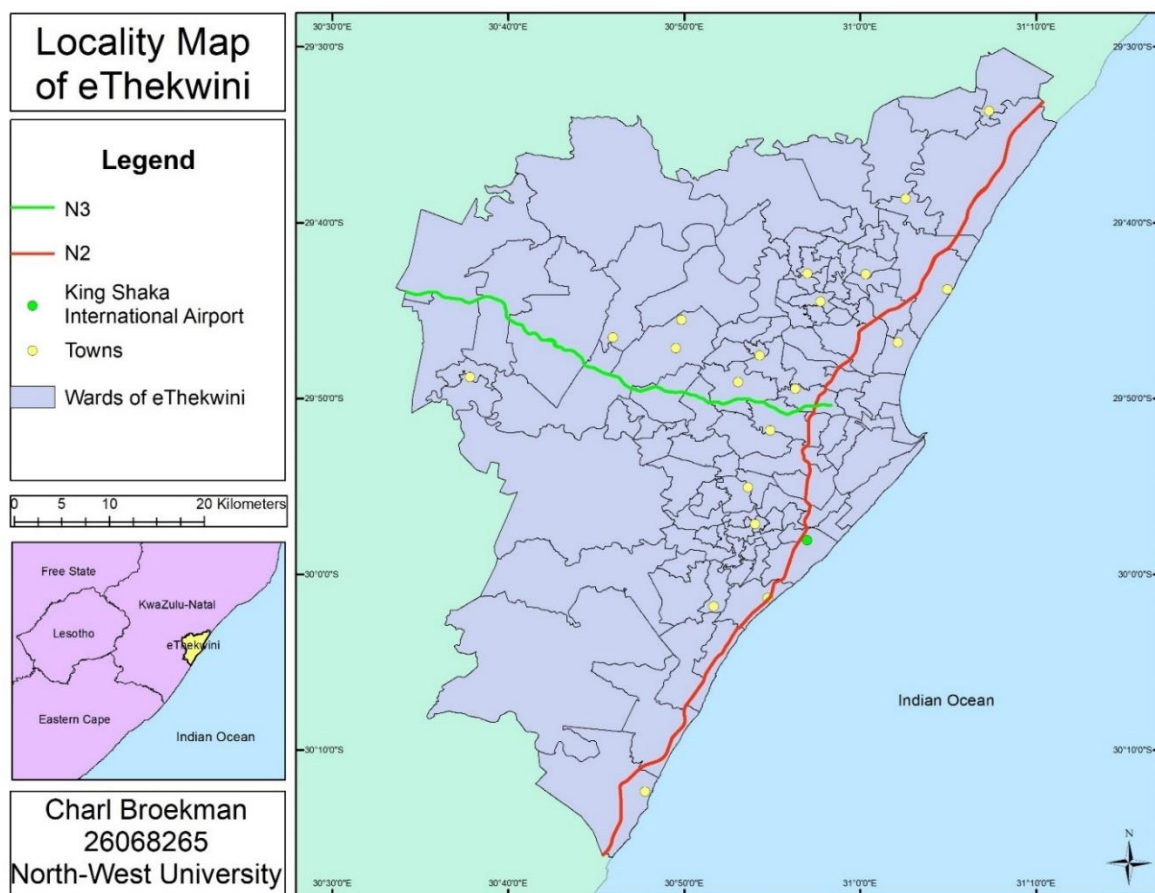


**Figure 1.1: Locality map of eThekweni (eThekweni Municipality, 2024)**

The eThekweni Metropolitan Municipality experiences a warm subtropical climate due to Indian Ocean influences, characterised by hot, rainy summers and dry, moderate winters. The average temperature fluctuates with the season, demonstrating a minimum average temperature of 16.79°C and a maximum average temperature of 25.07°C (Zungu *et al.*, 2018). Coastal and ocean influences drive the prevailing rainfall pattern, which fluctuates from summer to winter with an average rainfall of 996 millimetres per annum (mm/a). The East Coast experiences warm and moist south-moving air, resulting in prevailing wind directions that are north-easterly in the

morning and south-easterly in the evening (Zungu et al., 2018). The topographical characteristics of the eThekweni Metropolitan Municipality range from a steep escarpment in the west to a narrow and flat coastal plain in the east (eThekweni Municipality, 2023).

The study area is drained by 18 rivers, 12 of which are perennial rivers, with a catchment area of approximately 4 000 km<sup>2</sup> (see Figure 1.2) (eThekweni Municipality, 2023). The uTongati, uMdloti, Ohlanga, uMngeni, Palmiet, uMbilo, Sterkspruit, uMlazi, Mbokodweni, Nungwane, Lovu, and uMkomazi are perennial rivers that drain the study region from north to south.

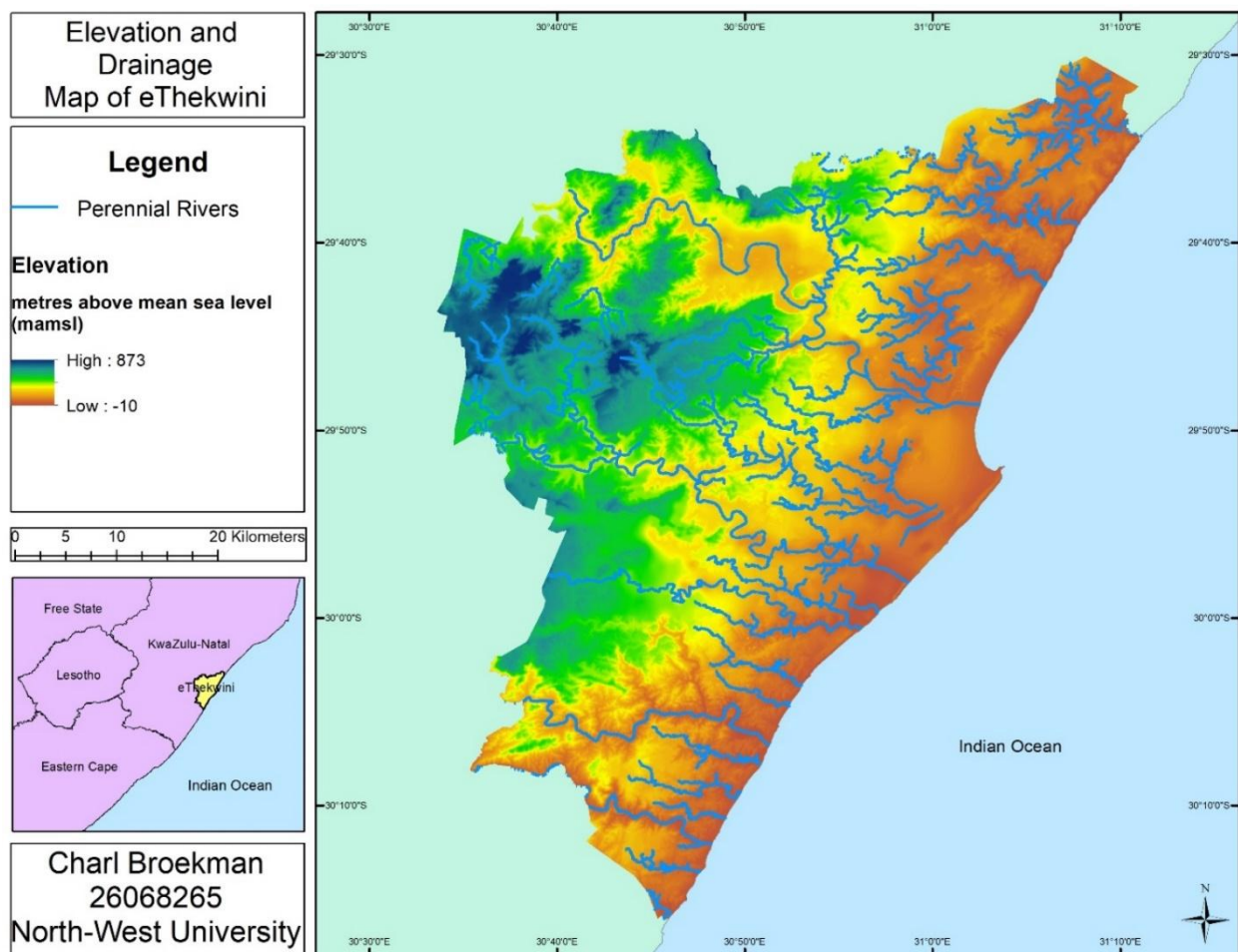


**Figure 1.2: Elevation and drainage map of eThekweni (eThekweni Municipality, 2024)**

The many global and mesoscale atmospheric circulation systems found on Earth collaborate to generate recurrent weather systems (Schumacher & Rasmussen, 2020). Eleven recurrent weather systems influence Southern Africa (Tyson, 1986), seven of which commonly occur in the eThekweni Metropolitan Municipality. They deliver considerable amounts of rainfall, resulting in flooding. The above-mentioned weather systems include easterly waves and tropical/subtropical lows, westerly waves and cut-off lows, thunderstorms and tropical cyclones/depressions. Of the

systems mentioned, cut-off lows have historically been associated with flooding in the eThekweni Metropolitan Municipality, prevailing from September to May (Preston-Whyte & Tyson, 1988). A crucial aspect to consider as part of the study area description is a brief historical account of flooding in the eThekweni Metropolitan Municipality, as this informs current and future flood risk mapping.

#### **1.4.1.1 Flooding history of eThekweni and KwaZulu-Natal**

This section addresses the first research objective: to establish the background of urban flood risk trends on a regional and local scale. By examining the flooding history of KwaZulu-Natal province and the eThekweni Metropolitan Municipality, this study establishes the context for understanding urban flood risks in the study area.

KwaZulu-Natal, the province in which the eThekweni Metropolitan Municipality is situated, has a long history of recurrent and devastating flooding events. Over the years, the region has faced numerous flood-related disasters that have caused significant damage to property and infrastructure, loss of lives, and disruptions to daily life. The table (see Table 1.1) of the recent history of flooding in the region was compiled from the studies conducted by Grab and Nash (2023), Botes (2014) and Olanrewaju and Reddy (2022), as well as FloodList (2024).

**Table 1.1: Flooding events in KwaZulu-Natal from 1985–2023**

| <b>Year</b> | <b>Month</b> | <b>Location of flood</b>     |
|-------------|--------------|------------------------------|
| 1985        | February     | KwaZulu-Natal, province-wide |
| 1985        | October      | South Coast of KwaZulu-Natal |
| 1986        | August       | South Coast of KwaZulu-Natal |
| 1987        | September    | KwaZulu-Natal, province-wide |
| 1988        | February     | KwaZulu-Natal, province-wide |
| 1988        | March        | KwaZulu-Natal, province-wide |
| 1988        | May          | Durban                       |
| 1988        | December     | Durban                       |

|      |          |                                              |
|------|----------|----------------------------------------------|
| 1989 | March    | South Coast of KwaZulu-Natal                 |
| 1989 | April    | South Coast of KwaZulu-Natal                 |
| 1989 | November | KwaZulu-Natal, province-wide                 |
| 1990 | March    | KwaZulu-Natal, province-wide                 |
| 1991 | October  | Durban                                       |
| 1991 | November | South Coast of KwaZulu-Natal                 |
| 1991 | December | Durban                                       |
| 1993 | October  | North Coast of KwaZulu-Natal                 |
| 1993 | December | South Coast and North Coast of KwaZulu-Natal |
| 1994 | January  | Durban                                       |
| 1994 | March    | Durban                                       |
| 1994 | October  | Durban                                       |
| 1995 | February | Tongaat                                      |
| 1995 | March    | Durban                                       |
| 1995 | December | Durban                                       |
| 1997 | March    | KwaZulu-Natal                                |
| 1997 | July     | Durban                                       |
| 1999 | February | KwaZulu-Natal, province-wide                 |
| 1999 | October  | KwaZulu-Natal, province-wide                 |
| 1999 | December | Durban                                       |
| 2000 | February | Durban and Tongaat                           |
| 2000 | May      | Tongaat                                      |

|      |           |                                              |
|------|-----------|----------------------------------------------|
| 2003 | November  | Durban                                       |
| 2005 | March     | Verulam and Tongaat                          |
| 2006 | November  | KwaZulu-Natal, province-wide                 |
| 2006 | December  | KwaZulu-Natal, province-wide                 |
| 2007 | March     | North Coast and South Coast of KwaZulu-Natal |
| 2008 | June      | Durban                                       |
| 2010 | February  | KwaZulu-Natal, province-wide                 |
| 2011 | January   | KwaZulu-Natal, province-wide                 |
| 2011 | November  | Durban South                                 |
| 2012 | March     | Durban                                       |
| 2012 | September | Durban                                       |
| 2012 | December  | Durban                                       |
| 2016 | March     | Durban                                       |
| 2016 | May       | Durban                                       |
| 2016 | July      | Durban                                       |
| 2017 | May       | KwaZulu-Natal, province-wide                 |
| 2017 | October   | Durban                                       |
| 2019 | March     | Durban                                       |
| 2019 | April     | Durban                                       |
| 2019 | November  | KwaZulu-Natal, province-wide                 |
| 2020 | February  | KwaZulu-Natal, province-wide                 |
| 2020 | November  | KwaZulu-Natal, province-wide                 |

|      |          |                              |
|------|----------|------------------------------|
| 2022 | January  | Ladysmith and Msinga         |
| 2022 | February | eMadlangeni and Kokstad      |
| 2022 | April    | KwaZulu-Natal, province-wide |
| 2022 | May      | KwaZulu-Natal, province-wide |
| 2023 | February | KwaZulu-Natal, province-wide |
| 2023 | June     | KwaZulu-Natal, province-wide |

The flooding history of KwaZulu-Natal and the eThekweni Metropolitan Municipality from 1985 to 2023 shows fluctuating patterns over time. While the highest number of recorded flooding events occurred in the first decade (1985–1994), there was a decrease over the following two decades. However, recent years (2015–2023) have shown an uptick in flooding frequency, with more events recorded in this nine-year period than in either of the two preceding full decades (see Figure 1.3).

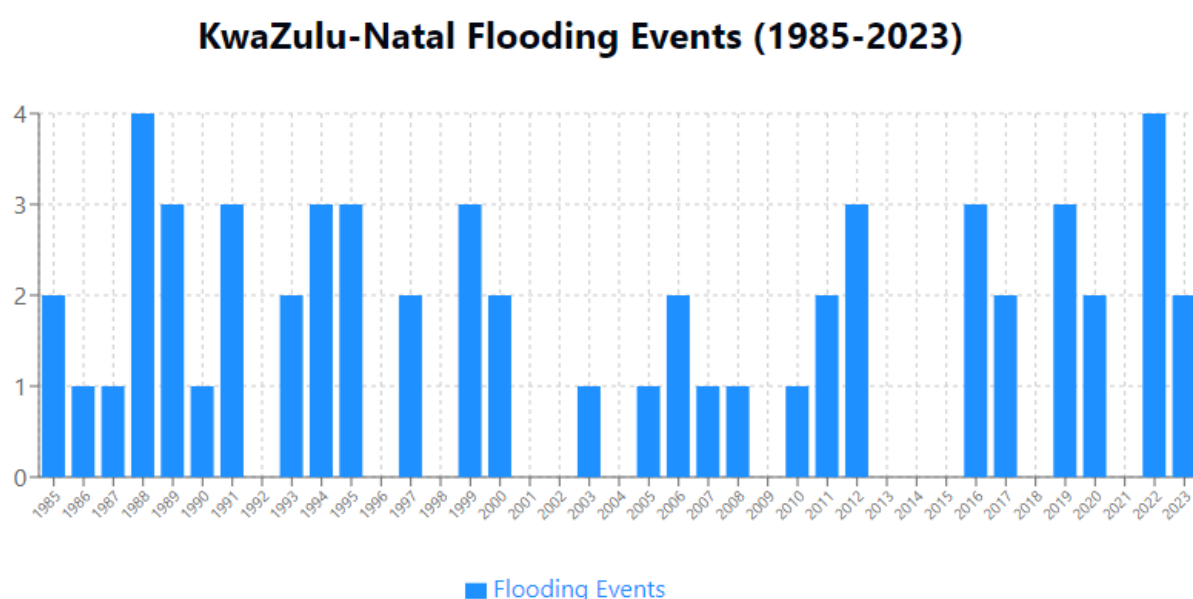


**Figure 1.3: KwaZulu-Natal flooding events (1985–2023)**

This increase in flooding can be ascribed to a variety of factors, including improved reporting, more flood occurrences from climate change, or increased vulnerability from urbanisation (Grab & Nash, 2023). The records show that some years, such as 1988, 1994, 2012, 2016, and 2022, had multiple flooding events, suggesting periods of higher vulnerability. Seasonal patterns are

clear in the data, with most flooding events occurring during the wet season (October to March). February, March, October, and December are peak months for flooding in KwaZulu-Natal and the eThekweni Metropolitan Municipality. However, the data also show floods in typically drier months like May, June, July, and August, which could indicate changing rainfall patterns or extreme weather events outside the usual wet season.

Geographically, the data show more flooding events in urban areas, with Durban and its surroundings (part of the eThekweni Metropolitan Municipality) affected in 26 of the historic flooding events documented. This suggests urban areas may be more vulnerable due to surfaces that do not absorb water and drainage issues. It could also reflect more reporting in populated areas. While coastal areas have more flood records, recent years show floods in inland areas like Ladysmith and Msinga, indicating floods might be affecting more areas in KwaZulu-Natal.

The flooding data for 2022 and 2023 show multiple events, including province-wide floods. This could indicate more intense weather events in KwaZulu-Natal, possibly due to climate change or long-term environmental changes and urbanisation. This analysis of flooding events in the eThekweni Metropolitan Municipality and KwaZulu-Natal as a whole shows how geographic, climatic, and human factors affect flood risk in the region. The data demonstrate that flooding events have been a recurring feature in KwaZulu-Natal throughout the period studied.

This overview of the flooding history in the eThekweni Metropolitan Municipality and KwaZulu-Natal successfully addresses the first research objective: creating a background of urban flood risk trends on a regional and local scale. This historical context provides a solid foundation for the understanding of the flood risks in the study area.

Another important aspect of creating a clear picture of the study area is the issue of urbanisation and the formation of informal settlements, as both these factors are also considered in the GIS mapping conducted in Chapter 3.

#### **1.4.1.2 Urbanisation and the formation of informal settlements in eThekweni**

The eThekweni Metropolitan Municipality's urbanisation history spans centuries and includes influences from various groups. In the 17th century, the Zulu people migrated to the region, establishing chiefdoms (Eggert, 2005). By the early 19th century, British colonial interests grew in the area, leading to the establishment of Durban as a trading post (Luckan, 2019). The 19th and early 20th centuries saw the arrival of Indian labourers and traders, further shaping the region's development (Maharaj, 2017). The mid-20th century brought the apartheid era, which introduced racial segregation through policies like the *Group Areas Act*, 41 of 1950 (Dubow,



2014). The post-apartheid period, beginning in 1994, saw changes in laws and policies aimed at addressing these inequalities. However, this current post-apartheid era has also included ongoing challenges, with the continued growth and expansion of informal settlements being a significant issue (Magidimisha-Chipungu & Chipungu, 2023).

The end of apartheid in 1994 led to increased rural-to-urban migration in the eThekweni Metropolitan Municipality, as people sought better economic opportunities in the city. This migration, combined with natural population growth, significantly increased the demand for housing and basic services (Schensul, 2009). However, the legacy of apartheid spatial planning, which created overcrowded townships for non-white populations, left the post-apartheid government with a massive backlog in housing and infrastructure provision (Maharaj, 2017). Despite efforts to address housing shortages through programmes like the Reconstruction and Development Programme (RDP), the supply of formal housing has consistently failed to meet the growing demand. This imbalance between housing supply and demand has been a primary driver in the proliferation of informal settlements across the eThekweni Metropolitan Municipality (Magidimisha-Chipungu & Chipungu, 2023). These settlements often develop on vacant land, including areas prone to environmental hazards such as flooding, due to the lack of affordable alternatives.

Informal settlements in the eThekweni Metropolitan Municipality are characterised by inadequate housing structures, often built with materials like corrugated metal or salvaged wood. More critically, these areas frequently lack access to basic services such as clean water, proper sanitation facilities, and reliable electricity (Saharan *et al.*, 2022). The geographical distribution of these settlements across the eThekweni Metropolitan Municipality often reflects persistent socio-economic disparities, with many informal settlements located near more developed areas, creating great disparities in living conditions in the study area (Dovey & King, 2011).

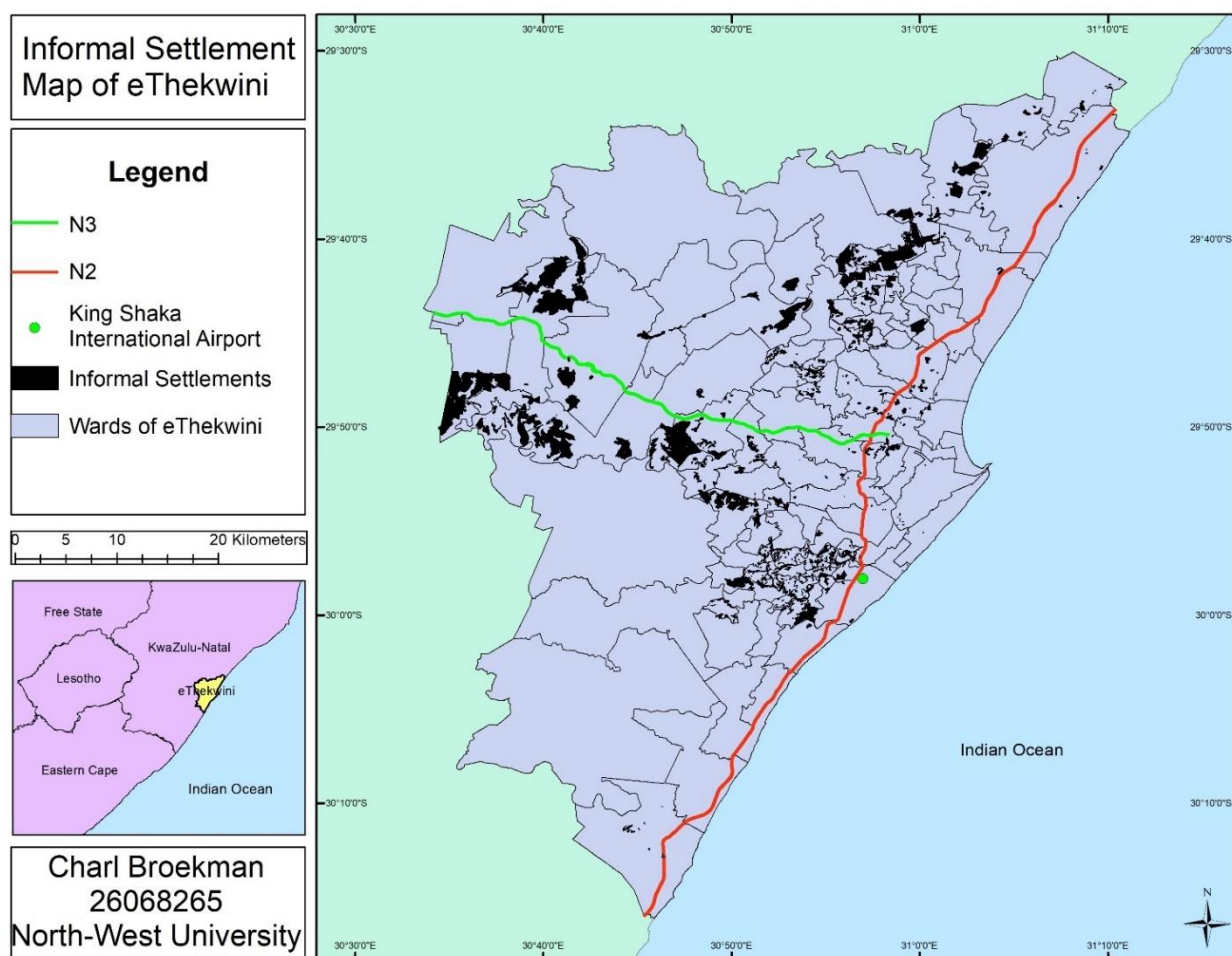


**Figure 1.4: Informal settlement map of eThekweni (eThekweni Municipality, 2024)**

The above information shows that informal settlements in the eThekweni Metropolitan Municipality are a result of a complex urbanisation history, the legacy of apartheid, rural-to-urban migration, and significant ongoing formal housing shortages. The map in Figure 1.4 shows the extent of these settlements across the municipality, highlighting the widespread nature of this urban challenge. This visual representation emphasises the scale of the issue facing the eThekweni Metropolitan Municipality decision makers. The presence of over 590 informal settlements as of 2023, demonstrates the ongoing struggle to provide adequate housing and services to a growing urban population. Again, in this study, informal settlements are defined and identified according to the official designations provided by the eThekweni Metropolitan Municipality. The municipal authorities have assigned each informal settlement within the municipality's jurisdiction a unique name. These official names serve as the primary identifiers for the informal settlements in this research. These growing informal settlements are particularly vulnerable to flooding, often due to their location in low-lying areas or near water bodies such as rivers. Furthermore, as climate change continues to affect weather patterns, these settlements are likely to become even more prone to flood risk in the future. This increased vulnerability poses additional challenges for the

residents of these informal settlements and for the eThekweni Metropolitan Municipality to manage urban development and flood risk.

The complex study in the study area described above relied on a specific research design and dedicated research tools and analysis methods. The next section briefly discusses the quantitative research design used to guide this study.

#### **1.4.2 Research design**

The quantitative approach, as advocated by several scholars (Leedy & Omrod, 2023; Michener & Sokal, 1957; Plonsey & Barr, 2007; Quick & Hall, 2015), allows for the systematic collection and analysis of numerical data. While this approach aims to enable objective measurement and quantification of factors contributing to flood risk, such as elevation, slope, soil type, drainage density, distance to rivers, land use, and rainfall patterns, it is important to acknowledge that the process of data analysis, particularly in ranking and weighting variables, can introduce elements of subjectivity.

The quantitative approach facilitates the production of statistically robust predictions and data-driven flood risk maps. The overarching strategy of this quantitative design provides a clear and rational approach to address the defined research questions, ensuring a structured process of data collection, interpretation, analysis and discussion (Goertzen, 2017). Consequently, the study's findings are grounded in empirical evidence rather than subjective interpretations, enhancing the reliability and validity of the research outcomes.

The quantitative design was appropriate for this study because it aims to use various GIS datasets to determine possible future flooding locations in the eThekweni Metropolitan Municipality. By using numerical data and statistical analysis, this approach allows for the identification of patterns and relationships in the flood risk mapping that might not be immediately apparent through qualitative methods, thus providing a more comprehensive understanding of flood risk factors in the municipality.

#### **1.4.3 Research tools**

This study primarily uses secondary data as its main research tool. Secondary data, as defined by Martins *et al.* (2018), refers to information that has been gathered by a party other than the primary user. This choice of research tool is ideal for this study for several reasons. Firstly, it provides access to comprehensive datasets covering the entire the eThekweni Metropolitan Municipality over extended time periods. Secondly, it offers a resource-efficient approach, allowing access to high-quality information without the need for extensive and costly fieldwork.

Thirdly, it leverages the expertise of specialised agencies in collecting complex data such as rainfall patterns, topographical information, and soil characteristics.

However, it is important to acknowledge the limitations and potential biases associated with using secondary data. As this study did not conduct the original measurements, it cannot fully account for the methodologies or potential errors in the data collection process. Furthermore, the analysis of the secondary data, particularly in terms of rating and weighting variables for flood risk assessment, introduces an element of subjectivity. Even when basing this study's approach on established studies, the decision-making process in allocating ratings and weightings inevitably involves human judgement. This subjectivity is an inherent aspect of such analyses and is acknowledged for the sake of transparency.

The specific datasets used in this study include spot heights and contour data sourced from National Geo-spatial Information (NGI), used for creating elevation and slope datasets; soil types obtained from the Soil and Terrain Database (SOTER) for South Africa; river data acquired from the eThekweni Metropolitan Municipality GIS website, used for generating datasets on drainage density and distance to rivers; land use data also sourced from the eThekweni Metropolitan Municipality GIS website; and rainfall data obtained from the Water Resources of South Africa, 2012 Study (WR2012).

These datasets are primarily available in the public domain and have been sourced from reputable organisations and government agencies. The research is predominantly desktop-based, using existing GIS data and records. This approach allows for a comprehensive analysis of flood risk factors in the eThekweni Metropolitan Municipality, using data collected by large multinational or national organisations with the necessary resources to conduct extensive data-gathering efforts.

#### **1.4.4 Sampling**

The sampling technique employed in this study is based on scientific literature and understanding of flood risk factors (Ahmed *et al.*, 2019; Blistanova *et al.*, 2016; Danumah *et al.*, 2016; Elsheikh *et al.*, 2015; Gazi *et al.*, 2019; Hagos *et al.*, 2022; Hussain *et al.*, 2021; Jagtrap & Medhe, 2023; Mahmoud & Gan, 2018; Negese *et al.*, 2022; Osman & Das, 2023; Paquette & Lowry, 2012; Pham *et al.*, 2021; Rincón *et al.*, 2018; Rendana *et al.*, 2023; Vojtek & Vojteková, 2019; Wondim, 2016). This approach is widely used in research to identify and select key variables that significantly influence the phenomenon being studied. In the context of this study, this sampling approach was applied to both the identification of critical variables and their corresponding datasets for flood risk mapping.

Seven key datasets were chosen based on their established significance in flood risk studies. These include elevation data, slope data, soil type information, drainage density data, distance to rivers, land use data, and rainfall data. Each of these datasets was selected based on its known contribution to flood risk assessment and its coverage of the eThekweni Metropolitan Municipality area (Hagos *et al.*, 2022; Rendana *et al.*, 2023). The datasets were primarily sourced from national and local government agencies, ensuring their reliability and authority. This selection strategy allowed for the compilation of a comprehensive set of data that covers various aspects of flood risk, from topographical features to hydrological factors.

The selection of these specific variables and their corresponding datasets ensured that the most pertinent and information-rich data could be used, thereby enhancing the depth and quality of the subsequent analysis. This approach aligns well with the study's quantitative design and its aim to provide a thorough, data-driven assessment of flood risk in the eThekweni Metropolitan Municipality.

#### **1.4.5 Data analysis**

This study employs a multi-criteria decision analysis (MCDA) approach to develop comprehensive current and future flood risk maps for the eThekweni Metropolitan Municipality. MCDA was chosen for its ability to evaluate complex scenarios by considering multiple criteria or factors (Belton & Stewart, 2002). This method is particularly valuable for flood risk mapping as it accounts for the intricate interplay of various factors influencing flood risk. The analysis considers seven significant factors contributing to flood risk: land slope, elevation, rainfall patterns, drainage effectiveness, soil type, land use, and distance from rivers. These factors form the criteria for the MCDA. The process involves constructing a structured hierarchy of these factors and conducting pairwise comparisons to determine their relative importance.

To ensure the reliability of the findings, the methodology incorporates rigorous quality assurance processes, including the computation of the consistency index (CI) and the evaluation of the consistency ratio (CR).

Furthermore, the study extends its scope by incorporating AG principles to develop future flood risk scenarios. This involves exploring changes in precipitation patterns based on different shared socioeconomic pathways (SSPs) and investigating the effects of population growth in informal settlements on future flood risk.

A more detailed discussion of the specific GIS methodologies and MCDA techniques used is provided in Chapter 3 of this study.

#### **1.4.6 Reliability and validity of data**

Ensuring the reliability and validity of the data is crucial for the integrity and credibility of this research. The study primarily relies on secondary data from authoritative sources, which inherently provides a degree of reliability. Several measures have been taken to further enhance the reliability and validity of the data used.

To ensure validity, the selected datasets have been carefully evaluated to confirm they adequately represent the constructs being measured, such in this case, the flood risk factors. The elevation data, which were used to map the slope and elevation of the eThekweni Metropolitan Municipality, was validated using Root Mean Square Error (RMSE) analysis. The hydrological datasets, specifically the river data which were used to map the drainage density and the distance from rivers, underwent verification against a government publication (eThekweni Municipality, 2023). This cross-referencing process confirmed the rivers and their location within the study area, ensuring the completeness and accuracy of the hydrological datasets.

Furthermore, the use of the MCDA approach, which includes quality assurance processes such as the CI and CR, adds another layer of validity to the data analysis process. These measures help ensure that the weighting and prioritisation of different factors are logically consistent and reflect their true importance in flood risk assessment.

It is important to note that while every effort has been made to ensure data reliability and validity, limitations may exist due to the inherent nature of secondary data. These limitations, if any, will be acknowledged and discussed in the relevant sections to maintain the integrity of this research study.

#### **1.4.7 Ethics**

This study has been reviewed and approved by the Faculty of Natural and Agricultural Sciences Ethics Committee (FNASREC) of North-West University with ethics number NWU 01375-22-A9. The committee classified this study as "No Risk" and granted permission for it to be conducted.

Although this study primarily relies on secondary data and does not directly involve human participants, ethical considerations remain an important aspect of the research process. The ethics framework for this study focuses on the responsible use of existing datasets and the potential implications of the research findings. The use of the datasets adhered to their respective terms of use and licensing agreements, ensuring compliance with data sharing and usage protocols.

While the data do not contain personally identifiable information, care was taken to ensure that the analysis and presentation of results do not inadvertently reveal sensitive information about specific locations or communities within the eThekweni Metropolitan Municipality. The focus remains on providing a broad, municipality-wide assessment of flood risk.

Given the potential influence of flood risk maps on public perception and policy decisions, there is an ethical obligation to ensure the accuracy and reliability of the results. The use of the MCDA approach, including quality assurance measures such as the CI and CR, helps fulfil this obligation by providing a transparent methodology. In line with the principles of responsible research, this study aims to contribute positively to flood risk management in the eThekweni Metropolitan Municipality. The incorporation of AG in developing future flood risk scenarios demonstrates a commitment to producing research that can inform long-term planning and decision making for the benefit of the community.

All sources of data and methodologies used in this study are clearly documented to ensure transparency and reproducibility of the research. This approach allows for scrutiny by peers, further enhancing the ethical standing of the research. By adhering to these ethics principles and the conditions set in the ethics approval by the North-West University, this study aims to contribute knowledge to the field of flood risk mapping while maintaining high standards of research integrity and social responsibility.

#### **1.4.8 Dissertation layout**

Chapter 1 (Introduction) provides a comprehensive background of urban flood risk trends on both regional and local scales. The purpose of this chapter was to establish the context of the study, highlighting the significance of flood risk in the eThekweni Metropolitan Municipality and KwaZulu-Natal. By examining historical flood events and urbanisation patterns, this chapter highlighted the necessity of the research and lays the foundation for the subsequent analysis.

Chapter 2 (Literature Review) concentrates on two key theoretical foundations: AG and GIS. The purpose of this chapter is twofold: first, to explore how AG principles can be applied to urban flood risk management, providing a framework for proactive decision making; and second, to demonstrate the capabilities and relevance of GIS in flood risk mapping. This theoretical grounding aims to justify the methodological approach and provide a lens through which to interpret the study's results.

Chapter 3 (Methodology) focuses on the technical process of creating current and future flood risk maps for the eThekweni Metropolitan Municipality. The purpose of this chapter is to provide a

clear, replicable methodology for flood risk mapping that integrates GIS techniques with MCDA. By detailing this process, the study aims to contribute to the broader field of flood risk assessment and provide a model that could be adapted for other urban areas.

Chapter 4 (Results) centres on presenting and analysing the flood risk maps produced using the methodology. The purpose of this chapter is to visually represent the spatial distribution of flood risk in the eThekweni Metropolitan Municipality, both current and future. By doing so, it aims to provide tangible evidence of flood-vulnerable areas, which can inform urban planning and disaster management strategies.

Chapter 5 (Conclusion and Recommendations) focuses on translating the study's findings into actionable insights. The purpose of this chapter is to bridge the gap between academic research and practical application, providing concrete recommendations for disaster risk reduction and the implementation of AG principles in the eThekweni Metropolitan Municipality. By doing so, it aims to enhance the real-world impact of the research and contribute to improving flood resilience in the eThekweni Metropolitan Municipality's informal settlements.

## **1.5 Conclusion**

This chapter has introduced the study on mapping informal settlements in the eThekweni Metropolitan Municipality at risk of flooding using GIS through the lens of AG. The research problem has been clearly stated, highlighting the critical need for improved flood risk management in informal settlements, particularly after the floods experienced in KwaZulu-Natal in April 2022. The study's aims and objectives have been carefully defined, focusing on the creation of current and future flood risk maps for the eThekweni Metropolitan Municipality, based on a detailed understanding of urban flood risk trends and the theoretical tenets of AG and GIS. The research methodology has been outlined, detailing the quantitative research design, the use of secondary data as the primary research tool, and the selection of datasets based on scientifically established flood risk variables. The MCDA approach has been identified as the key analytical method, incorporating seven significant factors contributing to flood risk.

The description of the study area has provided context to this study, detailing the geographical, climatic, and socio-economic characteristics of the eThekweni Metropolitan Municipality. The historical account of flooding events in the wider region, coupled with an analysis of urbanisation patterns and the formation of informal settlements, highlights the relevance of this research. These elements show a rapidly urbanising area struggling with recurrent flooding events and the challenges posed by expanding informal settlements. Importantly, this chapter has also addressed the ethical considerations of the study, emphasising the responsible use of secondary



data and the potential implications of the research findings. The approval granted by the Faculty of Natural and Agricultural Sciences Ethics Committee (FNASREC) of North-West University underscores the study's adherence to ethics research principles.

The subsequent chapters explore in more detail the theoretical concepts of GIS and AG, present the detailed methodology for producing current and future flood risk maps, analyse the results, and lastly discuss the conclusions and recommendations for further flood risk reduction measures in the eThekweni Metropolitan Municipality.

## **CHAPTER 2      LITERATURE STUDY**

### **2.1    Introduction**

This literature study is divided into two distinct yet interconnected halves, each exploring an aspect of using GIS as a tool for AG to achieve flood risk mapping in the eThekweni Metropolitan Municipality. This literature review addresses two research objectives.

The first half of the study examines the concept of AG, exploring its origins, definitions, and various approaches. It investigates how AG can be applied to complex problems, with a particular focus on climate change mitigation and flood risk reduction. This section aims to provide a comprehensive understanding of AG as a proactive framework for addressing future challenges and uncertainties, laying the groundwork for its application in flood risk management. In doing so, it addresses Research Objective 2: To investigate the theoretical tenets of AG and its relevance to the management of urban flood risk in the eThekweni Metropolitan Municipality.

The second half of the chapter focuses on GIS and their role in supporting AG, particularly in the context of flood risk mapping and management. This section analyses the evolution of GIS technology, its components, and the types of data it can process. It explores the application of GIS in urban disaster risk management and flood management, highlighting its importance in decision-making processes. Additionally, this section investigates how GIS can serve as a tool for AG, enhancing our ability to anticipate, map, and prepare for current and future flood risks. It fulfils the third research objective: To discuss the use of and utility of GIS in mapping urban flood risk.

By examining these two key areas – AG and GIS – this literature study provides a holistic view of how proactive governance approaches and advanced spatial analysis tools can be combined to better manage and mitigate flood risks in an increasingly uncertain future.

### **2.2    Anticipatory governance**

AG is a forward-looking approach to decision making and policy formulation that aims to address future challenges and uncertainties proactively. The discussion begins by examining the origins and conceptualisation of AG, tracing its roots in the broader context of governance as a means to organise human civilisation.

### **2.2.1 The rationale for the inclusion of anticipatory governance in the study context**

South Africa is grappling with the complex issue of informal housing and the inherent exposure of its occupants to disaster risks (Barry & Rüther, 2005; Huchzermeyer & Karam, 2006; Hunter & Posel, 2012; Marutlulle, 2017). Historically, the apartheid government's laws coerced black Africans to relocate to peripheral areas, resulting in an influx of people to informal settlements (Barry & Rüther, 2005; Hunter & Posel, 2012; Iliffe, 1987). As of 2020, over five million people in South Africa, approximately 11.4% of the population, were living in informal settlements that are often situated in vulnerable areas such as floodplains and steep slopes that make them susceptible to a variety of hazards, including hydro-meteorological hazards (Barry, 2003; Musungu *et al.*, 2016; Le Quéré *et al.*, 2020; Williams *et al.*, 2019). In 2022, South Africa experienced heavy rainfall triggered by the prevailing La Niña weather pattern, causing devastating floods that claimed hundreds of lives and destroyed homes and infrastructure in the eThekweni Metropolitan Municipality (Grab & Nash, 2023; Olanrewaju & Reddy, 2022). As informal settlements continue to burgeon in size and number, and as climate change exacerbates flooding events, the identification and estimation of vulnerable areas in flood-prone municipalities such as the eThekweni Metropolitan Municipality are increasingly vital (Olanrewaju & Reddy, 2022). In this context, it is imperative to make use of innovative and complex approaches to disaster risk management that combine tools such as AG and GIS to enable enhanced preparedness and mitigation efforts at all levels of government. By anticipating and mapping flood-prone areas, governments and communities can collaboratively work towards minimising the impact of disasters on vulnerable populations while also building disaster resilience. Therefore, integrating AG and GIS in a disaster risk management framework can enhance South Africa's resilience to future floods and reduce the vulnerability of its population.

This chapter explores the origins and conceptualisation of AG by examining its definition, contexts of application, and approaches. Additionally, the chapter analyses the application of AG in addressing complex problems, specifically the mitigation of climate change, as well as flood mitigation. By providing an in-depth analysis of the theory and practice of AG, this chapter aims to contribute to a better understanding of this emerging concept and its potential to address the complex challenges facing modern society. Before the discussion on AG can start, it is important to elaborate on how the broad concept of governance came into being, as it provides a historical context for the development of AG. The origin of governance is therefore the first point of discussion in this chapter.

### **2.2.2 The origin of governance as a concept to organise human civilisation**

The concept of governance developed over several centuries and has undergone significant changes throughout history (Bartels, 2018; Scholte, 2021). It can be traced back to ancient civilisations such as Greece, Rome, and China, where rulers and officials were responsible for managing public affairs and enforcing laws (Ando, 2017; Ober, 2015; Zhou, 2011). The concept of governance can be seen as a response to the fundamental human need for order, stability, and security (Fukuyama, 2011). As social creatures, humans have always lived in groups and communities, and the need to coordinate and manage their collective affairs has been an essential part of human existence (Moffett, 2019). In this sense, governance can be seen as a natural and necessary aspect of human society (Kaldor, 2020). At its core, governance is about establishing rules, norms, and institutions that help to regulate social behaviour and manage collective resources (Bovens *et al.*, 2014; Bevir & Rhodes, 2016; Rosenau & Czempiel, 1992).

The Western concept of governance further evolved during the Enlightenment period in Europe (Hood, 2010). During this time, philosophers such as John Locke and Jean-Jacques Rousseau proposed new ideas about the nature of government and the rights and responsibilities of citizens (Bertram, 2012; Marshall, 2006). At this time governance came to be regarded not only as a practical necessity, but a deeper, philosophical dimension of human being (Fukuyama, 2011; Kjaer, 2004). Concepts of governance emerged, such as the social contract theory, which articulated revolutionary ideas such as that the legitimacy of government is based on the consent of the governed (Dunn, 1982). According to this view, individuals agree to surrender some of their individual rights and freedoms to a governing authority in exchange for protection, security, and the promotion of the common good (Klosko, 1987). In this sense, governance is not just a means to an end, but an expression of the collective will and values of a society (Chhotray & Stoker, 2008). Moreover, governance can be seen as a reflection of our human desire for justice and fairness (Kjaer, 2004). Through governance, we can create institutions and processes that ensure that all members of society are treated fairly and have equal access to opportunities and resources (Held, 1992). This can include promoting democratic participation, protecting human rights, and creating systems of accountability and transparency (Gaventa & McGee, 2013).

A further evolution in the concept of governance followed after the end World War II, when the United Nations was established to promote global cooperation and peace (Kooiman, 1993; Pierre & Peters, 2020; Rosenau & Czempiel, 1992). The UN Charter established the principles of democracy, human rights, and the rule of law as the foundations of governance (Fassbender, 2009). This involved defining the rights and responsibilities of individuals and groups, as well as the mechanisms for decision making, conflict resolution, and enforcement of rules (Weiss &

Thakur, 2010). Through greater international governance and cooperation, it was believed societies can promote peace, justice, and social cohesion, and create the conditions for economic growth and prosperity (Kaufman *et al.*, 2010). The post-WW2 governance discourse increasingly focused on issues such as economic development, environmental sustainability, and social justice (Grindle, 2017). Presently, governance is seen as an important element in achieving social and economic progress, and there are ongoing debates about the best ways to promote effective and accountable governance from local to global levels (Kooiman, 1999).

It is important to examine various definitions of governance as a concept, since it has implications for the term AG. The next section incorporates definitions from scholars and international organisations.

### **2.2.3 Defining governance**

Governance is a complex and multi-dimensional concept that has been studied in various fields, including political science, sociology, and public administration (Beetham, 2013; Jessop, 2015; Pollitt & Bouckaert, 2017). While there is no universally agreed-upon definition, governance generally refers to the processes, structures, and institutions through which public decisions are made and implemented (Rhodes, 1996; Stoker, 1998). It involves the distribution and exercise of power, authority, and responsibility among different actors in society, including government officials, civil society organisations, and private sector actors (Fukuyama, 2004). Effective governance requires the establishment of clear rules and regulations, the allocation of resources, and the provision of public goods and services (Grindle, 2004).

Scholars have identified several key dimensions of governance, including legitimacy, accountability, transparency, and participation (Batory & Svensson, 2019; Grindle, 2017; Sørensen & Torfing, 2015). Legitimacy refers to the extent to which citizens and stakeholders view the decision-making process as fair and just, while accountability refers to the mechanisms through which those in power are held responsible for their actions (Beetham, 2012; Goetz & Jenkins, 2005). Transparency involves making information about the decision-making process and outcomes readily available to the public, while participation refers to the extent to which citizens and stakeholders can participate in the decision-making process (Fung, 2004; Pateman, 1970). According to Bevir (2012), governance refers to the process of decision making and the exercise of authority in the management of a country, organisation, or community. It involves the formulation and implementation of laws, policies, and regulations that are aimed at ensuring the effective and efficient use of resources, the protection of citizens' rights and interests, and the achievement of common goals and objectives (Kooiman, 1999; Rhodes, 1996). According to Olowu and Sako (2002), governance in the African context can be understood as the exercise of

authority in the political, economic, and administrative spheres to manage the affairs of a nation. This includes the various methods, both good and bad, that societies use to distribute power and manage public resources and problems.

According to the World Bank (2021), governance can be defined as:

*"...the traditions and institutions by which authority in a country is exercised. This includes the process by which governments are selected, monitored, and replaced; the capacity of the government to effectively formulate and implement sound policies; and the respect of citizens and the state for the institutions that govern economic and social interactions among them."*

The United Nations Development Programme (UNDP) (2021) defines governance as:

*"...the system of values, policies and institutions by which a society manages its economic, political and social affairs through interactions within and among the state, civil society and private sector. It is the way a society organizes itself to make and implement decisions-achieving mutual understanding, agreement and action."*

Looking at the above definitions from scholars and international organisations, the operational definition of governance for the purpose of this study is as follows: *Governance is a multi-faceted concept that encompasses the mechanisms, processes, and institutions through which authority is exercised and decision making is carried out in a participatory and inclusive way in a country, organisation, or community.*

The traditional conceptualisation of governance has allowed humanity to deal with many challenges throughout the millennia and allowed humanity to attain its current level of technological development (Acemoglu & Robinson, 2012; Ridley, 2012). However, this traditional approach to governance is becoming more strained in delivering lasting solutions to ever more complex problems, such as disasters, that have emerged since the advent of the Anthropocene (Dryzek & Pickering, 2018). In the context of the increasing complexity of problems, such as disasters, that have arisen since the Anthropocene began, the traditional approach to governance is facing challenges in providing long-term solutions (Quay, 2010). Consequently, there is a growing need to embrace a more anticipatory approach to governance to effectively manage these intricate problems. Before the concept of AG is discussed in greater detail, it is necessary to define what is meant by the concept of anticipation.

#### **2.2.4 Defining anticipation**

According to Roberto Poli, anticipation can play a big role in increasing awareness about the different futures that may be encountered and making society more aware of the outcomes of individual and collective decisions and actions (Poli, 2009; 2010; 2011; 2017; 2019a; 2019b). Due

to the utility of the concept of anticipation as highlighted by Poli, it becomes important to define what is meant by the concept. However, a cursory review of the literature reveals that various fields of study have studied the concept of anticipation, and consequently, there is not a singular agreed-upon definition of the concept (Miller *et al.*, 2013). Fields of study that have explored the concept of anticipation include biology (Clark, 2020a; Friston, 2008; Llinás, 2002), psychology (Louie, 2009; Louie & Poli, 2011; Poli, 2009, 2010, 2011, 2017, 2019a, 2019b), resilience (Almedom *et al.*, 2007; Martin-Breen & Anderies, 2011; Zolli & Healy, 2012), future studies (Miller, 2006, 2007, 2011, 2012), and governance (Fuerth, 2009, 2011; Karinen & Guston, 2010; Fuerth & Faber, 2012). This is by no means an exhaustive list; it merely shows the proliferation in the study of the concept of anticipation in recent decades. Some of the seminal definitions of anticipation that have emerged out of different fields of study are worth mentioning.

From the perspective of physical sciences, many unique definitions of anticipation have emerged. Specifically, Rosen (2012) states that in the field of biology an anticipatory system is a system that contains a predictive model of itself or of its environment, or both, enabling it to change its state in accordance with its model's predictions for a later time. Rosen (2012) further suggests that anticipation is not limited to living systems and that even non-living or non-biological systems can possess anticipatory capabilities. Poli (2010) supports this idea by stating that even non-living systems can be anticipatory. One example of non-living systems exhibiting anticipatory behaviour is the Belousov-Zhabotinsky (BZ) reaction (Epstein & Pojman, 1998). The BZ reaction is a chemical reaction that produces oscillations in the concentrations of different chemical species (Field *et al.*, 1972). The reaction can be triggered by a pulse of a certain chemical, and after a few oscillations, it settles into a stable pattern (Winfree, 1972). Researchers have found that if the pulse of the triggering chemical is applied repeatedly at regular intervals, the reaction can "anticipate" the pulse and start oscillating before it arrives (Epstein & Pojman, 1998; Field *et al.*, 1972).

Dubois (2000), in the field of physics, differentiates between two types of anticipation: weak and strong. Weak anticipation refers to a system that uses a model of itself to calculate its future states, while strong anticipation refers to the system that uses itself to create its future states (Barandiaran & Di Paolo, 2014; Moreno & Mossio, 2015). One example of weak anticipation is weather forecasting, where meteorologists use mathematical models to simulate the behaviour of the atmosphere and predict weather patterns (Kalnay & Cai, 2003; Roulston & Smith, 2002). These mathematical models are based on physical laws and observations of past weather patterns, and they allow meteorologists to make predictions about future weather conditions (Lynch, 2008). An example of strong anticipation is self-organising systems (Haken, 2006). Self-organising systems are a class of complex systems that exhibit strong anticipation by actively

creating their future states (Ashby, 1962; Holland, 1995; Kauffman, 1993). One example of a self-organising system is found in the study of phase transitions in materials, such as the transition from a liquid to a solid (Goldenfeld, 2018). During this process, the material changes its structure and properties, and it actively creates its future state by redistributing its atoms or molecules to minimise its free energy (Huang, 2008). According to Martin-Breen and Anderies (2011), in the field of resilience, anticipatory adaptation focuses on using the best models of potential impacts from climate change to create systems such as engineering resilience (or 'common sense' resilience), systems resilience (called robustness in economics) and resilience in complex adaptive systems. These can maintain stability during unexpected events, for example extreme weather events such as floods, droughts, and heatwaves that may occur with greater frequency and severity due to climate change.

The concept of anticipation has also been discussed extensively within the social sciences. Philosophers Husserl (1913) and Heidegger (1927) both have their own views on the concept of anticipation. According to Husserl (1913), anticipation is a key aspect of a person's consciousness and is present in their perceptual experience. Anticipation is present in a person's perceptual experience in several ways (Bar, 2020). When a person sees a chair, they don't merely perceive its current sensory qualities like the shape, colour, and texture. Instead, they anticipate the chair's affordances and potential interactions based on their previous experiences with chairs and the current context (Gibson, 2014). For example, the person might anticipate the chair's stability, comfort, and the effort required to sit down or stand up from it (Norman, 2013). If the chair appears unstable or broken, the person might expect it to collapse when they attempt to sit on it. This anticipatory aspect of perception allows the person to understand the chair's function and make appropriate decisions about how to interact with it (Costall, 1995).

Heidegger (1927), on the other hand, defines anticipation as the potential for understanding one's own being and the possibility of living an authentic existence. According to Fukukura *et al.* (2013), anticipation in the field of psychology is defined as the process of imagining the outcomes of future events that bring pleasure and the future-oriented aspect of cognitive studies. The authors emphasise that anticipation is rooted in a person's understanding of the potential consequences of their actions and their ability to anticipate these outcomes (Fukukara *et al.*, 2013). Nuttall (2010) argues in the field of anthropology that anticipation is an important aspect with respect to climate change. Anticipation involves intentionality, action, agency, imagination, possibility, and choice to help individuals and communities respond proactively to future challenges and to shape their own futures in desirable ways (Nadin, 2015). In the context of climate change, anticipation can help us to prepare for the potential effects of climate change, to reduce greenhouse gas emissions, to adapt to changing conditions, and to build resilience in the face of climate risks (Vervoort & Gupta,



2018). According to Nuttall (2010), anticipation is essential for thinking about climate change adaptation.

It is clear from the above definitions that anticipation is a characteristic of both human and biological systems. Considering all the above definitions it can be said that anticipation relates to a system's capacity to envision the possible consequences certain actions or events may have for the system itself and what the system can do to change the consequences positively and proactively. Due to the benefits of proactively averting negative consequences on a systemic level, anticipation could hold many benefits for improving governance. Consequently, the section that follows focuses on the emergence and conceptualisation of AG.

### **2.2.5 Origin and definition of anticipatory governance**

AG is a concept that emphasises the importance of forward-looking decision making to address emerging or potential issues and risks before they become crises (Guston, 2014; Mazzucato, 2018). The concept of AG has its origins in the field of futures studies, which emerged in the mid-20th century as a way of exploring possible futures and developing strategies for managing uncertainty and change (Bell, 2017; Slaughter, 1995). The idea of AG gained traction in the 1990s and 2000s, as governments and other organisations began to grapple with increasingly complex and uncertain global challenges such as climate change, pandemics, and financial instability (Quay, 2010; Fuerth, 2009). The rise of digital technologies and social media also played a role in the emergence of AG, as these tools have made it easier to gather and analyse information, anticipate trends and risks, and mobilise collective action (Poli, 2010; Fuerth & Faber, 2012). The concept of AG has been further developed by scholars such as Roberto Poli, David Fuerth and Robert Quay, who emphasise the need for more participatory and collaborative approaches to decision making to build resilience and adaptability in the face of uncertainty and change (Fuerth, 2009; Quay, 2010; Poli, 2010). The concept of AG has also been adopted by a range of organisations and institutions, including the United Nations and various national and local governments (Fuerth, 2009; Guston, 2014; Quay, 2010).

In recent years, AG has been recognised as a critical tool for addressing a range of complex and interconnected global challenges (Cutter, 2016). The COVID-19 pandemic, for example, has highlighted the need for AG approaches that can help to anticipate and prepare for emerging health risks, as well as the need for more coordinated and collaborative decision making across sectors and levels of governance (Zaratin *et al.*, 2022). The concept of AG has also been applied in a variety of fields beyond traditional governance and policymaking, including business, healthcare, and environmental management (Fuerth, 2013; Muiderman *et al.*, 2020; Poli, 2018). In these contexts, AG approaches have been used to help organisations anticipate and adapt to

emerging trends and risks, and to develop more flexible and adaptive strategies for navigating uncertainty and change (Bulkeley & Castán Broto, 2013). Now that the concept of AG has been contextualised, the next part of this study delves into a more focused discussion on the various definitions surrounding AG.

The most simplistic definition of AG is given by Heo and Seo (2021), who state that AG comes from a combination of (1) governance and (2) anticipatory. Heo and Seo (2021) elaborate that AG can be described as a long-lasting decision-making process that involves collaboration and agreement among a variety of stakeholders, such as the government, market, public, and the academic community, to achieve a common desired future or objective. Fuerth and Faber (2012) define AG as the processes and practices through which public actors seek to identify, assess, and address future risks and uncertainties that are likely to affect governance and policy outcomes. According to Guston (2014), AG is a comprehensive capability that extends throughout society, enabling society to proactively respond to diverse inputs and effectively manage emerging technologies based on knowledge, all within a timeframe that allows for timely and feasible management actions. AG is defined as the processes and practices through which public actors seek to prepare for future challenges, opportunities, and risks to enhance their capacity to manage complex policy problems (Poli, 2010). It is a novel approach that aims to incorporate reflexivity into decision-making processes. It does so by enhancing the ability of actors and institutions to foresee and influence the path of technological advancement (Barben *et al.*, 2008).

An alternative definition of AG was also put forward by the US Department of Government Affairs. Here, Fuerth (2009) defines AG as a system of systems, involving four basic components or “systems”:

1. **Foresight system:** This component involves gathering and analysing information about potential future trends, events, and scenarios. It includes various methods and tools for futures thinking, such as horizon scanning, scenario planning, and modelling. The foresight system aims to anticipate potential risks and opportunities that may emerge in the future and to develop strategies to address them proactively. The foresight system is not limited to internal analysis, but also incorporates external input from stakeholders and experts. The foresight system as visualised by Fuerth (2009) can be found in Figure 2.1.

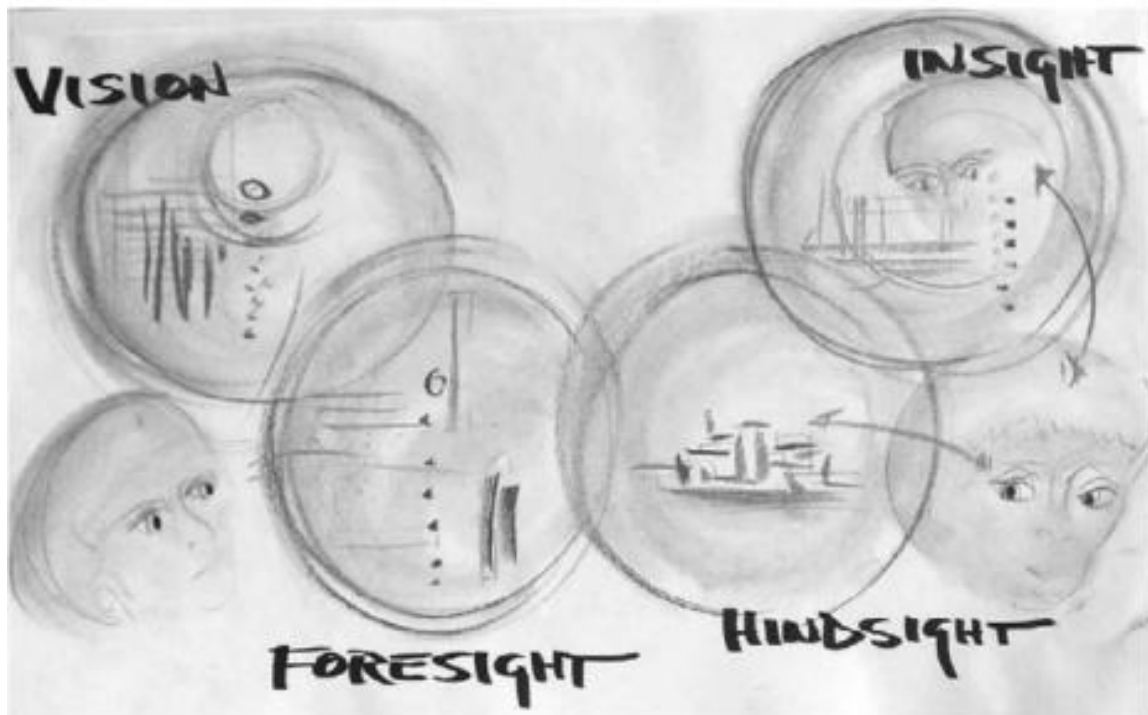


**Figure 2.1: The foresight system (Fuerth, 2009)**

2. **Networked system:** This component involves building and maintaining relationships with various stakeholders, including government agencies, NGOs, industry partners, and other relevant organisations (see Figure 2.2). The networked system is important for sharing information and resources, coordinating efforts, and ensuring that all parties are working towards a common goal. The networked system is also critical for ensuring that diverse perspectives and expertise are represented in decision-making processes.

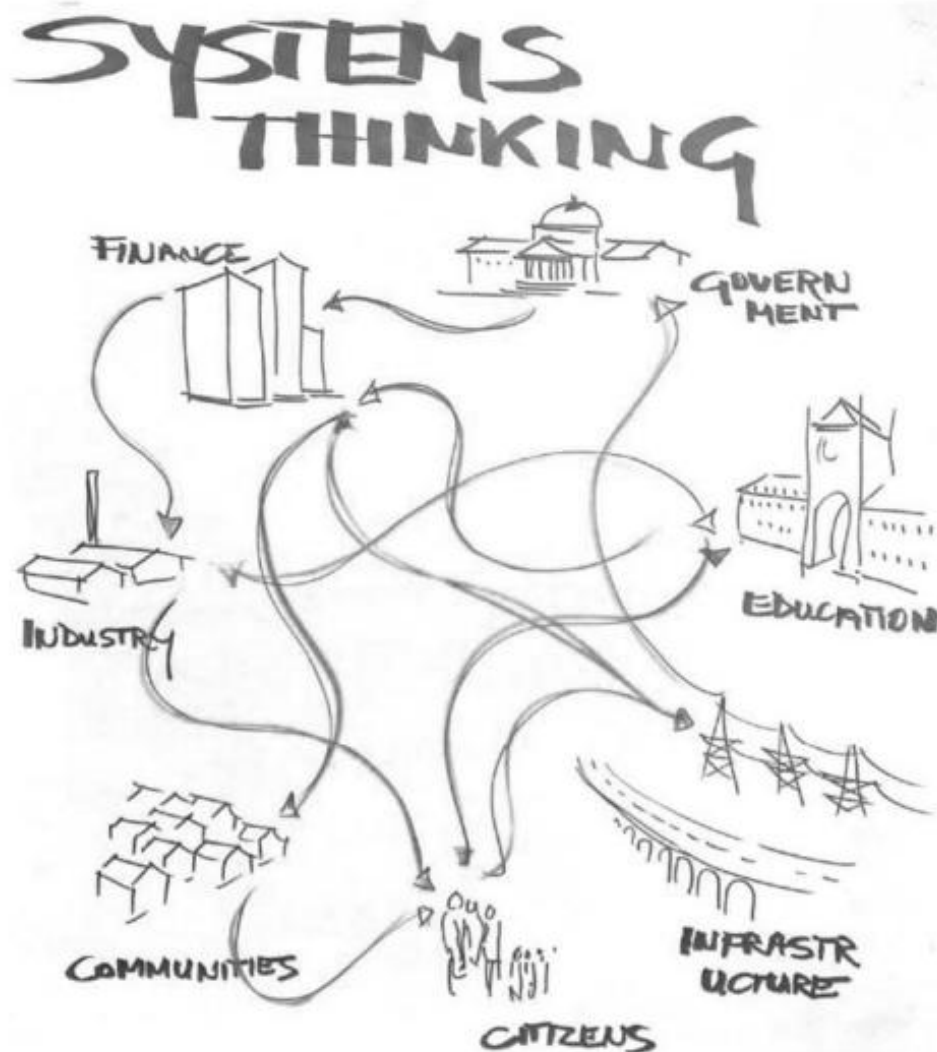


Figure 2.2: The stakeholders involved in a networked system (Fuerth, 2009)

3. **Feedback system:** This component involves monitoring and evaluating the effectiveness of AG strategies and adjusting them as needed. The feedback system is critical for continuous learning and improvement, and it involves collecting and analysing data on the outcomes of AG initiatives. The feedback system also involves engaging with stakeholders to gather their feedback and insights and incorporating these perspectives into decision-making processes.
4. **Open-minded organisational culture:** This component involves creating a culture within organisations that is receptive to change and innovation, and that is open to new ideas and perspectives. An open-minded organisational culture is important for fostering creativity and collaboration, and for overcoming resistance to change. This component

also involves promoting transparency and accountability and ensuring that decision-making processes are inclusive and participatory.

Fuerth further states that AG uses foresight to develop future plans and take action. AG uses foresight as a method or process that helps governments manage rapid and complicated changes (Fuerth, 2009; 2013). Heo and Seo (2021) argue that AG is connected to foresight and aims to use foresight to address potential dangers before they become severe, using foresight to help governments handle rapidly evolving and complex changes. The goal of increased foresight and anticipation is for governments to have the ability to react to a diverse range of possible futures with flexibility and resilience. Guston (2014) states that AG requires a comprehensive understanding of future-focused governance to support decision making that is forward-thinking and informed. Guston (2014) deduces that this leads to better policymaking outcomes among stakeholders.

Van Niekerk (2021) is of the opinion that a fifth component can be added to Fuerth's (2009) "system of systems" definition of AG. This fifth component is that of *Auftragstaktik* within the context of foresight and AG. According to Wittmann (2012), *Auftragstaktik*, also known as mission command, is a military concept that emphasises the decentralisation of decision making and the delegation of authority to subordinates. Shamir (2011) argues that *Auftragstaktik* can be applied to non-military contexts, particularly in situations where the future is uncertain and complex. In these contexts, Shamir (2011) suggests that traditional top-down command and control approaches may be inadequate and that more flexible and adaptive approaches are needed. Van Creveld (1985) identifies several key elements of *Auftragstaktik*, including the use of broad, flexible objectives rather than specific orders, the delegation of decision making authority to lower levels of the organisation, and the need for effective communication and feedback systems. Bungay (2022) also notes that the success of *Auftragstaktik* depends on the development of a culture of trust and mutual respect among team members, as well as a willingness to embrace experimentation and learn from mistakes. Furthermore, Dempsey (2012) suggests that the concept of *Auftragstaktik* offers valuable insights into how organisations can navigate uncertain and complex futures, and that it provides a useful framework for developing more adaptive and resilient approaches to decision making and governance.

AG is a proactive and collaborative approach to decision making and strategy development that aims to anticipate future challenges, identify opportunities, and effectively manage risk, uncertainty, and change before they become significant problems. It involves four key components or "systems": a foresight system that gathers and analyses information about potential future trends and scenarios, a networked system that builds and maintains relationships

with stakeholders, a feedback system that continuously monitors and evaluates the effectiveness of strategies, and an open-minded organisational culture that embraces change and innovation. Additionally, AG incorporates the concept of *Auftragstaktik*, which decentralises decision making and delegates authority to subordinates, with the intention of fostering self-organisation within the system, allowing for greater flexibility and resilience. Through collaboration and agreement among various stakeholders, AG seeks to achieve a shared vision and desired outcomes for the future.

Having established a definition of AG, it is now important to explore the different contexts of AG and how they can be applied in various fields. This will form the next part of the theoretical discussion on AG.

## **2.2.6 Contexts in which anticipatory governance has been applied**

There is no singular approach to how AG is implemented within the governance context. Rather, there are various contexts in which AG has been applied that should be noted, as they could all make unique contributions to how people manage emerging disaster risk.

The selection of the following five contexts of AG application is driven by their recurring prevalence and importance in contemporary problem solving. Anticipatory climate governance is an essential context where AG has been applied for its widespread applications in fighting climate change. Anticipatory innovation governance is specifically directed at future-oriented technologies. Anticipatory regulation is closely linked to anticipatory innovation governance, as it encompasses the proactive oversight and management of emerging technologies and their associated risks. Given the rapid pace of technological advancements in contemporary times, it is essential to stay informed and regulate these innovations. The inclusion of anticipatory disaster management is particularly relevant to the context of this study, as this study has a focal point of flooding. Anticipatory risk management is closely intertwined with anticipatory disaster management and addresses the broader concept of risk across various domains, and this integration of risks can be seen as a crucial concept for this study. The following section discusses these five prominent contexts of AG application.

### **2.2.6.1 Anticipatory climate governance**

Anticipatory climate governance involves the use of foresight and proactive measures to address environmental challenges before they become crises (Laukkonen, *et al.*, 2009). Anticipatory climate governance involves assessing and managing risks, building resilience, and promoting sustainable development (Biermann & Pattberg, 2012). The aim is to avoid or minimise harm to

the environment, human health, and the economy (Muiderman *et al.*, 2020). One way that anticipatory climate governance is used is through scenario planning (Glaas *et al.*, 2017). Scenario planning involves developing plausible scenarios of future environmental change and analysing the potential effects and responses (Liu *et al.*, 2019). Scenario planning can help identify emerging risks and opportunities and inform policy decisions (Haasnoot *et al.*, 2013). Another way that anticipatory climate governance is used is through adaptive management, which involves continuous monitoring, evaluation, and adjustment of environmental management practices based on new information and changing conditions (Folke *et al.*, 2005). Adaptive management can help build resilience to environmental change and improve the effectiveness of environmental management (Williams *et al.*, 2009).

Anticipatory climate governance also involves the use of anticipatory risk management, a context of AG application that is discussed in the section on anticipatory risk management (see Section 2.2.6.5) (Boston & Lempp, 2011). The process of anticipatory climate governance involves identifying and assessing emerging risks, developing strategies to mitigate or prevent harm, and continuously monitoring and reassessing risks over time (Gupta & Vegellin, 2016). Anticipatory risk management can help prevent or minimise environmental harm and promote sustainable development (O'Rourke & Macey, 2003). Finally, anticipatory climate governance involves stakeholder engagement and collaboration, which includes engaging diverse stakeholders in environmental decision-making processes and promoting dialogue, collaboration, and learning across sectors and scales (Tompkins *et al.*, 2010). Stakeholder engagement can help build trust, enhance transparency, and promote more effective and legitimate environmental governance (Driessen *et al.*, 2001). In anticipatory climate governance, the use of GIS as a decision support tool is of great importance as it aids in offering a visual depiction of different factors influencing climate vulnerability and the geographical distribution of hazards. The integration of GIS enhances the capacity to anticipate climate-related risks, providing valuable insights into potential areas prone to climate impacts.

One example of anticipatory climate governance in action is the city of Rotterdam in the Netherlands. Rotterdam is highly susceptible to the effects of climate change, including sea-level rise and increased frequency of extreme weather events (Francesch-Huidobro *et al.*, 2017). To address these challenges, the city of Rotterdam has implemented several innovative initiatives to proactively adapt and mitigate the effects of climate change (Francesch-Huidobro *et al.*, 2017).

One notable example is the Rotterdam Climate Proof (RCP) programme, which aims to make the city resilient and adaptive to future climate risks (den Exter *et al.*, 2015). The programme focuses on integrating climate considerations into urban planning, infrastructure development, and policy-

making processes (Molenaar & Gebraad, 2014). The RCP involves collaboration between government agencies, businesses, and communities to anticipate and prepare for potential climate impacts (Molenaar & Gebraad, 2014).

In the South African context, there is a notable attempt at anticipatory climate governance in the country's response to climate change (Ziervogel *et al.*, 2014). Climate governance in South Africa is characterised by a framework of key institutions, strategies, emission reduction targets, and legislation, all aimed at enabling effective climate action (Altieri & Keen, 2016; Klausbruckner *et al.*, 2016; Marquard *et al.*, 2011). At the institutional level, South Africa has established important bodies such as the Presidential Climate Commission, which plays a large role in coordinating climate-related initiatives and policies (Tyler & Steyn, 2021). Strategically, South Africa has developed the National Climate Change Response Policy, a comprehensive framework that guides the country's climate action efforts. This policy sets out the vision, goals, and key actions required to address climate change impacts and promote sustainable development (Popoola *et al.*, 2020). Further demonstrating its commitment to mitigating climate change, South Africa has established emission reduction targets as part of the Nationally Determined Contribution (NDC) framework of the Paris Agreement. These targets outline the country's specific goals for reducing greenhouse gas emissions and transitioning to a low-carbon economy (Mantlana *et al.*, 2021). Supporting the institutional and strategic framework, South Africa has enacted legislation such as the *National Environmental Management Act*, 107 of 1998. This legislation provides a legal basis for environmental management and governance, including provisions that support climate change mitigation and adaptation measures.

Collectively, these initiatives and actions highlight South Africa's proactive approach to climate governance, demonstrating its commitment to addressing climate change and transitioning to a low-carbon and climate-resilient economy.

#### **2.2.6.2 Anticipatory innovation governance**

Anticipatory innovation governance is a framework (see Figure 2.3) for governing innovation in a way that anticipates and manages potential social and environmental risks, while also fostering innovation and economic growth (Guston, 2014; Karinen & Guston, 2010). Anticipatory innovation governance aims to proactively identify and address emerging risks and uncertainties associated with new technologies or innovations, and to promote the development of innovations that are socially responsible and environmentally sustainable (Foley *et al.*, 2016; Quay, 2010). It is based on the recognition that innovation can have both positive and negative effects on society and the environment (Guston, 2008). Anticipatory innovation governance seeks to create a regulatory environment that encourages innovation while also managing its potential risks (Fuerth, 2009).



Anticipatory innovation governance involves a range of policy instruments and governance mechanisms, including regulations, incentives, public-private partnerships, and stakeholder engagement (Foley *et al.*, 2016; Karinen & Guston, 2010).

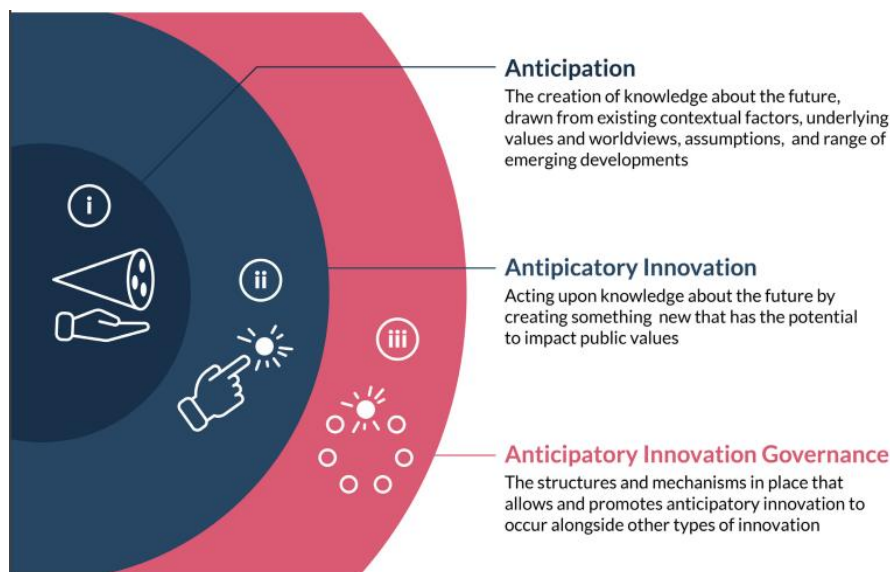


**Figure 2.3: The framework of anticipatory innovation governance (Tönurist & Hanson, 2020)**

One example of anticipatory innovation governance in practice is the European Union's (EU) Precautionary Principle, which requires that new technologies be proven safe before they are approved for use (Botes, 2023). The Precautionary Principle allows for the introduction of new technologies while also minimising the risks to human health and the environment (Marr, 2003). The need for a precautionary approach to possible environmental threats and concern for human health is also highlighted in South African law (van Rijssen *et al.*, 2015). Regarding the innovation of genetically modified organisms (GMO's) in South Africa, the *Genetically Modified Organisms Act*, 15 of 1997 is a piece of legislation that governs the use and management of GMOs in South Africa. This act was enacted to ensure the safe and responsible handling, import, export, and release of GMOs, with the aim of protecting the environment and human health.

Another example of anticipatory innovation governance in practice is the EU's General Data Protection Regulation (GDPR), which was adopted in 2016 and became fully enforceable in 2018 (Hoofnagle *et al.*, 2019). The GDPR is a comprehensive data protection law that regulates the processing of personal data by companies operating in the EU (Hoofnagle *et al.*, 2019). The GDPR aims to protect the privacy and personal data of EU citizens while also promoting innovation and economic growth (Tikkinen-Piri *et al.*, 2018). It can be seen as an example of anticipatory innovation governance because it seeks to proactively identify and address potential

risks associated with the use of personal data, while also fostering innovation and entrepreneurship (Gellert, 2018; Tankard, 2016). The regulation requires companies to implement privacy by design and default, meaning that data protection and privacy considerations must be taken into account at the earliest stages of product and service development (Bincoletto, 2019). This encourages companies to develop new products and services that are privacy-friendly and minimise the risks of data breaches and other privacy violations (Johansen & Fischer-Hübner, 2020).

### **2.2.6.3 Anticipatory regulation**

Anticipatory regulation is a proactive approach to regulating emerging technologies, products, or activities to anticipate and address potential risks while promoting positive outcomes (Armstrong & Rae, 2017; Brey, 2012). It involves developing forward-looking and adaptable regulations and policies that keep pace with the changing landscape of technological developments and their potential effects on society, the economy, and the environment (Bennear & Wiener, 2019). The goal of anticipatory regulation is to foster innovation and growth while minimising negative consequences, such as unintended consequences or adverse effects on the public or society (Jasanoff, 2015). It seeks to strike a balance between innovation and risk management by identifying and addressing risks and uncertainties associated with emerging technologies and activities in a timely and effective manner (Renn & Roco, 2006).

The concept of anticipatory regulation has gained more attention in recent years, particularly in the context of emerging technologies such as nanotechnology and artificial intelligence (Bowman *et al.*, 2013; Scherer, 2015). Several scholars have contributed to the development of this concept. Guston (2014) proposed a framework for AG that involves foresight, engagement, and integration to identify and address potential risks associated with emerging technologies. Kuhlmann *et al.* (2019) argue that anticipatory regulation should be based on a combination of foresight methods, stakeholder involvement, and regulatory experimentation to develop adaptive and flexible regulatory approaches. Similarly, Brey (2017) proposed a model of anticipatory technology ethics that emphasises the importance of proactive ethical assessment, public participation, and the development of ethics guidelines for emerging technologies.

Other scholars have focused on specific areas of anticipatory regulation. Yeung (2018) discussed the challenges of regulating emerging technologies in the context of algorithmic decision making, where the complexity and opacity of algorithms pose new regulatory challenges. Butenko and Larouche (2015) argue that anticipatory regulation in the context of the sharing economy should be based on a better understanding of the disruptive potential of platform-based business models and their impact on existing regulatory frameworks.

In anticipatory regulation, the use of GIS as a decision support tool becomes highly relevant as it provides a visual representation of various factors influencing regulatory vulnerability and the spatial distribution of regulatory challenges (Janssen & Helbig, 2018). By incorporating GIS, the anticipation capacity is improved, offering deeper insights into areas where regulatory interventions may be required to address emerging issues proactively (Talen, 2000).

One example of anticipatory regulation is the use of "sandbox" regulatory frameworks, which allow for the testing and development of new technologies and business models in a controlled environment (Ranchordás, 2021). Sandboxes create a space where innovators can experiment with new products or services without the risk of violating existing regulations or exposing consumers to undue harm (Fenwick *et al.*, 2016). By allowing for controlled testing, sandboxes help regulators anticipate potential risks associated with new technologies or business models and develop appropriate regulations to ensure that these risks are effectively managed (Zetzsche *et al.*, 2017). For instance, the UK's Financial Conduct Authority (FCA) has implemented a regulatory sandbox that allows fintech startups to test new financial products and services in a safe and controlled environment (Arner *et al.*, 2016). This approach enables the FCA to anticipate potential risks associated with new financial technologies and develop regulations that can effectively manage these risks while promoting innovation and competition in the industry (Buckley *et al.*, 2020).

In the context of financial services regulation, the South African Reserve Bank's Fintech Unit has embraced anticipatory regulation measures to support technological advancement while safeguarding the interests of its citizens (Coetzee, 2018). The Fintech Unit has adopted a proactive approach to engage with innovators, understand emerging technologies, and develop appropriate regulatory frameworks. This collaborative effort aims to foster innovation, promote competition, and enhance financial inclusion while ensuring consumer protection and maintaining financial stability (Coetzee, 2019). By striking a balance between innovation and regulation, the South African Reserve Bank seeks to create an enabling environment for the growth of fintech while mitigating potential risks (Abor *et al.*, 2022).

#### **2.2.6.4 Anticipatory disaster governance**

Anticipatory disaster governance refers to a set of practices and strategies that aim to manage the risks of disasters proactively and effectively before they occur (Lassa *et al.*, 2018; van Niekerk & Terblanché-Greeff, 2019). The concept of anticipatory disaster governance is based on the idea that disasters are not inevitable, but rather the result of complex interactions between natural hazards, human activities, and social and economic conditions (Birkmann *et al.*, 2021). At its core, anticipatory disaster governance involves the systematic identification and analysis of risks, the

development of proactive policies and strategies, and the implementation of actions to reduce vulnerability and increase resilience (Tierney, 2019). Anticipatory disaster governance requires collaboration among different sectors, including government agencies, private sector organisations, civil society groups, and individuals, to ensure that all stakeholders are involved in the process of disaster risk management (Tierney, 2012).

One of the key principles of anticipatory disaster governance is the use of early warning systems (EWSs) and advanced technologies to detect and monitor potential disasters (Marchezini *et al.*, 2018). For example, scientists can use weather forecasting, seismic monitoring, and other tools to predict the likelihood and severity of natural hazards such as floods, earthquakes, or hurricanes (Woo, 2019). This information can then be used to develop contingency plans, mobilise emergency resources, and evacuate vulnerable populations before disasters occur (Paton & Johnston, 2017). Another important aspect of anticipatory disaster governance is the emphasis on community participation and empowerment (Aldrich & Meyer, 2015). Community participation and empowerment involves engaging local communities in the process of disaster risk management and ensuring that they have the knowledge, skills, and resources necessary to prepare for and respond to disasters (Twigg, 2015). This may include providing training on emergency preparedness, establishing community-based EWSs, and creating local disaster response committees (Shaw *et al.*, 2016).

Anticipatory disaster governance also recognises the importance of addressing the underlying social, economic, and political factors that contribute to vulnerability and increase the likelihood of disasters (Kelman *et al.*, 2015). Addressing these underlying factors may involve addressing issues such as poverty, inequality, and environmental degradation, as well as promoting sustainable development practices that reduce the risks of disasters (Pelling & Garschagen, 2019). In anticipatory disaster governance, the use of GIS as a decision support tool becomes very important as it assists in providing a visual representation of various drivers of disaster vulnerability and locations of hazard. The use of GIS improves anticipation capacity and gives greater insight into where disasters could strike (Tomaszewski, 2020).

Anticipatory action for disaster risk management in Africa is exemplified by the forecast-based financing (FbF) projects implemented by the Red Cross Red Crescent Movement in various African countries. These projects aim to use weather forecasts and risk assessments to predict the likelihood and potential impact of natural hazards, such as floods and droughts (Coughlan de Perez *et al.*, 2016). When the forecasts indicate a high probability of a hazardous event, pre-defined early action protocols are activated, triggering the release of funds for the implementation of preventive measures (Jjemba *et al.*, 2018).

In Uganda, the FbF system successfully anticipated the risk of flooding in the Teso sub-region in 2015. As a result, funds were released to the Uganda Red Cross Society. They took various anticipatory actions, such as the distribution of water purification tablets, the provision of temporary latrines, and the deployment of volunteers to support affected communities (Jjemba *et al.*, 2018). These measures helped to mitigate the impact of the floods, reducing the risk of waterborne diseases and other negative consequences (Jjemba *et al.*, 2018).

The successful implementation of FbF projects in various African countries showcases the potential for anticipatory action to mitigate the effects of disasters on vulnerable populations in Africa. By integrating scientific forecasting with pre-planned early action protocols and dedicated funding, the Red Cross Red Crescent Movement and its partners have demonstrated the effectiveness of proactive approaches to disaster risk management (Wilkinson *et al.*, 2018).

#### **2.2.6.5 Anticipatory risk management**

Anticipatory risk management has been applied in various contexts, including environmental risk management, financial risk management, and public health (Berrang-Ford *et al.*, 2011; Mikes, 2011; Oppenheim *et al.*, 2019). It focuses on anticipating and proactively addressing potential risks before they become actualised (Ogiela & Ogiela, 2014). Anticipatory risk management recognises that traditional risk management, which typically involves reacting to risks once they have already occurred, may not be sufficient in complex and uncertain environments, such as climate change (Haasnoot *et al.*, 2013). It involves identifying and assessing potential future risks and developing strategies to mitigate or adapt to them before they occur (Blaikie *et al.*, 2004). Anticipatory risk management also involves monitoring for changes and adapting strategies as needed (Pelling, 2010). It typically involves a combination of quantitative and qualitative risk assessment methods, scenario planning, and stakeholder engagement to ensure that potential risks are identified, and strategies are developed with input from relevant stakeholders (Furlanetto & Poli, 2019; Mahmoud *et al.*, 2009). The goal is to develop flexible strategies that can be adapted as the future unfolds and new information becomes available (Amer *et al.*, 2013). In anticipatory risk management, the use of GIS as a decision support tool is important as it aids in providing a visual representation of various factors contributing to risk vulnerability and the spatial distribution of potential hazards. The integration of GIS enhances the capacity to anticipate and proactively manage risks, providing valuable insights into areas that require targeted risk mitigation measures (Aye *et al.*, 2015).

Examples of anticipatory risk management can be found in various contexts. In the context of environmental risk management, anticipatory risk management has been used to anticipate and address risks associated with climate change, such as sea level rise and extreme weather events

(Bauer *et al.*, 2012). One specific South African initiative in the context of environmental risk management is the Working for Water (WfW) programme. The programme was launched by the South African government in 1995 to address the environmental risks associated with invasive alien plant species, particularly in water catchment areas (Ntshotsho *et al.*, 2015). AG is reflected in the WfW programme's proactive approach, aiming to prevent and manage potential risks rather than simply reacting to them after they have caused significant damage.

In the financial sector, anticipatory risk management has been used to anticipate and address risks associated with market volatility and systemic risks (Borio & Drehmann, 2009). One specific South African example in the context of financial risk management is the establishment of the Financial Sector Conduct Authority (FSCA). The FSCA is the regulatory body responsible for supervising and enforcing financial market conduct in South Africa (Godwin, 2017). It plays a role in mitigating financial risks, ensuring market integrity, and protecting the interests of consumers and investors (Millard, 2016). The FSCA proactively monitors and regulates various financial sectors, including banking, insurance, pensions, and investments (Sibanda & Sibanda, 2016). The proactive monitoring, risk identification, and enforcement actions undertaken by bodies like the FSCA contribute to a more resilient and stable financial system while protecting the interests of consumers and investors (Osinski *et al.*, 2013).

In the context of public health, anticipatory risk management has been used to anticipate and address risks associated with emerging infectious diseases, such as Ebola (Sands *et al.*, 2016). A South African example in the context of health risk management is the National Institute for Communicable Diseases (NICD). The NICD is a public health institution that plays a vital role in anticipating, detecting, and responding to communicable diseases and other health risks in South Africa (Blumberg *et al.*, 2020).

Now that five prominent contexts of AG application have been discussed, a more complete picture emerged of how AG is implemented in various fields of study. However, identifying the context of AG application is only one first step in gaining a holistic and complete understanding of the complex concept of AG. To understand AG completely, it is also important to have knowledge of the different approaches and strategies AG can use. This forms the basis for the next section of the chapter. There is a clear distinction between the context of AG application and the approaches to AG. The contexts of AG application refer to specific domains of application or fields of study, while the approaches to AG represent different strategies and mindsets for engaging with the future. The approaches to AG aim to address future challenges by considering different aspects such as risk reduction, adaptability, societal participation, critical thinking, and political implications.

### 2.2.7 Approaches to anticipatory governance

This section relies on the work by Muiderman *et al.* (2020) to provide four approaches to AG from the perspective of mitigating climate change, because mitigating climate change has a direct correlation with reducing the effects of disasters (Mora *et al.*, 2018). Muiderman *et al.* (2020) were able to identify four approaches to AG by using three criteria, i.e., considering the different ways of thinking about the future, actions taken in the present, and desired outcomes. In analysing the different ways of thinking about the future, Muiderman *et al.* (2020) examined assumptions about how the future can be understood and managed. They identified four ways in which the future is conceptualised and engaged in the literature: assessing probable and improbable futures, contending with multiple plausible futures, imagining diverse pluralistic futures, and scrutinising the performative potential of future imaginaries. In considering actions taken in the present, Muiderman *et al.* (2020) identified four categories of present-day actions based on diverse conceptions of the future: formal planning and strategy development, building broad-based societal preparedness and capacities, mobilising diverse actors, and interrogating discursive and material effects in the present. Lastly, in terms of the desired outcomes, Muiderman *et al.* (2020) identified four ideal-typical goals of using AG: to mitigate or reduce future risk, to reflexively navigate diverse uncertain futures, to imagine and co-create new futures, and to shed light on the political implications in the present of speculative future imaginaries. Figure 2.4 displays the four approaches along an x-axis representing the different perspectives on future concepts and a y-axis that illustrates the range of viewpoints on the consequences for present actions. These are elaborated on below.

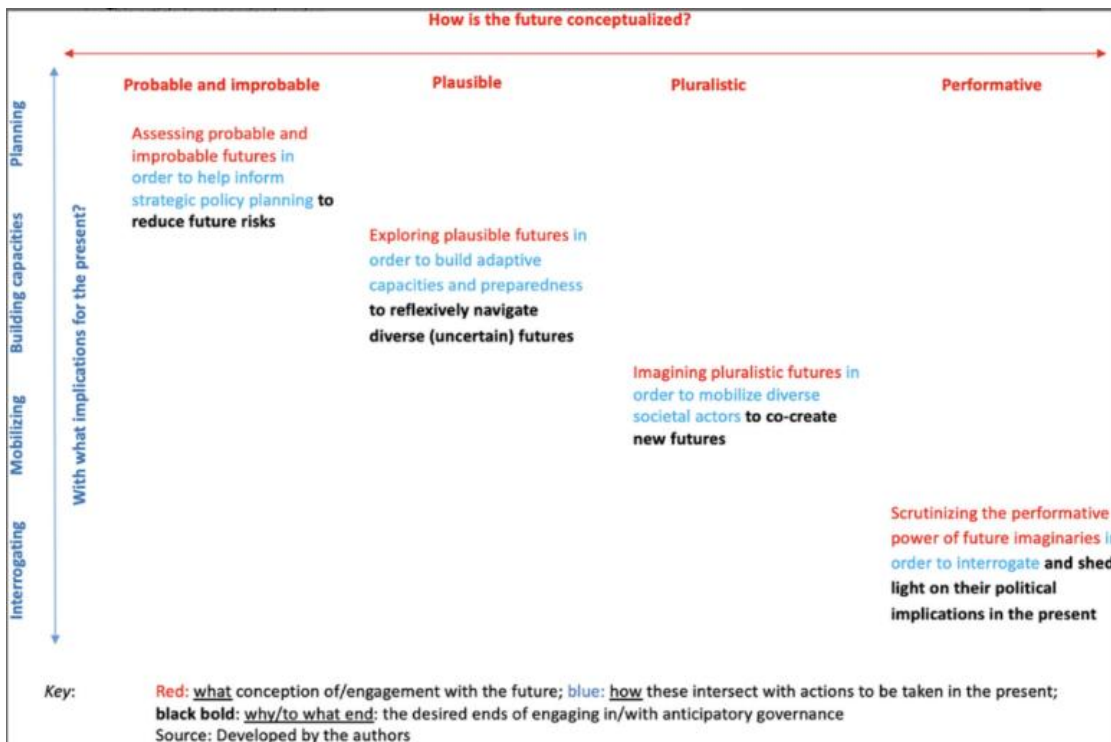


Figure 2.4: Approaches to anticipatory governance (Muiderman *et al.*, 2020)

#### 2.2.7.1 Approach 1: Probable futures, strategic planning, and risk reduction

The first approach to AG evaluates likely and unlikely futures and focuses on present-day strategic planning with the goal of reducing future risks (Muiderman *et al.*, 2020). This can be seen in the public policy and planning literature that specifically includes the concept of AG, as well as in some futurist studies that are probabilistic in nature (Muiderman *et al.*, 2020). While both this approach and the second approach recognise that futures are complex and uncertain, advocates of Approach 1 primarily contend that future risks can be prevented and future opportunities can be constructed (Muiderman *et al.*, 2020).

Thinking about the future, i.e., actively thinking about and identifying and evaluating the likelihood of different future scenarios makes up a major part of the first approach to AG (Muiderman *et al.*, 2020). This approach assumes that the risks and uncertainties of the future can be partly understood and managed by reducing scientific uncertainty and analysing past patterns to explore future trends and their probabilities (Börjeson *et al.*, 2006; Cuhls, 2003, as cited in Muiderman *et al.*, 2020). Probable futures are identified during this analysis, while the exploration of improbable or low-likelihood futures is also important to detect early warnings of high-impact contingencies. The goal of this approach is to develop knowledge infrastructures that can help society better prepare for and respond to potential future challenges (Fuerth, 2009; Fuerth & Faber, 2013, as cited in Muiderman *et al.*, 2020).



The actions taken in the present when using the first approach to AG leads to the prioritisation of "mission-oriented" policy action in the present (Fuerth & Faber, 2013, as cited in Muiderman *et al.*, 2020). This is achieved by analysing the policy consequences of futures with different probabilities, allowing scientists, engineers, and policymakers to strategically prioritise and plan for the future, in the present (Fuerth & Faber, 2013; Stockdale, 2013, as cited in Muiderman *et al.*, 2020). The goal is to pre-empt future threats and protect long-term societal interests and future investments (Boston, 2017, as cited in Muiderman *et al.*, 2020). AG is seen as improving the capacity of governments to organise planning and action by mobilising their full capacities, detecting errors and propagating successes (Fuerth, 2009, as cited in Muiderman *et al.*, 2020). This approach assumes that the future contains reducible risks that can be addressed through improved knowledge infrastructures and strategic planning processes (Muiderman *et al.*, 2020).

The goal or desired outcome of the first approach is to proactively reduce future risks by designing policies that avoid high-risk scenarios, anticipate potential challenges, and create a favourable future (Kuzma *et al.*, 2013; Cuhls, 2003; Fuerth, 2009; Fuerth & Faber, 2013, as cited in Muiderman *et al.*, 2020). Expert-driven strategic planning can assist in achieving this desired future by reducing risks and seizing opportunities (Muiderman *et al.*, 2020).

#### **2.2.7.2 Approach 2: Plausible futures, enhanced preparedness, and navigating uncertainty**

The second approach to AG involves considering multiple possible futures and aims to increase readiness and develop capabilities in the present to be able to adapt to various unpredictable futures (Muiderman *et al.*, 2020). This approach to AG can be found in discussions on responsible research and innovation and in some aspects of climate policy and governance, as well as in the literature of interdisciplinary transitions and transformations that focus on anticipation (Muiderman *et al.*, 2020). Key themes in this approach include the future environmental and social effects of climate change and the governance of new technologies like nanotechnology, biotechnology, or geoengineering (Douglas & Stemmerding, 2014; Fonseca & Pereira, 2014, as cited in Muiderman *et al.*, 2020).

The second approach acknowledges that there are fundamental uncertainties in predicting and thinking about the future that cannot be simplified or narrowed down to one single outcome (Guston, 2014; Michelson, 2016, as cited in Muiderman *et al.*, 2020). As a result, there are numerous possible future scenarios that are all reasonable and cannot be ranked in terms of likelihood (Muiderman *et al.*, 2020). Recognising the subjective nature of plausibility and the fact that different individuals and groups may have different perspectives, it is essential to engage in extensive discussion and consideration to envision the potential futures (Ramírez & Selin, 2014,

as cited in Muiderman *et al.*, 2020). This approach emphasises the need for broad deliberation to explore multiple plausible futures (Muiderman *et al.*, 2020).

The second approach states that in order to engage with the possibility of multiple plausible future outcomes, it is necessary to develop adaptive capacities and preparedness in the present to navigate diverse future trajectories (Muiderman *et al.*, 2020). This preparation should involve a range of actors engaging in reflexive modes of future-making and decision making based on future scenarios (Guston, 2014; Sadowski & Guston, 2016, as cited in Muiderman *et al.*, 2020). For instance, Guston (2014, as cited in Muiderman *et al.*, 2020) emphasises the importance of reflexivity in considering technological progress, anticipating contingencies and disruptions, and preparing for them. It is important to bring future stakes into decision-making conversations that include scientists, engineers, policymakers, and the general public (Davies & Selin, 2012; Wiek *et al.*, 2013, as cited by Muiderman *et al.*, 2020). Upstream public engagement is essential in this approach (Fuller, 2009; Macnaghten, 2009; Macnaghten *et al.*, 2014, as cited in Muiderman *et al.*, 2020) to incorporate the concerns and hopes of the public and support socially robust technological development or climate adaptation planning (Lister *et al.*, 2015; Nykvist *et al.*, 2017; Serrao-Neumann *et al.*, 2013, as cited in Muiderman *et al.*, 2020). Anticipatory methods are used to exchange knowledge between experts and lay people, and anticipation is more about practicing or exercising capacity in a logically, spatially, or temporally prior way than predicting the future (Guston, 2014, as cited in Muiderman *et al.*, 2020).

While the first approach of AG aims to minimise future risks, the ultimate aim of the second approach is to prioritise preparedness to adjust to technological innovation and socio-ecological changes, with the goal of navigating uncertain futures automatically (Muiderman *et al.*, 2020).

### **2.2.7.3 Approach 3: Pluralistic futures, societal mobilisation and co-creating alternatives**

The third approach to AG recognises the diverse and subjective nature of futures and focuses on imagining multiple possibilities to engage and mobilise different societal actors towards co-creating the desired future (Muiderman *et al.*, 2020). This approach draws on the field of futures studies and the perspectives of sustainability sciences and emphasises the importance of collective imagination in shaping and transforming the future (Muiderman *et al.*, 2020).

The third approach shares similarities with the second approach when thinking about the future, in that it also acknowledges that the future is uncertain and unpredictable with multiple possible outcomes (Muiderman *et al.*, 2020). However, it takes a more transformational stance by challenging the limited perspectives offered by probability-based and plausibility-based concepts of the future that are restricted to present circumstances (Muiderman *et al.*, 2020). For instance,

Ramírez and Selin (2014, as cited in Muiderman *et al.*, 2020) suggest that exploring potential future scenarios should not be restricted by the plausibility of current circumstances. Since knowledge about the future is shaped by interactions and interpretations of the world, different societal views of the future reflect fundamentally diverse future scenarios (Patterson *et al.*, 2017; Robinson & Herbert, 2004; Zehfuss, 2002, as cited in Muiderman *et al.*, 2020). Thus, Vervoort *et al.* (2015, as cited in Muiderman *et al.*, 2020) link the fundamental diversity of future scenarios to a variety of societal presents and pasts.

According to Muiderman *et al.* (2020), the third approach rejects the present-future duality, and therefore expresses a postmodern ontology that prioritises interaction between multiple presents and future scenarios that can be co-created and mobilised through collective action taken in the present. This perspective emphasises prioritising the development of pluralistic and actionable pathways for change, which can bring together and mobilise societal actors in novel configurations (Swart *et al.*, 2004, as cited in Muiderman *et al.*, 2020). To ensure social robustness under various future conditions, all assumptions for change processes can be investigated and all action trajectories can be tested (Muiderman *et al.*, 2020). Rossel (2010), as cited in Muiderman *et al.* (2020), further clarifies that "robust" does not equate to "true" or "definitively ascertained," but rather refers to pathways that are "recognised, shaped, used and perceived as relevant by a variety of social constituencies," instead of only by one expert or interest group. The collective imagination of new and more sustainable futures is considered an important first step to realising and achieving alternative futures (Hajer & Pelzer, 2018; Hajer & Versteeg, 2019, as cited in Muiderman *et al.*, 2020). One way to accomplish this is by bringing societal actors together to imagine new futures through new pathways for change, which can be acted upon in the present (Robinson *et al.*, 2011, as cited in Muiderman *et al.*, 2020). Anticipation in this approach involves mobilising stakeholders to imagine and bring desirable futures to life. It entails co-creating futures through social processes, while also considering which future challenges to engage with (Vervoort *et al.*, 2015, as cited in Muiderman *et al.*, 2020).

Regarding the desired outcomes of this approach, the third approach emphasises the strong link between futures, anticipation, and sustainability transitions (Hajer & Versteeg, 2019; Hebinck *et al.*, 2018, as cited in Muiderman *et al.*, 2020). It focuses on exploring anticipation in settings where various societal actors collaborate to facilitate fundamental change (Bennett *et al.*, 2016, as cited by Muiderman *et al.*, 2020), with the ultimate goal of co-creating more transformative futures (Bendor, 2018; Hajer & Pelzer, 2018; Robinson & Herbert, 2004; Sova *et al.*, 2015, as cited by Muiderman *et al.*, 2020).

#### **2.2.7.4 Approach 4: Performative futures, critical interrogation, and political implications**

The fourth approach to AG focuses on the impact that people's thoughts and ideas about the future have on current decision making and governance (Muiderman *et al.*, 2020). It looks at how the future is imagined and the role it plays in shaping present-day choices and governance (Muiderman *et al.*, 2020). This approach is mainly discussed in science and technology studies, sociology of the future, and critical environmental governance (Muiderman *et al.*, 2020). There are similarities with the first two approaches, including the belief that the future is uncertain and the need for wider public involvement in decision making (Muiderman *et al.*, 2020). However, the main emphasis of this approach is to examine the influence and political implications of engaging with and imagining the future (Muiderman *et al.*, 2020).

When thinking about the future, the fourth approach to AG acknowledges that the future is characterised by insurmountable uncertainties and unknowns (Muiderman *et al.*, 2020). Any attempt to simplify it and to make it more manageable inevitably involves individual perspectives and biases (Muiderman *et al.*, 2020). This approach views all statements about the future as political interventions, as projections or "constructions of the future" (Jasanoff & Kim, 2015, as cited in Muiderman *et al.*, 2020) that have actual effects in the present (Anderson, 2010; Selin, 2008, as cited in Muiderman *et al.*, 2020). All statements about the future, even those developed through participatory processes, can shape present-day choices and bring about specific futures (Muiderman *et al.*, 2020). This can manifest in various ways, such as limiting future climate mitigation and adaptation options to the practicality of current systems (Pulver & VanDeveer, 2009; Sarkki *et al.*, 2017; Sova *et al.*, 2015, as cited by Muiderman *et al.*, 2020), or influencing how novel climate engineering technologies are perceived and governed in the present (Gupta & Möller, 2018, as cited in Muiderman *et al.*, 2020). These future projections can encompass both idealistic and negative visions that create distorted views of social realities and "colonise" the future (Selin, 2007, as cited in Muiderman *et al.*, 2020). For example, portraying "climate emergencies" could legitimise and prioritise the development of socially and politically problematic technological solutions in the present (Bellamy, 2016; Gupta, 2019, as cited in Muiderman *et al.*, 2020).

The actions taken in the present by this approach is primarily concerned with exploring the political and discursive implications of future imaginaries, and how they influence current decision making (Esguerra, 2019, as cited in Muiderman *et al.*, 2020). The focus is on questioning the role of scientific expertise and expert knowledge in shaping the future (Muiderman *et al.*, 2020). For instance, when discussing sustainability, climate engineering, or climate change responses, this

approach questions whether expert-driven visioning is a neutral and objective process (Gupta & Möller, 2018; Hulme, 2010; Low, 2017, as cited in Muiderman *et al.*, 2020). Rather, it suggests that claim-making about the future is a site of negotiation and conflict that should be analysed in terms of its discursive effects on the present (Gupta, 2011, as cited in Muiderman *et al.*, 2020). The emphasis is on understanding how anticipatory practices generate and advance frames or fabrications of the future, and how they exert power over the present (Muiderman *et al.*, 2020). The approach seeks to recognise how making assertions about the future can constrain present-day decisions (Nordmann, 2014, as cited in Muiderman *et al.*, 2020).

The primary objective of this approach is to examine how AG and the critical examination of future visions can affect present circumstances (Muiderman *et al.*, 2020). This includes assessing how future imaginaries may favour or exclude particular policy options, paths, sectors, investments, or the interests of stakeholders (Muiderman *et al.*, 2020). As a result, this approach seeks to shift the focus back to the present and the complex political decisions and trade-offs that need to be addressed in the here and now, rather than in an imaginary future (Nordmann, 2014, as cited in Muiderman *et al.*, 2020).

The important theoretical components of AG were outlined above. The discussion that follows focuses on how AG can specifically help address the problem of this study, namely flood risk. Before delving into how AG can mitigate the effects of flooding, context should be established with respect to how climate change exacerbates flooding. Thus, this discussion first provides context on how climate change affects flooding, and the subsequent section of this chapter explores how AG can help address the effects of climate change.

## **2.2.8 The effect of climate change on flooding**

Climate change has significant effects on flooding, which can have far-reaching consequences for communities, ecosystems, and economies around the world (Alfieri *et al.*, 2018; Kundzewicz *et al.*, 2014; Reidmiller *et al.*, 2017). Some of the ways that climate change affects flooding are discussed below.

### **2.2.8.1 Sea level rise**

Climate change is causing the Earth's average temperature to rise, which causes the polar ice caps to melt and sea levels to rise (Church & White, 2011; Levermann *et al.*, 2013; Nerem *et al.*, 2018). As sea levels rise, coastal areas are more susceptible to storm surges, tidal flooding, and flooding from heavy rainfall (Nicholls & Cazenave, 2010; Vousdoukas *et al.*, 2018). This rise in sea levels exacerbates the risk of flooding in low-lying coastal areas, particularly during extreme

weather events such as hurricanes and typhoons (Marsooli *et al.*, 2019; Woodruff *et al.*, 2013). As global temperatures rise, the volume of water in the ocean increases, leading to a rise in sea levels (Gulev *et al.*, 2023). This is known as thermal expansion, and it is one of the most significant factors contributing to sea level rise (Nerem *et al.*, 2018). The melting of glaciers and ice sheets in Greenland and Antarctica in particular is causing a rise in sea levels (Fox-Kemper *et al.*, 2023). As massive ice formations melt, the water they contain flows into the ocean, raising sea levels and heightening flood risk for coastal communities across the globe (Rignot *et al.*, 2019).

Sea level rise can have significant implications for South Africa, particularly due to South Africa's long coastline and large coastal cities (Dube *et al.*, 2021; Erostate *et al.*, 2020). South Africa's coastal cities, such as Cape Town and Durban, are particularly vulnerable to sea level rise (Dube *et al.*, 2021; Mather & Stretch, 2012). Critical infrastructure, including roads, ports, airports, and residential areas, are at risk of being exposed to flooding and damage. The effects of sea level rise can disrupt transportation networks, economic activities, and human settlements along the coast (Colenbrander & Sowman, 2015).

#### **2.2.8.2 Increased precipitation**

Climate change can result in increased precipitation in some regions, leading to increased runoff and increased risk of flooding (Hirabayashi *et al.*, 2013). This can be due to more frequent and intense rainfall events, as well as changes in the timing and distribution of precipitation (Kundzewicz, 2014; Tabari, 2020). As the planet continues to experience climate change, precipitation is projected to increase in many regions due to the increased concentration of atmospheric water vapor, which is linked to the amount of precipitation through the thermodynamic Clausius-Clapeyron relationship (O'Gorman, 2015). The relationship states that for every degree increase in temperature, the concentration of atmospheric water vapor will increase by 6–7% (Allen & Ingram, 2002; Trenberth *et al.*, 2003; Ingram, 2016). However, regional changes in atmospheric dynamics, such as the expansion of the tropical Hadley circulation towards the poles, can either weaken or strengthen the thermodynamic impact and affect the amplification of extreme precipitation (Scheff & Frierson, 2012; Pfahl *et al.*, 2017; Norris *et al.*, 2019; Li *et al.*, 2019).

It is unclear if South Africa will experience an increase or decrease in precipitation due to climate change. A study by McBride *et al.* (2022) analysed the daily time series of 70 manual rainfall stations in South Africa from 1921 to 2020. The results showed an increase in the probability of receiving significant to extreme daily rainfall events in the latter half of the analysis period for most regions in South Africa. The study highlights the concern of increased rainfall intensity and its potential consequences, such as flooding and damage to agriculture and infrastructure. Another

study by Adeola *et al.* (2022) examined historical observation data over the Olifants River Catchment and future climate change projections. The study found an overall decline in rainfall, and it did not detect significant changes in the distribution of rainfall over time. The results also indicated an increase in temperatures and the expectation of rising surface temperatures in the catchment. A third study by Makungo and Mashinye (2022) investigated long-term trends and changes in rainfall in a semi-arid catchment in South Africa. While the study found dominant non-statistically significant decreasing trends for annual and seasonal rainfall magnitude and duration, the study emphasises the need for further studies to understand the interactions between various environmental factors and their influence on rainfall trends.

These studies provide insights into the changing rainfall patterns in South Africa and the potential increase in extreme rainfall events. It is important to note that individual regions in South Africa may experience variations in rainfall changes, and further research is necessary to refine people's understanding of the specific regional effects of climate change on rainfall.

### **2.2.8.3 Changes in precipitation patterns**

Changes in precipitation patterns can result in dry areas becoming drier, and wet areas becoming wetter, leading to increased risk of flooding in some regions (Feng *et al.*, 2019). For example, in some regions, heavy rainfall may be more frequent or intense, leading to flash floods, while in other regions, drought conditions may lead to decreased runoff and increased risk of riverine and coastal flooding (Trenberth, 2011).

The changes in precipitation patterns are not uniform across all regions, as different factors can interact to affect the intensity of precipitation (Tabari *et al.*, 2020). The rate at which extreme precipitation changes with land temperature is not constant, and in some regions a negative correlation has been observed (Sun *et al.*, 2021). This may be due to limited moisture availability or dry surface conditions, which can counteract the effect of increased precipitation (Panthou *et al.*, 2014). However, in wet regions, increased atmospheric moisture can amplify the effects of extreme precipitation (Allen & Ingram, 2002). Studies have shown that, on average, the maximum annual precipitation over both dry and wet regions is likely to increase (Westra *et al.*, 2013).

Changes in precipitation patterns can have significant effects on South Africa. As South Africa already faces water scarcity issues, changes in precipitation patterns will exacerbate this problem (Kusangaya *et al.*, 2014). Reduced rainfall or shifting rainfall patterns may result in decreased water availability for agriculture, industry, and households. This can lead to water stress, reduced crop yields, and potential conflicts over water resources (Ziervogel *et al.*, 2014). Conversely,

heavy rainfall and the increased frequency of extreme weather events can result in flooding, damaging crops and infrastructure (Abiodun *et al.*, 2019).

#### **2.2.8.4 Intensity and frequency of extreme weather events**

Climate change has a significant impact on extreme weather events, such as hurricanes, heatwaves, droughts, and floods (Stott *et al.*, 2016). Warmer temperatures result in more evaporation, increasing the amount of moisture available in the atmosphere, which can lead to more intense and frequent extreme weather events (Coumou & Rahmstorf, 2012; Douville *et al.*, 2023). Research shows that human activities, particularly the emission of greenhouse gases, have contributed to the observed increase in global temperatures, and thus have contributed to the increased frequency and intensity of extreme weather events (Eyring *et al.*, 2023).

The increasing frequency and severity of droughts can lead to water scarcity in many regions of South Africa. This can result in reduced water availability for agriculture, industry, and domestic use, affecting food production, economic activities, and livelihoods (Muller, 2007; Baudoin *et al.*, 2017; Nhamo *et al.*, 2016). Intense rainfall events and rising sea levels, on the other hand, can lead to increased flooding and coastal erosion. This can result in infrastructure damage, loss of property, displacement of communities, and disruptions to transportation and communication networks (Fitchett & Grab, 2014; Gulev *et al.*, 2023).

The discussion suggests that climate change will continue to have an impact on flooding events, in South Africa and across the globe. It is therefore important to discuss how AG can potentially help mitigate climate change, and as a result, have a mitigating effect on possible flooding events.

#### **2.2.9 The application of anticipatory governance in addressing complex problems: The case of mitigating climate change**

AG can help mitigate the effects of climate change by taking a proactive approach to addressing the challenges of a changing climate (Muiderman *et al.*, 2020; Pelling, 2010; Quay, 2010). The aim of AG is to identify potential risks and vulnerabilities, as well as develop strategies to address them (Jakku *et al.*, 2016; Quay, 2010; Wiek *et al.*, 2012). One of the strategies to address potential risks and vulnerabilities in the context of climate change, was developed by Robert Quay. Quay (2010) views AG in the context of preparing for climate change adaptation as a three-part process (see Figure 2.5). The steps are: (1) anticipating and forecasting, (2) establishing flexible adaptation strategies, and (3) monitoring and implementation.



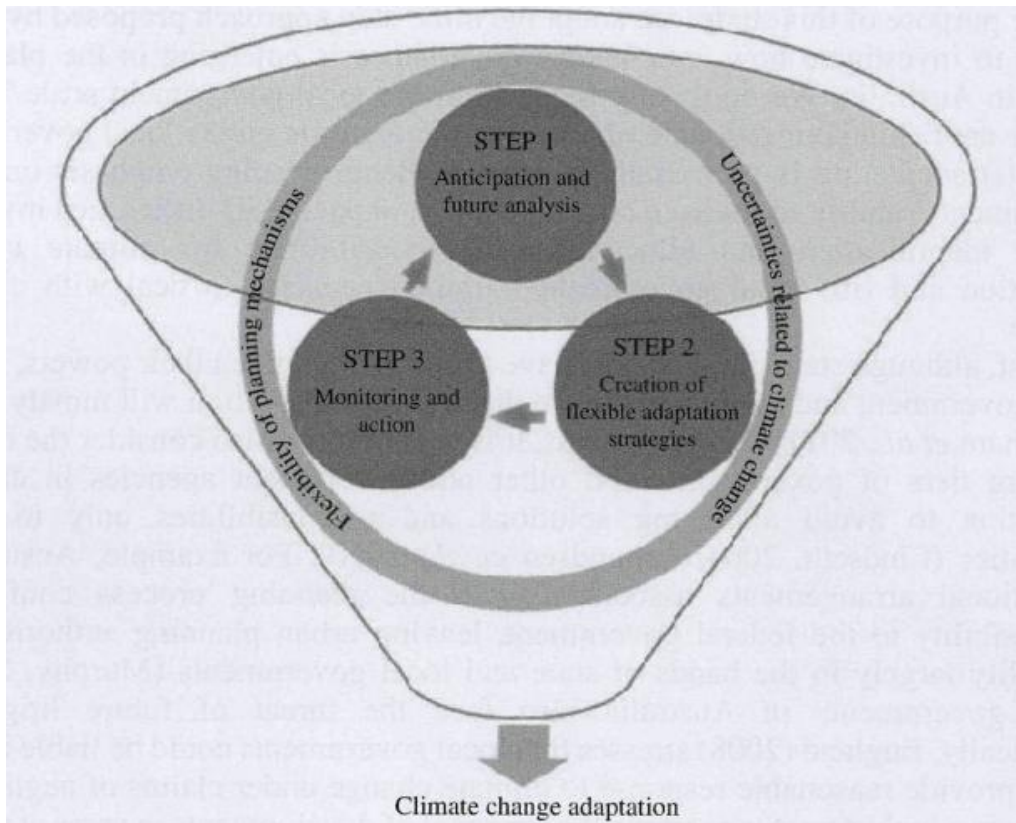


**Figure 2.5: The steps to mitigate climate change (Serrao-Neumann *et al.*, 2013)**

### **2.2.9.1 Step 1: Anticipating and forecasting**

The first step acknowledges that some aspects of the future are uncertain and that any forecast or prediction represents only one of many potential futures (Quay, 2010). Early scenario planning literature recognised the limitations of forecasting and suggested using scenarios to explore future uncertainties (Berger, 1964; Kahn, 1965; Kahn & Wiener, 1967; Ringland, 1998, 2002, 2006; Schwartz, 1991; van der Heijden, 1996, 2000, 2005; Wack, 1985a, 1985b, as cited in Quay, 2010). Advanced scenario planning methods have been proposed and used to consider numerous scenarios to cover a broad range of potential futures, especially when there is high uncertainty (Ahmed *et al.*, 2003; Bankes, 1993; Bankes *et al.*, 2003; Burke & Ewan, 1999; Menke, 1979; Quay, 1999, as cited in Quay, 2010). AG, therefore, relies on analysing and developing a range of potential scenarios instead of relying on a single forecast (Quay, 2010). This analysis involves using aggregated averages, sensitivity analyses, risk assessment, identifying unacceptable scenarios, worst-case scenarios, and assessing the shared and differing effects of scenarios (Quay, 2010).

An example of the first step being implemented in practice to help mitigate climate change is through climate modelling. Climate modelling is a complex scientific process that involves creating

computer simulations of the Earth's climate system (Flato *et al.*, 2014). These climate models are used to understand the Earth's climate and to make predictions about future changes (Hausfather & Peters, 2020). The climate models consider a wide range of factors that affect the climate, including greenhouse gas emissions, solar radiation, ocean currents, and atmospheric conditions (Griffies *et al.*, 2016; Heinze *et al.*, 2019; Nisbet *et al.*, 2019; Matthes *et al.*, 2017). The climate models also incorporate data from historical climate patterns, such as temperature and rainfall records, to help make more accurate predictions about future climate conditions (Knutti & Sedláček, 2013).

Climate models are developed using a combination of physical, chemical, and mathematical equations that represent the interactions between the atmosphere, oceans, land, and ice (Taylor *et al.*, 2012). These equations are then programmed into computer models that can run simulations of the Earth's climate system (Eyring *et al.*, 2016). Climate models can be used to make a wide range of predictions, including predicting future changes in temperature and precipitation patterns, changes in sea levels and ocean acidity, effects on agriculture and food production, as well as changes in the frequency and severity of extreme weather events, such as hurricanes, droughts, and floods (Betts *et al.*, 2018; Bopp *et al.*, 2013; Chen *et al.*, 2023; Seneviratne *et al.*, 2012). Decision makers can use climate modelling data to make informed decisions about how to mitigate and adapt to the impacts of climate change (Nissan *et al.*, 2019). For example, decision makers may use the data to set targets for reducing greenhouse gas emissions, to design infrastructure that can withstand extreme weather events, or to plan for future water resource management (Koutroulis *et al.*, 2018; Pregnoiato *et al.*, 2017; Rogelj *et al.*, 2019). Overall, climate modelling is a critical tool in this first step to mitigate climate change, as climate modelling helps decision makers understand and forecast the influence of human activities on the Earth's climate system and develop strategies to address the impacts.

#### **2.2.9.2 Step 2: Establishing flexible adaptation strategies**

After analysing a range of possible future scenarios, the second step ensures that strategies are developed to adapt to one or more of these anticipated futures. Hallegatte (2009, as cited in Quay, 2010) and Easterling *et al.* (2004, as cited in Quay, 2010) suggest creating adaptable actions that can be modularised and implemented as needed, which allows for spreading out costs over time and reducing losses if investments must be abandoned. Strategies for adapting to future uncertainties can include preserving future options, developing contingency plans to respond to specific scenarios, and implementing no-regrets or worst-case strategies (Quay, 2010). Robust actions are those that can work effectively across many potential futures, based on acceptable levels of risk (Quay, 2010).

An example of the implementation of the second step in practice to help mitigate climate change is through coastal adaptation. Coastal adaptation is an important strategy to mitigate the impacts of sea level rise and storm surges due to climate change (Haasnoot *et al.*, 2021). In many coastal regions, rising sea levels and increased frequency and intensity of storms are posing a significant threat to infrastructure and communities (Vousdoukas *et al.*, 2020). Flexible adaptation strategies are essential to reduce the vulnerability of coastal regions to these threats (Hinkel *et al.*, 2018). Building coastal defences is a common approach to coastal adaptation. Sea walls, dikes, and other engineered structures can provide protection against storm surges and rising sea levels (Lenk *et al.*, 2017). These structures can be designed to be flexible and adaptable, allowing for changes in sea level and other conditions over time (Temmerman *et al.*, 2013). Natural defences such as dunes and wetlands can also be used to reduce the risk of flooding and erosion in coastal areas. These habitats provide important ecosystem services such as buffering storm surges and protecting against erosion (Morris *et al.*, 2018). The habitats can be restored or enhanced to provide greater protection against the consequences of climate change (Temmerman *et al.*, 2013). Elevating buildings is another strategy to reduce the risk of flood damage in coastal areas (Highfield *et al.*, 2014). Buildings can be designed to be elevated above the flood zone, reducing the risk of damage from storm surges and rising sea levels. Elevated buildings are especially important in areas where sea level rise is expected to be significant over the coming decades (Hendricks *et al.*, 2018).

In addition to these adaptation measures, there are other strategies that can be employed to reduce the risk of coastal flooding and erosion. These include improving land use planning to reduce development in high-risk areas, promoting the use of green infrastructure such as rain gardens and bioswales, and developing EWSs to provide advance notice of approaching storms and floods (Cools *et al.*, 2016; Sutanta *et al.*, 2013; Vogel *et al.*, 2015).

From the above-mentioned examples it is clear that coastal adaptation is an important strategy in this second step to reduce the impacts of climate change by using establishing flexible adaptation measures. By employing a range of flexible coastal adaptation measures, decision makers can help reduce the risk of damage from storm surges, sea level rise, and other climate-related threats, and promote more resilient and sustainable coastal communities.

### **2.2.9.3 Step 3: Monitoring and implementing**

To achieve successful adaptation, the third step insists that monitoring and response to change must be ongoing (Bankston & Key, 2006; Camacho, 2009; Chi, 2008; Fuerth, 2009, as cited in Quay, 2010). Since climate change will occur gradually over the next century, decisions about and implementation of adaptation actions will be spread over a long period of time (Quay, 2010).

Therefore, it is important to monitor indicators of change regularly and to make decisions about implementing anticipated adaptation strategies based on actual trends (Quay, 2010).

An example of the third step in practice is the monitoring of greenhouse emissions. Monitoring greenhouse gas emissions is a critical step in identifying sources of emissions and tracking progress in reducing them (Friedlingstein *et al.*, 2020). There are a variety of methods for monitoring emissions, including direct measurement of emissions from sources such as power plants, factories, and vehicles, as well as indirect methods such as satellite observations of atmospheric concentrations of greenhouse gases (Reuter *et al.*, 2019; Yver Kwok *et al.*, 2015). Governments play a key role in monitoring emissions by setting regulations and standards for emissions reporting and implementing monitoring programmes. For example, the US Environmental Protection Agency (EPA) requires large industrial facilities to report their greenhouse gas emissions annually (Matisoff, 2013). The European Union Emissions Trading System (EU ETS) is a cap-and-trade system that requires companies to report their emissions and purchase allowances to cover their emissions (Bayer & Aklin, 2020).

Companies can monitor their own emissions to identify opportunities for reducing emissions and to comply with regulations (Tang & Demeritt, 2018). Many companies have implemented sustainability reporting and carbon accounting to track their emissions and set reduction targets (Qian & Schaltegger, 2017). This information about the companies' emissions can also be used to inform investors and stakeholders about a company's environmental performance (Flammer, 2013).

Individuals can also monitor their own emissions by tracking their energy use and transportation habits (Büchs & Schnepf, 2013). Many individuals use carbon calculators to estimate their carbon footprint and identify areas for reducing their emissions (Mulrow *et al.*, 2019). Regular monitoring of emissions is important because it allows people to identify which sectors and sources contribute the most to greenhouse gas emissions (Pandey *et al.*, 2011). This information on people's emissions can be used to inform policy decisions and investment in technologies and practices that can reduce emissions (Lamb *et al.*, 2021). Regular monitoring of people's emissions allows decision makers to track progress in reducing emissions over time and evaluate the effectiveness of policies and programmes aimed at mitigating climate change (Rogelj *et al.*, 2016).

While AG can indirectly help with flooding by mitigating climate change, it can also have a more direct impact on flood management and prevention. The discussion that follows focuses on how AG helps to mitigate flooding in a more direct manner.

### 2.2.10 How anticipatory governance can help mitigate the effects of flooding

In the context of flooding, AG can play a critical role in reducing the risks and impacts associated with this type of natural disaster. This is because AG, in an anticipatory capacity, can improve preparedness, enhance resilience, and help mitigate the consequences of disasters. (Cools *et al.*, 2016; Keating *et al.*, 2017; Meerow & Mitchell, 2017). Improving preparedness for flooding is critical to reduce the risks and impacts associated with this natural disaster (Jongman, 2018). One approach to enhancing preparedness is the implementation of AG, which involves proactive decision making and planning based on future scenarios (Fuerth & Faber, 2012). This section explores the intersection of AG and preparedness in the context of flooding, emphasising the importance of proper urban planning, robust EWSs, resilient infrastructure, and community participation.

Effective urban planning plays a vital role in flood mitigation by designing and constructing cities in a manner that reduces flood risk (Liao *et al.*, 2016). Effective urban planning for flooding involves implementing zoning regulations, land-use planning, and stormwater management systems (D'Ambrosio *et al.*, 2021; Der Sarkissian *et al.*, 2022; Porse, 2013). By incorporating measures such as green infrastructure, permeable surfaces, and adequate drainage systems, cities can better absorb and manage rainfall, thereby minimising the risk of flooding (Dou *et al.*, 2015; Reu Junqueira *et al.*, 2021; Zhou *et al.*, 2012). AG in urban planning includes considering future climate scenarios and integrating resilience measures into city development plans (De Barbieri, 2019)

Another key aspect of improving flooding preparedness is the establishment of robust EWSs (Kreibich *et al.*, 2017). These systems rely on real-time monitoring of weather patterns, river levels, and rainfall intensity (Krzyszhanovskaya *et al.*, 2011). By detecting potential flood events in advance, authorities can issue timely alerts and evacuation orders, allowing people to move to safer areas (Di Baldassarre *et al.*, 2013). AG can potentially ensure the development and maintenance of effective EWS by establishing clear protocols for communication and evacuation procedures (Béné *et al.*, 2012; Gupta *et al.*, 2010; Pelling & Dill, 2010).

Investing in infrastructure that can withstand and manage flooding is important for enhancing flood preparedness (Aerts *et al.*, 2014). This involves constructing and maintaining dams, levees, flood barriers, and stormwater management systems (Lempérière, 2017; Lendering *et al.*, 2016; Temmerman *et al.*, 2013; Zischg *et al.*, 2018). AG can play a role in long-term planning of resilient infrastructure, as it considers future climate projections, engages with stakeholders, and makes informed decisions to possibly develop infrastructure that can adapt to changing flood risks (Quay, 2010).

Active community participation and awareness are also essential in reducing the risks and effects of flooding (Nugraheni & Suyatna, 2020). AG emphasises the importance of engaging communities, and this could entail including communities in flood risk management processes (Ramos, 2014). Community engagement involves educating residents about flood risks, promoting preparedness measures, and facilitating community-based initiatives such as local flood response teams and neighbourhood flood plans (Grothmann & Patt, 2005; Samuels, 2012; Tyler *et al.*, 2019). By involving communities, decision makers can enhance preparedness, response, and recovery efforts.

In summary, the intersection of AG and the improvement of preparedness for flooding involves several strategies. Proper urban planning focuses on reducing flood risk through zoning regulations, land-use planning, and stormwater management systems. Robust EWSs enable timely alerts and evacuation orders. Investment in resilient infrastructure ensures long-term planning to withstand and manage flooding. Active community participation and awareness contribute to enhanced preparedness and response. By implementing these approaches, decision makers can reduce the risks and impacts of flooding, ultimately fostering more resilient communities.

Enhancing flood resilience involves a range of strategies and approaches, and AG can play a crucial role in this process. This section discusses the intersection of AG and resilience enhancement in the context of flooding, focusing on the use of nature-based solutions (NbS), multi-level governance and stakeholder engagement, resilience frameworks, and strategic land use planning.

One approach to enhancing resilience is the implementation of NbS (Bush & Doyon, 2019). NbS can use natural elements such as wetlands, green spaces, and forests to mitigate flood risks (Bradshaw *et al.*, 2007; Endter-Wada *et al.*, 2020; Green *et al.*, 2021). This can absorb and slow down water, reduce erosion, and provide additional benefits like improved air quality and biodiversity (Ascenso *et al.*, 2021; Gonzalez-Ollauri, 2022; Oral *et al.*, 2020; Liu *et al.*, 2021). AG can potentially promote the integration of NbS in urban planning and flood management strategies (Albert *et al.*, 2019; Kaufman *et al.*, 2022). The integration of NbS into urban planning and flood management strategies emphasises the interconnectedness of green spaces and understanding the effectiveness and co-benefits of green spaces compared to traditional grey infrastructure solutions (Alves *et al.*, 2018; Lepczyk *et al.*, 2017).

Multi-level governance and active stakeholder engagement are important for enhancing resilience to flooding (Vedeld, *et al.*, 2015, 2016). AG emphasises the involvement of diverse stakeholders, including government agencies, community groups, and private sector entities in decision-making

processes (André *et al.*, 2012). By fostering collaboration, information sharing and participatory approaches, decision makers can enhance flood resilience measures, ensure the effectiveness of strategies, and address the diverse needs and perspectives of stakeholders (Evers *et al.*, 2016; Fekete *et al.*, 2021).

Resilience frameworks provide a conceptual basis for understanding and enhancing resilience in the face of flooding (Bulti *et al.*, 2019; de Bruijn *et al.*, 2022). Examples of such a framework is the Community-Based Resilience Assessment (CoBRA). CoBRA is a framework developed by the UNDP to assess community resilience to different hazards, including floods (Sharifi, 2016). By applying resilience frameworks, decision makers can assess and strengthen the resilience of physical infrastructure and ecological systems to better withstand and recover from flood events (Davis *et al.*, 2023; Talubo *et al.*, 2022). AG can contribute to this process by promoting the integration of resilience frameworks into decision-making processes, facilitating cross-sector collaboration, and encouraging the adoption of adaptive management strategies (Buurman & Babovic, 2016).

Strategic land use planning is also essential for enhancing flood resilience (Der Sarkissian *et al.*, 2022). This involves identifying safer, higher ground for development and avoiding construction in flood-prone areas. AG structures can potentially integrate future flood projections into land use planning decisions, taking potential flood risks into account (Zevenbergen *et al.*, 2008). By regulating construction, promoting resilient design principles, and ensuring that new developments are located in areas less susceptible to flooding, decision makers can enhance resilience to flood events (Rose *et al.*, 2009).

In summary, the intersection of AG and resilience enhancement in the context of flooding involves several key strategies. NbS harnesses the benefits of natural elements to mitigate flood risks. Multi-level governance and stakeholder engagement foster collaboration and inclusivity in decision-making processes. Resilience frameworks provide a basis for assessing and strengthening the resilience of infrastructure and ecological systems. Strategic land use planning considers future flood projections to minimise construction in flood-prone areas. By implementing these approaches, authorities can enhance flood resilience and promote the development of more resilient communities.

Reducing the impact of flooding by mitigating its consequences involves various strategies and approaches, and AG plays a crucial role in this process. This section discusses the intersection of AG and consequence mitigation in the context of flooding, focusing on risk assessment and anticipation, social safety nets, property modifications, and integrated flood management.

A comprehensive understanding of flood risks and their potential consequences is essential for effective flood management (Kreibich *et al.*, 2022). AG can assist in assessing and anticipating these risks through proactive decision making, stakeholder engagement, and the integration of scientific knowledge and technology (Guston, 2014; Sarewitz, 2011). By considering the potential consequences of flooding, decision makers can develop strategies to minimise impacts and protect vulnerable communities (Few, 2003).

Social safety nets can mitigate the consequences of flooding by giving valuable assistance to the people most vulnerable to flooding (Awal, 2013). AG can potentially promote the development of social safety nets that provide support to vulnerable populations during and after a flood event (Tanner *et al.*, 2009). This support can involve measures such as providing food and shelter to those in need, offering employment opportunities to affected individuals, and providing mental health services to those affected by the flood event (Bealt & Mansouri, 2018; Fekete & Sandholz, 2021; Kirchberger, 2017).

Property modifications involve adapting existing structures to reduce their vulnerability to flooding (Sandink & Binns, 2021). Examples of property modifications include raising floor levels, installing flood barriers or flood-resistant materials, and implementing proper drainage systems (Attems *et al.*, 2020; Bhattacharya-Mis & Lamond, 2016; Jiang *et al.*, 2018; Oladokun & Proverbs, 2016). AG can facilitate the adoption of property modification measures by promoting awareness, providing incentives, and supporting the development and enforcement of building codes and regulations that can incorporate flood resilience standards (De Barbieri, 2019; Berten & Kranke, 2022; Guston, 2014).

Integrated flood management refers to a comprehensive approach that considers the entire water basin in flood management that aims to shift from reactive practices to proactive and integrated strategies (Abdi-Dehkordi *et al.*, 2021). Seeing as AG involves coordinated planning, implementation, and evaluation of measures to achieve sustainable development, it can provide a framework for integrating different sectors and stakeholders, and in this manner, it can contribute to flood management (Guston, 2014; Muiderman, 2022).

In summary, the intersection of AG and consequence mitigation in the context of flooding involves several key strategies. AG can support risk assessment and anticipation, the implementation of social safety nets and property modifications. AG can also facilitate the integration of different sectors and stakeholders in integrated flood management. By implementing these approaches, decision makers can reduce the effects of flooding and enhance the resilience of communities.



### 2.2.11 Conclusion

The concept of governance has played a significant role in organising human civilisation, with its various definitions and approaches evolving over time. The governance of South Africa is a prime example of how changes in governance can shape a country's political and economic landscape. In some instances, South Africa's governance of certain problems, e.g., power supply and disasters, is very reactive and not ideally suited to emerging complex environmental problems. For this reason, more anticipatory methods of governance are important. This chapter explored the origins and definitions of AG, along with its implementation and various contexts of application, including anticipatory regulation, innovation governance, climate governance, risk management, and disaster governance. The approaches to AG were also discussed. These theoretical discussions indicated that AG is an important proactive tool to prepare for future challenges and ensure the resilience of societies. The chapter also showed that AG has transcended its theoretical bounds and is already finding practical application and helping to effectively address real-world challenges, such as climate change and flooding, by improving preparedness, resilience and the mitigating capacities of governments, first responders and local communities across the world. As the world continues to grapple with global challenges such as climate change and its consequences, AG will undoubtedly play an increasingly critical role in building a sustainable and resilient future for all by improving the understanding of risk, enhancing management capacity and enabling more flexible prevention measures to be developed for all risks, including flooding. The significance and potential impact of AG cannot be overstated, and further research and implementation of AG will undoubtedly continue to be an essential area of focus in the coming years.

This comprehensive exploration of AG, its theoretical foundations, and practical applications achieves the third research objective of investigating the theoretical tenets of AG and demonstrating its relevance to the management of urban flood risk. The discussion has shown how AG's proactive approach can be particularly beneficial in addressing complex environmental challenges like those faced by the eThekweni Metropolitan Municipality in managing urban flood risks.

GIS, however, can play a valuable role in visually illustrating various AG scenarios, thereby providing decision makers with the information they need to make informed choices about the future. The next section explores the concept of GIS in great depth, with consideration of its uses in AG.

## **2.3 Geographical information systems**

The first part of this literature study explored the origins and conceptualisation of AG, examining its definition, types, and approaches, as well as its potential to address complex problems, including climate change and flood risk mitigation, through direct and indirect means. Building on this foundation, the second part of this literature study takes a look into the role of GIS in AG and the significance of GIS in flood risk management and disaster risk reduction.

As a start, this second part of the literature study defines GIS and provides a historical overview of its evolution, tracing its development from early cartography to the present day. The chapter then explores the different types of elements that are recorded and stored by GIS. Additionally, the chapter analyses the two primary data models used in GIS – raster and vector – and their respective strengths and limitations as they relate to flood risk mapping. This literature study also highlights the potential of GIS in addressing urban disaster risk, also considering the limitations of GIS when addressing urban disaster risk. This literature study then takes a closer look at how GIS is used in flood management, including the importance of GIS in helping flood management and the limitations of GIS with respect to flood management.

Finally, this second part of the literature study explores how GIS can be used as a tool of AG, examining how GIS data can be analysed and applied to anticipate and mitigate the effects of disasters such as floods. By providing an in-depth analysis of the role of GIS in AG and its practical applications in flood management, this literature study aims to contribute to a better understanding of the potential of AG to address complex challenges facing modern society.

### **2.3.1 Defining a geographical information system**

There are multiple definitions of GIS as it is a multi-disciplinary field that involves a wide range of components, including geographic data, hardware, software, people, and processes (Maguire, 1991). As is discussed below, some definitions of GIS focus on the technical components, while others focus on the applications and benefits of GIS. The first group of definitions in this discussion focuses on the technical components of GIS.

Chirikure *et al.* (2017) established a definition of GIS as a system for storing, capturing, manipulating, managing, presenting, and analysing all geographical information. According to Liu *et al.* (2016), a GIS is a system for organising, interpreting, and acquiring data. According to Goodchild (2010), GIS is a computer setup designed to collect, verify, present, and preserve data related to the earth's surface locations. GIS technologies, with its cooperation and understanding tools, are appropriate for use in the science of geography. It is a computer-based tool for

acquiring, saving, modifying, presenting, interpreting, and producing spatially linked data (Chang, 2019). It is a system designed to capture, store, manipulate, analyse, manage, and present all types of geographical data, including spatial and non-spatial data (Bolstad, 2019).

These definitions all focus on the technical aspects of GIS, describing it as a system or tool for managing and analysing geographical information using computer-based software and hardware. These definitions highlight the various functions and capabilities of GIS, such as data storage, manipulation, presentation, and analysis. The second group of definitions in this discussion focuses on the applications and benefits of GIS.

GIS is a geographic science that combines numerous data kinds, analyses spatial information, and organises data layers into desired visualisations via 3D models and maps (Mayunga, 2018). A GIS, through its distinctive features, provides users with greater insight about information, such as trends, scenarios, and correlations, allowing them to make smarter and more capable judgments (Malczewski & Rinner, 2015). GISs are computer programmes that record geographic information by modifying, assessing, and evaluating the user's requirements or desires with the aim to assess geographic or geographical information for a possible or a specified purpose (Mathey, 2018). A GIS assists people and organisations in achieving a common aim, which is to obtain useful insight from all data kinds (Longley, 2000). GIS technologies, according to Boyda *et al.* (2019), merge with financial and enterprise resource planning (ERP) systems, project management software, and the guiding software programmes on work-order maintenance and management to boost efficiency and aid in explaining complicated organisational or municipal difficulties.

These definitions focus more on the application and benefits of GIS, describing how GIS can be used to analyse and interpret geographical information to achieve various goals and improve decision making. These definitions also highlight the integration of GIS with other software and systems to improve efficiency and solve complex problems.

Overall, these two groups of definitions provide complementary perspectives on GIS, with the technical definitions emphasising the functionality and capabilities of the system, while the application-focused definitions highlight the benefits and uses of GIS for various purposes.

For the purpose of this study on flood risk mapping, GIS can be defined as a computer-based system that integrates and analyses various geographical data types, including elevation, precipitation, land cover, and infrastructure, to identify areas at risk of flooding. GIS is used to capture, store, manage, manipulate, and present geographical information in a way that allows for the creation of accurate flood risk maps. By using GIS, it is possible to model different flood

scenarios and assess their potential impact on different areas, helping to inform decision making for flood risk management and emergency planning.

### 2.3.2 The history of geographical information systems



**Figure 2.6: John Snow's cholera map of Soho (Koch, 2004)**

represented lines as arcs with genuine embedded topology, and kept attribute and geolocation data in different folders (Coppock & Rhind, 1991).

Computer-based hydrological models began to emerge in the 1960s, marking a significant advancement in water resource management and flood prediction. These early models, though not classified as GIS in the modern sense, laid important groundwork for future developments. An example of such a computer-based hydrological model is the Stanford Watershed Model, developed in 1966 by Crawford and Linsley, which stands as one of the earliest computer-based hydrological models (Crawford & Linsley, 1966). This computer model formed the foundation for integrating spatial data with hydrological processes, which later led to modern GIS applications in flood risk assessment and management (Singh & Woolhiser, 2002).

In the 1970s, early applications of computer-based spatial analysis, which would later evolve into GIS, began to emerge in the field of flood risk assessment. A significant development during this period was the work done by the US Army Corps of Engineers' Hydrologic Engineering Center (HEC). Feldman (1981) discusses the development of HEC-1, a flood hydrograph package that incorporated spatial data analysis for flood modelling. While not a full GIS, HEC-1 again represented an important step towards integrating spatial data with hydrological modelling for flood analysis.

The importance of these early developments in spatial analysis for flood risk management is further highlighted in a study by Tate and Maidment (1999). They highlight how these computer-based models of the 1970s, including HEC-1, led to more advanced GIS applications in hydrology and flood risk assessment over the next decades.

By the late 1970s, publicly available GIS systems were in development, and by the early 1980s, companies like the Environmental Systems Research Institute (ESRI), the CAD (computer-aided design) platform, and ERDAS (Earth Resource Data Analysis System) started selling GIS software, integrating numerous CGIS features (Aronoff, 1989; Maguire, 1992; Singleton & Arribas-Bel, 2021). In 1981, ESRI launched Esri ARC/INFO, which became a popular GIS software (Lovell & Atkinson, 2004). The Mapping and Integrated Data Analysis System (MIDAS) was published for the DOS operating system in 1986 and was the first personal use GIS in the world (Jangra *et al.*, 2013).

Throughout the 1980s and 1990s, GIS technology continued to evolve and improve, leading to more sophisticated flood risk mapping and management tools (Singh & Fiorentino, 2013). The introduction of satellite and aerial imagery allowed for more accurate and detailed mapping of floodplains, while the development of digital elevation models (DEMs) enabled the creation of 3D

maps that could show the potential effect of floods in much greater detail (Maidment, 2002; Xu *et al.*, 2021).

By the turn of the 21st century, the rapidly developing multiple systems were already streamlined and standardised on a small number of platforms, and people were starting to experiment with accessing GIS data through the Internet, necessitating data format and transmission standards (Fu & Sun, 2011). This led to the growth of public and open-source GIS applications that run on several different operating systems that can be modified to accomplish certain activities (Fu & Sun, 2011).

The merging of GIS technologies with other information technology and internet services, including database systems, cloud-based services, software as a service (SAAS), and smartphones, has been a prominent development in the 21st century (Tsai *et al.*, 2014). Recently, GIS technology has continued to evolve and improve, with the development of more advanced flood risk modelling tools and the integration of GIS data with real-time sensor data and other sources of information (Ahmad *et al.*, 2013). This evolution of GIS has allowed for more accurate and up-to-date flood risk mapping, as well as more effective emergency response planning (ERP) and management (Trepekli *et al.*, 2022).

Now that the history of GIS has been covered, it is important to discuss the technical aspects of a modern GIS, because understanding the various technical aspects will ultimately help in identifying the areas that are vulnerable to flooding in the eThekweni Metropolitan Municipality. The first part of the technical discussion considers the components of a GIS. The elements that are recorded by a GIS form the second part of the discussion below. The types of GIS spatial data models, with their respective advantages and disadvantages, conclude the technical discussion regarding GIS.

Understanding the three elements recorded by a GIS, namely spatial, temporal and attribute, is essential as they enable the GIS system to function and provide value to its users. This is why the next section of this study will focus on the elements that are recorded by a GIS.

### **2.3.3 Elements recorded by a geographical information system**

According to Chrisman (2002), as well as Siabato and Manso-Callejo (2011), a GIS can record three elements. These elements are as follows:

### 2.3.3.1 The spatial or location element

The spatial element of GIS is often referred to as the geometric element because it deals with the geometric properties of space, including the location, size, shape, and orientation of geographic features (Chrisman, 2002; DeMers, 2008; Siabato & Manso-Callejo, 2011).

Spatial data in GIS can be represented in various ways, but the most common approach is to use a coordinate system to define the location of each feature on the earth's surface (Heywood *et al.*, 2011; Chang, 2019). A coordinate system is a reference framework that defines how geographic features are located in space, typically using latitude and longitude or some other projection system (Arctur & Zeiler, 2004; Cressie & Wikle, 2011). Spatial data can also be represented as geometric objects such as points, lines, polygons, and surfaces (O'Sullivan & Unwin, 2010). Points represent a single location on the earth's surface, such as a city or a landmark (Chang, 2019). Lines represent linear features such as roads, rivers, or borders (Huisman & de By, 2009). Polygons represent areas such as countries, states, or parks (Longley *et al.*, 2015). Surfaces represent three-dimensional objects such as buildings or terrain (Burrough *et al.*, 2015).

The spatial element of GIS is essential because it provides the geographic context and spatial relationships between different features on the earth's surface (De Smith *et al.*, 2007). By analysing and visualising spatial data in GIS, people can identify patterns and relationships between different features, such as the proximity of urban areas to water resources or the spatial distribution of wildlife habitats (Ahammed, 2017; Turner *et al.*, 2015). Spatial data are often represented via a two-dimensional map, which provides a visual representation of spatial relationships between different features (Kraak & Ormeling, 2020). Maps can be used to communicate complex spatial information to a wide audience and are essential for decision making in many fields, including urban planning, environmental management, and emergency response (Batty, 2013; Cova, 2005; Haddaway *et al.*, 2016).

In conclusion, the spatial element of GIS is a fundamental component that provides the geometric properties of geographic features on the earth's surface. By representing and analysing spatial data in GIS, a person can better understand the relationships and patterns of the physical world around them, allowing them to make informed decisions and solve complex problems. Furthermore, the spatial element of GIS also serves as a fundamental component in disaster risk assessment by providing precise geometric properties and spatial relationships of geographic features. The ability to represent and analyse multiple spatial layers - from elevation and drainage patterns to settlement locations - enables comprehensive understanding of flood risk patterns and their distribution. This spatial element of GIS, when integrated with AG principles, can become powerful for identifying at-risk informal settlements and projecting future scenarios flood risk. By

using these spatial capabilities, decision-makers can better visualise and understand the relationship between flood risk factors and socioeconomic developments, leading to more informed and proactive risk management strategies.

### **2.3.3.2 The temporal element**

The temporal element of GIS is also known as the basic temporal component because it deals with time-related information in geographic data (Longley *et al.*, 2015). While the spatial element represents the geometric properties of geographic features, the temporal element represents how those properties change over time (Chrisman, 2002).

Temporal data in GIS can take many forms, including timestamps, dates, and time intervals (Lee *et al.*, 2014). Temporal data can be used to track changes in spatial features over time, such as changes in land use, population distribution, or natural resources (Johnson, 1990; Lu & Weng, 2007; Zeng & Comber, 2020). By analysing temporal data in GIS, people can identify patterns and trends in spatial data, which can be useful for making predictions and informing decision making (Chainey *et al.*, 2008). In maps, time often plays a passive role, meaning that it is implied or stated but not explicitly represented on the map itself (Ware, 2021). For example, a map of historical sites may not explicitly show the time period during which those sites were active, but the temporal connection is still implied by the subject matter of the map (Sui & Goodchild, 2011). Similarly, a map of current road networks may not explicitly show the date when those networks were constructed, but the temporal context is still implied (Miller, 2003).

A suitable analogy for understanding the role of time in GIS and maps is to think of a map as a photograph that captures a moment in time (Dyce, 2013). Like a photograph, a map represents a snapshot of the world at a particular moment, and the changes that occur after the map was created are not reflected on the map itself (Teghil *et al.*, 2019). However, by analysing temporal data in GIS, it is possible to create time-series maps that show how geographic features change over time, providing a more comprehensive understanding of spatial relationships and patterns (Thakur & Hanson, 2010).

In conclusion, the temporal element of GIS is an important component that represents how spatial features change over time. While time often plays a passive role in maps, it is still essential for understanding the temporal context of geographic data. By analysing temporal data in GIS, a person or decision maker can identify patterns and trends that are useful for making informed decisions and solving complex problems. Furthermore, the temporal element of GIS is also important for disaster risk assessment, particularly when examining how vulnerability patterns evolve across urban areas, such as flood risk in the case of this study. While traditional flood risk



mapping often provides static snapshots, GIS's temporal capabilities enable the analysis of both current flood risks and projected future flood risk scenarios. By integrating temporal analysis with informal settlement growth projections, GIS can model the dynamic interplay between changing environmental patterns and urban development. This temporal element is particularly valuable for AG, as it enables decision-makers to visualise and prepare for multiple possible futures, thereby supporting more informed and forward-looking risk management strategies

### **2.3.3.3 The attribute element**

The attribute element of GIS is also known as the descriptive element because it represents the descriptive or explanatory attributes of spatial features (Chrisman, 2002). The attribute element complements the spatial and temporal elements by providing additional information about the geographic features and their characteristics (Kraak & Ormeling, 2020).

The attribute element of GIS includes both qualitative and quantitative data, which are typically available in the attribute tables of GIS software (Longley *et al.*, 2015). Qualitative data describe the qualitative properties of spatial features, such as their type, category, or name (Jankowski & Nyerges, 2001). Examples of qualitative attributes include the name of a city, the type of vegetation cover in a particular area, or the type of land use in a specific region (Briassoulis, 2020). Qualitative data are usually represented using nominal or ordinal scales (De Leeuw *et al.*, 1976).

Quantitative data, on the other hand, represent the quantitative properties of spatial features, such as their size, area, height, or density (Slocum *et al.*, 2023). Examples of quantitative attributes include the population density of a city, the elevation of a mountain, or the temperature of a region (DeMers, 2008). Quantitative data are usually represented using interval or ratio scales (Pope *et al.*, 2000).

The attribute element of GIS is essential because it provides additional information about the spatial and temporal context of geographic features (Chang, 2019). By analysing attribute data in GIS, it is possible to identify relationships and patterns between different features, such as the correlation between land use and population density or the relationship between temperature and vegetation cover (Haining, 2003).

In conclusion, the attribute element of GIS is a crucial component that provides additional descriptive or explanatory attributes of spatial features. Qualitative and quantitative attributes are typically available in the attribute tables of GIS software and complement the spatial and temporal elements of GIS. By analysing attribute data in GIS, people can better understand the

characteristics and properties of geographic features, which can be useful for decision making and problem solving. Furthermore, the attribute element of GIS is important in disaster risk assessment frameworks, enabling the integration and analysis of multiple risk factors across urban areas. Through MCDA approaches, GIS can incorporate numerous attributes, from physical environmental factors that affects flooding to socioeconomic conditions in the form of informal settlement data. These attribute data, stored and analysed within GIS, provide essential information of flood risk for different areas, or as is the case in this study, informal settlements. The ability to process and combine diverse attributes enables the identification of high-risk flood areas, while the attribute capabilities of GIS facilitate the integration of future flood risk scenario data. This rich attribute framework strengthens the AG approach of this study by providing decision-makers with detailed, multi-dimensional understanding of risk factors and their potential future changes.

Now that the theory on the three elements that are recorded in a GIS has been discussed, it is important to understand how the three elements relate to each other, as their interactions can have a significant effect on the accuracy and usefulness of the maps produced by GIS (Bolstad, 2019). Understanding the relationships between these elements is important for effective map-making and to ensure that the information presented is accurately interpreted by the map user (Dent *et al.*, 2009).

The spatial element of GIS is closely related to the other two elements of time and attribute (DeMers, 2008). Spatial data represent the geographic location and extent of features on the earth's surface, while time and attribute data provide additional information about those features (Longley *et al.*, 2015). The temporal component of GIS allows us to analyse changes and trends over time, which is essential for modelling and predicting future events (Kwan & Ding, 2008). For example, a time series of satellite imagery can show the extent of urban growth over time, allowing planners to predict future growth patterns and allocate resources accordingly (Khalil *et al.*, 2017). Similarly, a time series of weather data can help predict the likelihood and severity of natural disasters such as floods (Hewage *et al.*, 2020). Attribute data provide additional information about spatial features that can be used to further understand their characteristics and relationships (Huisman & de By, 2009). Attribute data can be used to classify and group spatial features, perform queries and analysis, and create visualisations (DeMers, 2008). For example, demographic data can be used to analyse patterns of population distribution across a region, while land use data can be used to analyse patterns of urbanisation (Aneesha Satya *et al.*, 2020; Tatem, *et al.*, 2012).

All three elements of spatial, time, and attribute data have to be included to create a comprehensive map in GIS (Chrisman, 2002; Longley *et al.*, 2015). A map created without any of these elements would provide an incomplete representation of geographic features, and it would be difficult to analyse and interpret the data (Krygier & Wood, 2016). A map created without the temporal or attribute components would provide only a static representation of spatial features (Dent *et al.*, 2009). Without the temporal component, the map would not provide any information on how the features change over time (Slocum *et al.*, 2023). For example, a map of population density without a temporal component would not show how the population density changes over time or what factors may influence those changes (Kitchin & Tate, 2001). Similarly, a map without the attribute component would lack any descriptive or explanatory information about the spatial features (Bolstad, 2019). For example, a map of land use without any attribute data would not provide any information about what types of activities occur in each land use category (Huisman & de By, 2009). Likewise, a map created without the spatial component would lack any geographic context or spatial relationships between features, making it difficult to analyse and understand (Dent *et al.*, 2009). Without the spatial component, it would not be possible to determine the location or spatial relationships between different features (Siabato & Manso-Callejo, 2011). For example, a map of population density without any spatial component would not show where the areas of high and low population density are located (Leyk *et al.*, 2019).

In conclusion, all three elements of spatial, time, and attribute data are essential to create a comprehensive map in GIS. Without any of these elements, a map would provide an incomplete representation of the spatial features, and it would be difficult to analyse and interpret the data. By combining all three elements, GIS provides powerful tools for understanding the world, predicting future trends, and making informed decisions.

These three elements can be displayed using one of two data models: a vector data model or a raster data model (DeMers, 2008; Longley *et al.*, 2015). The two spatial data models are visually illustrated in Figure 2.8, which both display the same geographical area. These two spatial data models form the next part of the discussion.

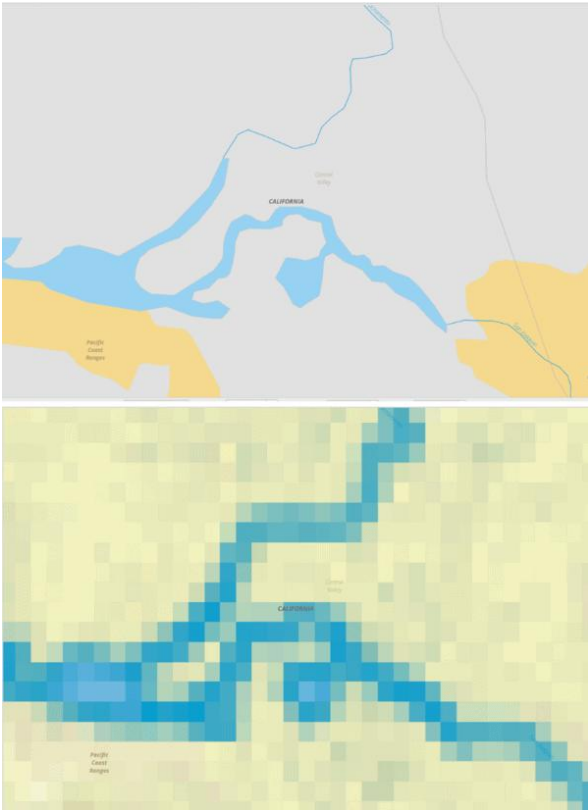


**Figure 2.7: Illustrations of vector spatial data (above) and raster spatial data (below)**  
(Dempsey, 2024)

### **2.3.4 Spatial data models in geographical information systems**

Understanding spatial data models in GIS is important for effective flood risk mapping in the eThekweni Metropolitan Municipality. The choice between raster and vector data models can significantly affect the accuracy and efficiency of flood risk mapping. This section explores these two primary spatial data models, their characteristics, and their potential applications for flood risk mapping in the eThekweni Metropolitan Municipality. By understanding these models, decision makers can select the most appropriate approach for capturing, analysing, and visualising flood-related spatial data, supporting more effective usage of GIS as a tool of AG strategies for flood risk management in the study area.

#### **2.3.4.1 Raster data model in geographical information systems**

The raster data model is comprised of columns and rows of pixels of uniform size that are combined to make a flat surface (Campbell & Shin, 2012). These pixels are used to construct points, arcs, areas, connections, and surfaces (Gonzalez & Woods, 2008). While pixels might be triangular or polygonal, square pixels are the most basic geometric shape to work with (Bolstad, 2019). As a result, a significant amount of accessible raster GIS data is based on square pixels

(Burrough *et al.*, 2015). Raster data examples include land use/cover classification, paper maps (two-dimensional maps), and orthophotos (Huisman & de By, 2009). Raster data models are also frequently applied in areas other than GIS (Campbell & Shin, 2012). The raster data format is made up of the widely used JPEG, BMP, and TIFF file formats, to list a few (Heywood *et al.*, 2011).

The raster data model is sometimes also called a grid-based system due to its dependency on a homogeneous set of square pixels (Tomlin, 2012). Each grid location is generally given one unique data value (Weng, 2010). Every cell in a raster contains one unique value that represents a spatial feature at a position defined by its column and row (Bernhardsen, 2002). To produce one unique data value per pixel, the raster model will aggregate all values inside a particular pixel (Bolstad, 2019). A visual illustration of the above-mentioned information can be found in Figure 2.9.

As a result, the greater the distance covered per pixel, the worse the accuracy of the corresponding data values (Weng, 2010). The spatial resolution of the raster model is determined by the distance covered by each pixel (Burrough *et al.*, 2015). The shortest distance between two neighbouring features in an image that can be identified is referred to as spatial resolution (Gonzalez & Woods, 2008). When establishing a raster's resolution, caution is advised because using an excessively coarse pixel resolution will result in information loss, while using an excessively fine pixel resolution will result in major increases in data size and computational requirements during display or analysis (Chang, 2019). An appropriate pixel resolution will consider both the map scale and the minimum mapping unit of all the other GIS data (Li & Heap, 2014).

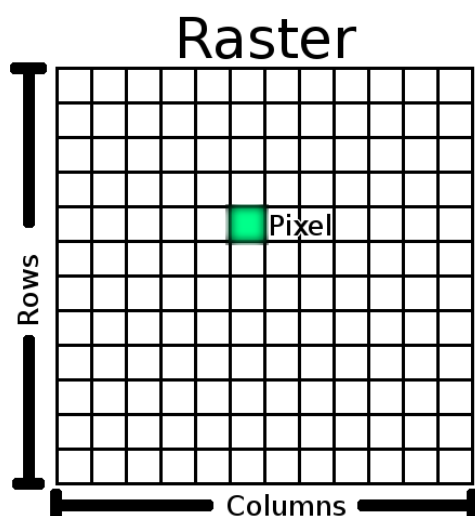


**Figure 2.8: Illustration of pixels, rows and columns (Ramsey, 2023)**

Now that the theoretical discussion on the raster data model has been concluded, it would be beneficial to include specific examples of when one data model might be more appropriate than the other, specifically within a flood risk context, as it is the focus of this study. The appropriateness of the raster data model for certain flood risk applications is therefore discussed in this section of the study.

Raster data models are commonly used to represent continuous data that varies over a surface, such as elevation, temperature, or precipitation (Osman & Das, 2023). In the context of flood risk, raster data models can be particularly useful for representing continuous variables such as water depth, velocity, or inundation extent (Noh *et al.*, 2016). Raster data models can also be useful for modelling terrain and land use, which can influence the flow and behaviour of floodwaters (Jiménez-Esteve *et al.*, 2018). Water depth, for instance, is a critical variable that can influence the extent and severity of flood events (De Moel *et al.*, 2009). Raster data models can be used to represent water depth as a continuous surface, with each cell in the raster representing the depth of water at a specific location (Pearlstone *et al.*, 2007). This depth of water information can be used to create flood maps that show the areas that are at risk of inundation, and to estimate the severity of the flooding in different areas (Hagemeier-Klose & Wagner, 2009). By using this information, flood risk analysts can identify areas that are at high risk of damage or loss of life and develop strategies to mitigate these risks (Hagemeier-Klose & Wagner, 2009). Similarly, by using a raster data model to represent elevation, it becomes possible to identify areas that are at risk of flooding due to their location within a floodplain or near a waterway (Domeneghetti *et al.*, 2019). Additionally, by using a raster data model to represent land use, it becomes possible to identify areas where the flow of floodwaters may be impeded by buildings or other infrastructure, increasing the risk of flooding in nearby areas (Garvin & Kelly, 2007).

Raster data models can also be used to represent the velocity of floodwaters as they flow through an area (Kalyanapu *et al.*, 2014). By representing this data as a continuous surface, it becomes possible to identify areas where the velocity of floodwaters is high, indicating a higher risk of erosion or damage to structures (Maidment, 2002). This information can be used to identify areas that are at high risk of damage or loss of life, and to develop strategies to mitigate these risks (Kundzewicz *et al.*, 2014).

Overall, raster data models are a powerful tool for representing continuous data related to flood risk and can be used to create detailed flood maps that show the extent and severity of flooding in different areas. By using raster data models to represent critical variables such as water depth and velocity, flood risk analysts can develop a more comprehensive understanding of the potential impacts of flooding and develop effective strategies to manage these risks.

#### 2.3.4.2 Vector data model in geographical information systems

Unlike the raster data model, space in the vector data model is not divided into separate grid cells (Burrough *et al.*, 2015). Vector data models represent the vertices of spatial features with points and their associated X, Y coordinate pairs, similarly to how they would be drawn on a map by hand (Huisman & de By, 2009). These features' data attributes are then saved in a different database management system. The spatial and attribute information for vector data models is connected by a simple unique identifier code assigned to each map element (Longley *et al.*, 2015).

The vector spatial data model has three basic vector types: points, lines, and polygons (Huisman & de By, 2009; Weng, 2010). Figure 2.10 can be found below as a visual illustration of these basic vector types. Points are zero-dimensional entities with a single coordinate pair. They are commonly used to represent solitary, distinct elements such as houses, boreholes, electricity poles and sampling locations, to name a few. The only characteristic of a point is its location (Longley *et al.*, 2015).

In the context of vector spatial data models, a node and a vertex can be considered as two types of points (Chang, 2019). A point is a distinct element, whereas a node is a geometrical connection that represents a shared X, Y coordinate pair among intersecting lines and polygons (Pucha-Cofrep *et al.*, 2018). Every curve somewhere along a line or polygon element that is not an intersection of lines or polygons is defined as a vertex (Menke *et al.*, 2016).

Lines are one-dimensional elements made up of many points that are deliberately connected (Law & Collins, 2013). They can be used to depict linear characteristics like highways, rivers, faults, and borders (Bolstad, 2019). The characteristic of length exists in lines (Weng, 2010). Lines that join two nodes together are known as chains, edges, segments, or arcs (Pucha-Cofrep *et al.*, 2018).

Polygons are two-dimensional elements made up of numerous lines that circle back on themselves to form a shape (O'Sullivan & Unwin, 2010). The first point on the first line segment of a polygon is the exact same point as the last point on the last line segment (Campbell & Shin, 2012). Polygons are commonly used to describe city boundaries, geologic formations, dams, soil associations and vegetation groupings, among other things (Bolstad, 2019). They have area and circumference attributes (Huisman & de By, 2009).

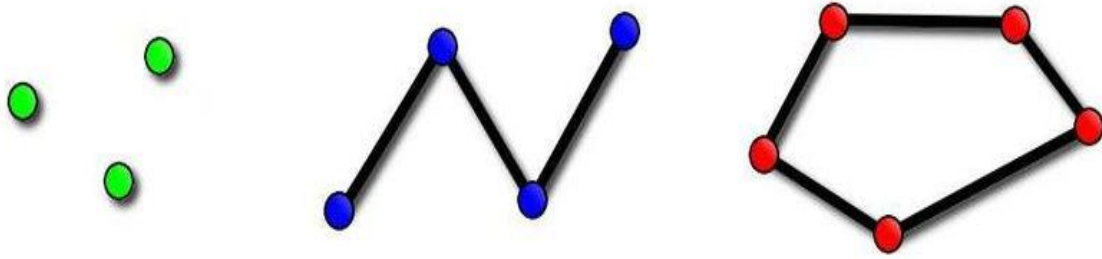


**Figure 2.9: Illustration of points, lines and polygons (Sabi'u *et al.*, 2015)**

Now that the theoretical discussion on the vector data model has been concluded, it would be beneficial to also include specific examples of when one data model might be more appropriate than the other, specifically within a flood risk context, as it is the focus of this study. The appropriateness of the vector data model for certain flood risk applications is discussed in the next section.

Vector data models are commonly used to represent point, line, and polygon features, such as buildings, roads, rivers, and other infrastructure (Longley *et al.*, 2015). In the context of flood risk, vector data models can be particularly useful for representing features that are critical to flood protection, such as levees, bridges, culverts, and drainage structures (Li *et al.*, 2011).

For example, levees are earthen embankments that are designed to prevent flooding by holding back water from adjacent rivers or other water bodies (Lempérière, 2017). Levees can be represented as polygons in a vector data model, which allows for detailed analysis of their location, height, and other physical characteristics (Chen & Shi, 2018). By analysing these attributes, it becomes possible to identify areas where levees may be at risk of overtopping or failure during flood events, and to develop strategies for mitigating these risks (Kundzewicz *et al.*, 2018).

Similarly, bridges and culverts are critical components of transportation infrastructure that can be vulnerable to flooding (Deshmukh *et al.*, 2011). By representing these features as points or lines in a vector data model, it becomes possible to identify their specific locations and attributes, such as their height, width, and load-bearing capacity (Albano *et al.*, 2014). This information can be used to assess their vulnerability to flooding and to identify potential mitigation strategies, such as raising the elevation of the roadway or strengthening the bridge structure (Pregolato *et al.*, 2017).

Vector data models can also be useful in representing the complex geometry of natural features related to flood risk, such as rivers and other waterways (Johnston & Smakhtin, 2014). Rivers and



other water bodies can be represented as connected line segments in a vector data model, which makes it easier to analyse their behaviour and potential flood risk (Singh & Woolhiser, 2002). By representing rivers in this way, it becomes possible to analyse their slope, flow rate, and other hydraulic characteristics, which can be used to predict their behaviour during flood events and to identify areas that may be at risk of inundation (Chow, 1959).

Overall, vector data models are a powerful tool for representing discrete features and complex geometries related to flood risk and can be used to identify potential points of failure or vulnerability within a flood risk context. By using vector data models to represent critical infrastructure and natural features, flood risk analysts can develop a more comprehensive understanding of the potential effects of flooding and develop effective strategies for managing these risks.

Seeing as a solid theoretical base regarding GIS has been established, the next section in this literature study will focus on more the practical application of GIS with regards to this study. Therefore, in the next two sections of this study the discussion turns to the use of GIS for urban disaster risk management and the use of GIS for the management of flooding events.

### **2.3.5 The importance of geographical information systems in managing urban disaster risk**

GIS plays an important role in managing urban disaster risk (Twumasi *et al.*, 2019). By integrating location-based data, GIS enables decision makers to identify, map, and analyse areas at risk of disasters, assess potential impacts, and develop effective mitigation and response strategies (Giardino *et al.*, 2012; Huang *et al.*, 2018; Tomaszewski *et al.*, 2015; Yu *et al.*, 2018). Directly relevant to this study's focus on flood risk mapping in an urban setting, this section discusses how GIS can help manage urban disaster risk before, during, and after a disaster.

Before a disaster occurs, GIS contributes significantly to hazard mapping and modelling. As a powerful tool for hazard mapping, GIS allows for the visualisation and analysis of spatial data related to potential hazards (Liu *et al.*, 2017; Tate *et al.*, 2010). The process involves integrating various data sources, such as topography, land use, population, infrastructure, and climate data, to produce maps that identify areas at risk of natural or man-made hazards (Huang *et al.*, 2018; Tadesse *et al.*, 2022). This integration of diverse data sets is a key strength of GIS, allowing for a comprehensive understanding of risk factors that might not be apparent when examining each data set in isolation.

One of the primary benefits of using GIS for hazard mapping is the ability to create multi-layered maps that highlight relationships between different data sets (Liu *et al.*, 2019). For instance, overlaying population density data with floodplain maps can identify areas where high population density coincides with flood risk (Ahlqvist, 2009). This layered approach allows for a nuanced understanding of risk, taking into account not just the physical hazard but also the social and demographic factors that contribute to vulnerability. Emergency managers can use this information to plan evacuation routes and identify areas that may require additional resources in the event of a flood (Rahman *et al.*, 2021). The ability of GIS to produce these detailed, multi-factor analyses is invaluable in developing targeted and effective disaster preparedness strategies.

GIS can also model the potential impact of natural hazards, such as earthquakes, landslides, or wildfires (Tarolli & Cavalli, 2013). This modelling involves creating spatial models that simulate the effects of a hazard event, such as the spread of fire, the movement of debris, or the displacement of soil (Apip *et al.*, 2010; Assilzadeh *et al.*, 2010; Singh *et al.*, 2019). These GIS models can identify vulnerable areas and develop mitigation strategies, such as building codes or land-use policies (Alexander, 2015). The predictive capability of GIS is particularly valuable in urban planning, allowing city officials to make informed decisions about future development and infrastructure projects with an eye towards disaster resilience.

Moreover, GIS can create publicly accessible hazard maps, allowing individuals to better understand the risks associated with living in a particular area (Hagemeyer-Klose & Wagner, 2009). These GIS-generated maps can be particularly useful for property owners who may need to take steps to protect their property from potential hazards (Hall *et al.*, 2003). By making this information readily available to the public, GIS plays a crucial role in raising awareness and promoting individual preparedness, which is an essential component of overall community resilience.

There are numerous examples of GIS being used for hazard mapping worldwide, demonstrating its versatility and effectiveness across different geographical and cultural contexts. The United Nations Office for Disaster Risk Reduction (UNDRR) has developed a hazard and risk Assessment methodology that uses GIS to identify and map hazard-prone areas (Guiliani & Peduzzi, 2011). This global application of GIS technology highlights its importance in international efforts to reduce disaster risk and build resilience.

In the USA, GIS is extensively used for flood hazard mapping and social vulnerability assessment. GIS techniques can be applied to analyse flood exposure and social vulnerability across the country, providing important information for disaster risk management and policymaking (Tate *et*

*al.*, 2021; Wing *et al.*, 2018). Such analyses offer valuable insights into areas at high risk of flooding and communities that may be particularly vulnerable, helping to inform targeted mitigation strategies and emergency response plans (Tate *et al.*, 2021). The integration of social vulnerability data with physical hazard information is a key strength of GIS, allowing for a more holistic understanding of disaster risk that takes into account both environmental and social factors (Rufat *et al.*, 2015).

In South Africa, the SAWS uses GIS to map flood hazard zones in the country. These GIS-generated maps are used by emergency services to prepare for and respond to flood events (Botai *et al.*, 2015). The use of GIS in this context allows for real-time updating of flood risk information, enabling more responsive and effective emergency management. Furthermore, the South African Council for Geoscience uses GIS to map earthquake hazard zones in South Africa. These GIS maps are used to inform building codes and land use planning decisions in areas at risk of earthquakes (Singh *et al.*, 2009). This application of GIS demonstrates its importance not just in immediate disaster response, but also in long-term planning and risk reduction efforts.

When a disaster strikes, GIS aids in risk assessment and emergency response through various means. GIS can help create real-time maps displaying the location of the disaster, affected areas, and resources such as hospitals, evacuation centres, and emergency responders (Ai *et al.*, 2016; Chatfield *et al.*, 2010). These GIS maps can be updated in real time as the situation evolves, providing decision makers with up-to-date information on the situation on the ground (Karnatak *et al.*, 2012). The ability of GIS to provide this real-time, spatially accurate information is crucial in the chaotic early stages of a disaster, allowing for more effective coordination of response efforts (Tomaszewski *et al.*, 2015).

GIS also analyses population data, including demographic and socioeconomic information, to identify vulnerable populations in affected areas (Chen *et al.*, 2021). This GIS analysis includes identifying the elderly, disabled individuals, and low-income families living in informal settlements. The information from GIS can be used to target emergency response efforts to those who need them most (Giardino *et al.*, 2012). This capability of GIS to rapidly identify and locate vulnerable populations is particularly valuable in urban areas, where complex social and demographic factors can significantly influence disaster impacts and recovery processes.

In addition, GIS identifies available resources such as emergency responders, medical supplies, and equipment, allocating them to areas where they are most needed. GIS can also track the movement of resources to ensure timely delivery to the right location (Chen *et al.*, 2011). This resource management capability of GIS is important for optimising the use of often limited emergency resources, ensuring that aid reaches those most in need as quickly as possible.

GIS develops evacuation plans that identify routes and safe locations for residents during a disaster (Bonilauri *et al.*, 2021). It can also track the movement of evacuees and ensure they are directed to safe locations (Ogawa *et al.*, 2020). The ability of GIS to model and visualise complex spatial relationships is particularly valuable in evacuation planning, allowing emergency managers to identify potential bottlenecks or hazards along evacuation routes and adjust plans accordingly.

Furthermore, GIS develops visual aids such as maps and infographics to communicate critical information to the public (Showstack, 2001). This GIS-generated information includes details on the disaster location, evacuation routes, and emergency services (Aghav *et al.*, 2023). The visual nature of GIS outputs makes complex spatial information more accessible to the general public, facilitating more effective risk communication and public engagement in disaster preparedness and response (Tomaszewski *et al.*, 2015).

After a disaster has struck, GIS continues to provide valuable support in reconstruction and rebuilding efforts. GIS helps assess the extent of damage caused by the disaster (Yamazaki, 2001). By overlaying pre-disaster and post-disaster images and data, GIS can determine the extent of the damage, helping to prioritise areas that need immediate attention (Walia, 2014). This damage assessment capability of GIS is crucial in the early stages of recovery, allowing for rapid identification of areas most in need of assistance and informing the allocation of recovery resources (Cutter, 2003).

GIS identifies critical infrastructure such as hospitals, fire stations, and police stations that may have been damaged or destroyed during a disaster (Arvidsson *et al.*, 2022; Hawchar *et al.*, 2020). This GIS-derived information can be used to prioritise the restoration of these critical facilities (Deshmukh *et al.*, 2011). The ability of GIS to quickly locate and assess the status of critical infrastructure is essential in restoring basic services and facilitating overall community recovery (Xie *et al.*, 2016).

GIS also helps identify the resources required for the reconstruction and rebuilding process (Duval-Diop *et al.*, 2010). For example, after a disaster, GIS technology can help assess the extent of damage to infrastructure, buildings, and utilities, allowing for efficient resource allocation for reconstruction and recovery efforts (Atif *et al.*, 2015). By integrating data on damaged areas, population density, and critical infrastructure, GIS provides valuable insights for decision makers who have to allocate resources such as materials, equipment, and personnel (Assilzadeh *et al.*, 2010). This comprehensive approach to resource allocation, facilitated by GIS, helps ensure that recovery efforts are efficient and tailored to the specific needs of affected communities (Cova, 2005).

GIS aids in the planning and design of the reconstruction process. By overlaying various data layers such as land use, zoning, and topography, GIS can determine the best locations for rebuilding (Ahlqvist, 2009; Haigh & Sutton, 2012). GIS can also create 3D models of the affected areas to help visualise the reconstruction process (Tiwari, 2015). This GIS-based visualisation can be particularly useful for stakeholders to understand the proposed reconstruction plans and make informed decisions (Yu *et al.*, 2018; Zlatanova & Fabbri, 2009). The ability of GIS to integrate and visualise multiple layers of spatial data is invaluable in the complex process of urban reconstruction, allowing planners to consider a wide range of factors in their decision making (Malczewski & Rinner, 2015; Opach & Rød, 2013).

Finally, GIS facilitates communication and collaboration between various stakeholders involved in the reconstruction process (Tomaszewski & MacEachren, 2012). By creating a centralised database of information, GIS allows all stakeholders to access and share information in real time (Haworth *et al.*, 2016; MacEachren & Brewer, 2004). This GIS-enabled collaboration can significantly improve the efficiency and effectiveness of the reconstruction efforts, ensuring that resources are used optimally and that the rebuilding process addresses the needs of the affected communities (Teeuw *et al.*, 2013). The role of GIS as a platform for information sharing and collaboration is particularly important in the context of urban disaster recovery, where multiple agencies and stakeholders must coordinate their efforts effectively (Comfort & Kapuco, 2006; Tomaszewski *et al.*, 2015).

While GIS in relation to urban disaster risk management offers many benefits, there are limitations to its usage, especially in developing countries. Limited infrastructure is a challenge when using GIS for managing urban disaster risk (Tran *et al.*, 2009). The necessary technological infrastructure, such as reliable internet connectivity, computer hardware, and software, may be lacking or inadequate to properly implement GIS in the event of a disaster (Sarangi & Pradhan, 2020). The lack of necessary technological infrastructure can make it difficult to access and share data and collaborate with other stakeholders, hindering the effectiveness of GIS in disaster risk management, especially in developing countries (Majlingova *et al.*, 2018; Sharma *et al.*, 2020). This hindered effectiveness of GIS can lead to delays in decision making, inadequate preparation and response to disasters, and increased risk to lives and properties (Tomaszewski *et al.*, 2015; Mathenge *et al.*, 2022). Moreover, limited technological infrastructure can make it difficult for developing countries to participate in global initiatives and collaborate with other stakeholders on disaster risk management (Enenkel *et al.*, 2018). This can result in the marginalisation of developing countries in the global community, hindering their capacity to access financial and technical support for disaster risk reduction efforts (Aitsi-Selmi *et al.*, 2015).

Limited technical capacity is another significant challenge in using GIS for managing urban disaster risk in developing countries (Tomaszewski *et al.*, 2020). In many cases, there may be a shortage of personnel with the necessary technical skills to operate and maintain GIS software (Wilke & Fagen, 2014). Additionally, there may be a lack of funding for training and capacity building, which can further limit the effectiveness of GIS in disaster risk management (Montoya, 2003). The shortage of technical expertise can make it difficult to effectively use GIS software to analyse and interpret spatial data related to disaster risk (Bearman *et al.*, 2016). This can lead to a lack of understanding of the risk factors and limitations in planning and response efforts (Ye *et al.*, 2013). Without personnel who are trained in GIS, it may be difficult to integrate GIS into existing disaster management systems, resulting in missed opportunities for improved preparedness and response (Longley *et al.*, 2015). Moreover, the lack of funding for training and capacity building can further exacerbate the shortage of technical expertise in GIS (Ye *et al.*, 2013). Organisations may not have the resources to invest in the necessary training and may struggle to retain personnel with GIS expertise, leading to a lack of institutional knowledge and continuity (Gocmen & Venturac, 2010).

Limited data availability is a third significant challenge in using GIS for managing urban disaster risk in developing countries (Sauti *et al.*, 2021). In many cases, data may be scarce, outdated, or not exist at all, particularly in informal settlements and low-income areas where disaster risk is often highest (Kamalipour & Dovey, 2019). Data can be outdated or non-existent for a variety of reasons, including limited resources for data collection, poor record-keeping systems, and a lack of standardised data formats (Ahsan *et al.*, 2023). The lack of data can make it difficult to accurately model and predict disaster risk in these areas, as GIS relies heavily on the quality and quantity of data available (Antoniou, 2023). Without accurate data on the physical environment, social and economic characteristics of the population, and past disaster events, it is challenging to develop effective disaster risk reduction strategies (Hallegatte *et al.*, 2020). For example, without detailed data on the location and characteristics of critical infrastructure, such as fire stations, it may be difficult to plan and coordinate emergency response efforts (Shahparvari *et al.*, 2020). Similarly, without data on the population distribution and demographics, it may be challenging to identify vulnerable groups and prioritise interventions accordingly (Domingue & Emrich, 2019). Additionally, the lack of data may also result in inaccurate or incomplete risk assessments, which can lead to over- or underestimating the potential effect of disasters and hinder effective decision making (Landoll, 2021). The lack of data, which hinders effective decision making, can have serious consequences for disaster preparedness and response efforts, particularly in developing countries where resources may be limited (Al-Dabbagh, 2020; Ziad & Nathaniel, 2016).

The integration of GIS with remote sensing and machine learning technologies holds great promise for enhancing the capabilities of GIS in managing urban disaster risk (Avand & Moradi, 2021; Star *et al.*, 1997). By combining machine learning and GIS technologies, the researcher and the decision makers can leverage their unique strengths to improve people's understanding of urban environments, detect potential risks, and facilitate effective disaster response and management (Ngolo & Watanabe, 2022; Avand & Moradi, 2021). The integration of GIS with other technologies subsequently forms the next part of the discussion on the use of GIS in urban disaster risk management.

Remote sensing technologies, such as satellite imagery and aerial photography, can provide valuable data for GIS analysis (Chaminé *et al.*, 2021). For instance, satellite imagery can capture information on land use, vegetation cover, and building types in an area, which can be analysed and integrated with GIS data to create detailed maps and models (Bhatti *et al.*, 2019; Mansour *et al.*, 2020). Detailed maps and models can then be used to identify areas that are at high risk for disasters, such as floods, landslides, or earthquakes, and to develop effective response strategies (Khatakho *et al.*, 2021).

ML can also be used to analyse remote sensing data and GIS data, to identify patterns and trends that may not be immediately apparent to human analysts (Nikparvar & Thill, 2021). For instance, machine learning algorithms can be trained to identify areas that are most vulnerable to specific types of disasters, based on a range of factors, such as the location of buildings, the density of vegetation cover, and the type of land use in the area (Kuglitsch *et al.*, 2022; Linardos *et al.*, 2022).

Furthermore, the integration of GIS with other technologies can also help in planning effective response efforts after disasters. For instance, by combining GIS with social media data, it is possible to track the movements of people during an emergency and to identify areas where assistance may be needed urgently (Huang *et al.*, 2015). Similarly, by integrating GIS with communication technologies such as radio and mobile phones, it is possible to quickly disseminate information and coordinate response efforts during a disaster (Kawamura *et al.*, 2014).

However, the integration of these above-mentioned technologies also presents several challenges. The integration of remote sensing data with GIS can be complex and requires specialised knowledge and technical expertise (Yin *et al.*, 2021). In addition, remote sensing data can be expensive, and access to this data may be limited in developing countries (Papenfus *et al.*, 2020). Similarly, the integration of machine learning algorithms with GIS requires specialised knowledge and technical expertise, which may be in short supply in developing countries (Gao,

2021). Furthermore, the integration of remote sensing and ML technologies must be accompanied by effective community engagement and capacity building to ensure that the technology is tailored to local needs and can be effectively used in disaster risk management (Sandström *et al.*, 2020). It is important to involve local communities in the development and implementation of GIS systems to ensure that the technology is accessible and useful to them (Sandström *et al.*, 2020). The involvement of local communities in the development and implementation of GIS systems may require addressing cultural, linguistic, and social barriers to ensure effective community engagement (Rinner & Bird, 2009; Robinson *et al.*, 2017).

In addition to its use in urban disaster risk management, GIS can also play a vital role specifically in flood management (Ramlal & Baban, 2008; Sanyal & Lu, 2004). It can provide valuable insights into flood management by integrating data from various sources, including satellite imagery, topographic data, and hydrological data (Poole *et al.*, 2002). The use of GIS in flood management is discussed next.

However, one potential limitation of open data is the need for careful data management (Melin, 2016). Data custodians like SAWS, SANSA and DWS, in the case of South Africa, must ensure that the data they make available is accurate, complete, and appropriate for use by others (Dawes, 2010). Data custodians must also take steps to protect sensitive data and ensure that data privacy is maintained (Allen *et al.*, 2019). This may involve implementing security measures such as data encryption, access controls, and monitoring tools to detect and respond to any security incidents (Bertino & Sandhu, 2005). In addition, another potential limitation of open data is that it may not always be available at the level of detail required (Zuiderwijk & Janssen, 2014). An example in flood risk mapping is that open data on precipitation may be available at a regional level, but may not be available at a local level, where it may be necessary to accurately predict flood risk (Aggarwal, 2016). Data custodians must be aware of these limitations and work to address them by collecting additional data or using other methods to supplement open data (Zuiderwijk & Janssen, 2014).

### **2.3.6 The use of geographical information systems in flood management**

Flood management is the process of planning, designing, implementing, and monitoring activities aimed at reducing the negative impacts of flooding on people, infrastructure, and the environment (Lane, 2017; Plate, 2002). It encompasses a wide range of activities, from disaster preparedness and warning systems to infrastructure development, land-use planning, and risk assessment (Tariq *et al.*, 2020). Effective flood management requires a comprehensive and integrated approach, considering not only the physical aspects of floods but also the social, economic, and environmental dimensions (Ashley *et al.*, 2007; Dawson *et al.*, 2011).



GIS has been widely used in flood management due to its ability to provide a comprehensive and integrated view of the physical and human systems affected by floods (Opolot, 2013). There are many ways in which GIS can help in the management of a flood. This section of the study explores the ways in which GIS is used for flood management. Specific examples from different regions around the world are also discussed to illustrate the applications of GIS around the world. This provides specific insights into how GIS can be applied to flood risk mapping in the eThekweni Metropolitan Municipality.

The first way in which GIS is used for in flood management is flood mapping (Figure 2.11). GIS can be used to create digital flood maps that show the extent of floods, including areas that are at risk and areas that have been flooded (Chormanski *et al.*, 2011). These maps can be created using satellite imagery, remote sensing data, and ground-based observations (Schumann & Moller, 2015; Tanim *et al.*, 2022). This information can be used to identify vulnerable areas, prioritise response efforts, and develop flood mitigation strategies (Flax *et al.*, 2002; Uddin *et al.*, 2019).

In Europe, the European Space Agency (ESA) uses satellite imagery and GIS to create maps that show flood extent, depth, and duration (Martinis *et al.*, 2015). After the 2014 floods in northern Italy, the ESA created maps that helped emergency responders assess the damage and plan recovery efforts (Pulvirenti *et al.*, 2015). The maps that the ESA produced for this and for other flooding events, show the extent of the flooding, which can help responders identify areas that are potentially cut off and prioritise rescue and recovery efforts. The maps also show the depth of the flooding, which helps authorities assess the damage to infrastructure and prioritise repairs. Finally, the maps show the duration of the flooding, which helps decision makers plan for the long-term recovery of affected communities (Schumann *et al.*, 2018).

In Africa, the World Bank uses GIS to create flood hazard maps that identify areas at risk of flooding and help governments develop disaster risk reduction strategies (Rentschler & Salhab, 2020). The World Bank uses high-resolution flood hazard maps, population maps, and other data sources to estimate the number of people in Africa, and globally, exposed to intense flood risks (Rentschler *et al.*, 2022). These maps serve as valuable tools in identifying areas at the highest risk of flooding and understanding the potential effects on communities and economies.

In South Asia, multiple agencies are involved in flood risk mapping. In Bangladesh, the Bangladesh Water Development Board (BWDB) and the Flood Forecasting and Warning Centre (FFWC) play important roles. The BWDB collects hydrological data and develops flood models, while the FFWC, operating under BWDB, provides flood forecasts and early warnings. These

agencies work together to enhance flood risk awareness, prevention, mitigation, and preparedness in Bangladesh, a country frequently affected by flooding (Gain *et al.*, 2015).

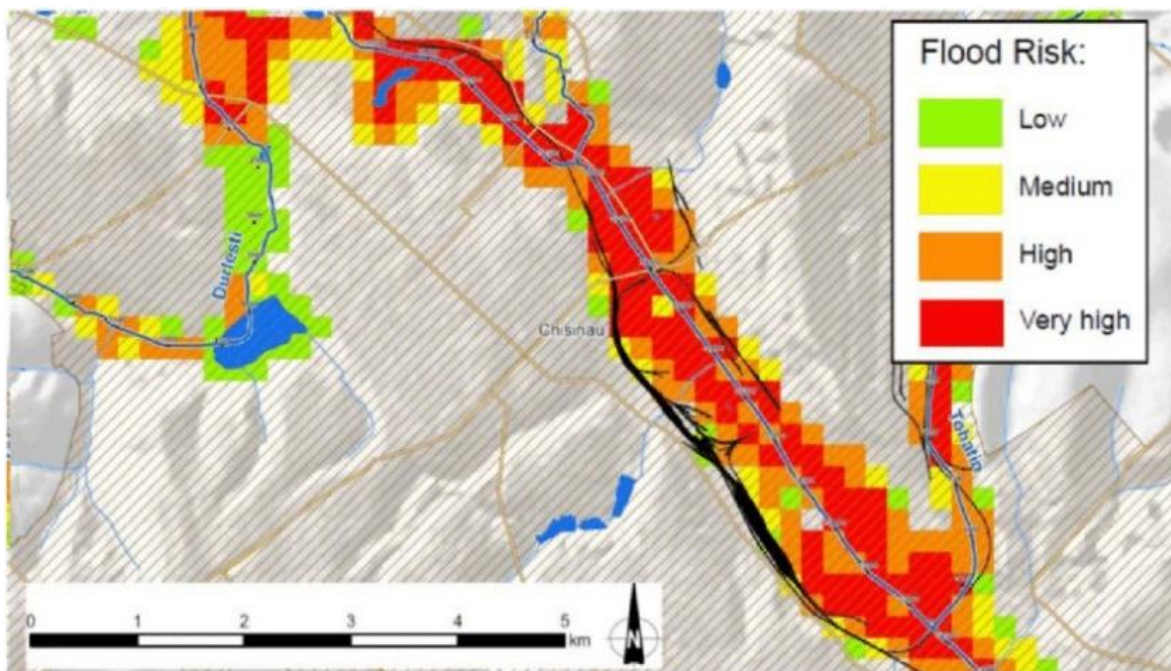


**Figure 2.10: Example of a flood risk map (Frank *et al.*, 2016)**

The second way in which GIS is used for in flood management is hydrological modelling (Figure 2.12) (Kourgialas & Karatzas, 2011; Zhou *et al.*, 2021a). Hydrological modelling is the process of simulating the flow of water in a river basin or watershed (Johnston & Smakhtin, 2014; Ogden, 2021). It uses mathematical and computational models to represent the components and processes of the hydrologic cycle (Essenfelder & Guipponi, 2020). Hydrological modelling is an essential tool in the field of hydrology and is used to understand the water cycle and its interactions with the land and atmosphere (Yang *et al.*, 2021). The main objective of hydrological modelling is to predict the flow of water through rivers, lakes, and groundwater aquifers and to understand the impact of human activities, such as land use change, on water resources (Becker, 2006; Devia *et al.*, 2015; Dwarakish & Ganasri, 2015). This information can be used to understand the dynamics of flooding and to develop models to predict future flood events.

In North America, the United States Geological Survey (USGS) uses GIS for hydrological modelling to predict floods and inform flood risk management (Perry, 2000). One specific example of this is the development of predictive flood inundation maps (Kim, 2015). These maps are created by combining hydrological data with high-resolution elevation data, which allows the USGS to model the areas likely to be flooded in different scenarios (Kim, 2015). The flood inundation maps are then used to inform flood risk management by identifying areas where

emergency responders should focus their efforts, where evacuation orders may need to be issued, and where infrastructure improvements may be necessary (Shastry *et al.*, 2023).

In Europe, the European Flood Awareness System (EFAS) uses GIS for hydrological modelling to predict floods and provide early warning to communities at risk (Smith *et al.*, 2016). The EFAS uses a range of data sources, including satellite data, weather forecasts, and hydrological models, to produce flood forecasts that are updated several times a day (Thielen-del Pozo *et al.*, 2016). The forecasts are then shared with national authorities, emergency responders, and the public to enable them to take appropriate action. By providing early warning of floods, EFAS helps communities to prepare and respond to floods more effectively, reducing the impact of flooding on people and property (Pappenberger *et al.*, 2015).

In Africa, the Water Resources Management Authority (WRMA) in Kenya uses GIS for hydrological modelling to manage water resources and reduce the risk of floods (Obando *et al.*, 2017). The WRMA uses GIS to develop water allocation plans that consider the potential for flooding and drought (King-Okumu *et al.*, 2018). By modelling different scenarios, the WRMA is able to identify areas where flood risk is highest and prioritise investments in flood protection infrastructure (Savenije *et al.* 2014). By managing water resources in a way that accounts for the risk of flooding, the WRMA is able to reduce the effects of floods on communities and minimise damage to property (Ondieki, 2013).

In Asia, the Mekong River Commission (MRC) uses GIS for hydrological modelling to manage the Mekong River basin and reduce the risk of floods (Lan, 2021). The MRC uses GIS to develop flood forecasting models that take into account river flow, rainfall, and other factors (Zhang *et al.*, 2020). The models help the MRC provide early warning of floods to communities at risk and enable emergency responders to prepare for and respond to floods more effectively (Zhang *et al.*, 2020).

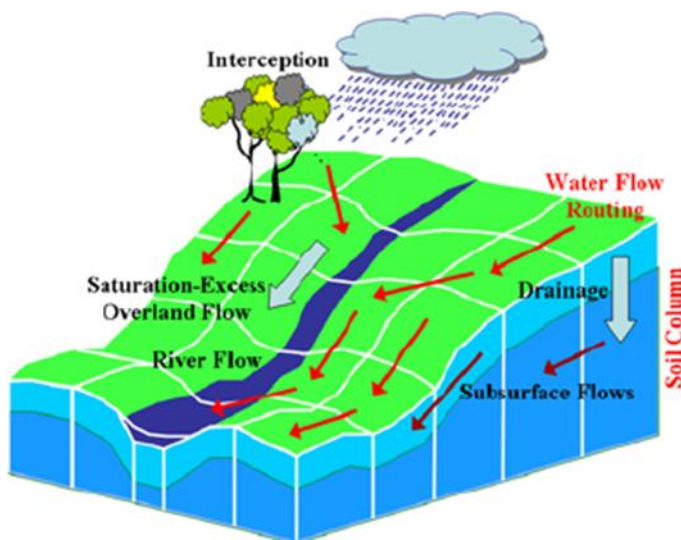


**Figure 2.11: Illustration of a hydrological model (Apip *et al.*, 2010)**

The third way in which GIS is used for in flood management is EWSs (Figure 2.13) (Moreri *et al.*, 2008; Sharif & Hashmi, 2006). EWSs are essential tools used for disaster risk reduction and management (Yekeen *et al.*, 2019). They provide advance notifications to communities and decision makers about imminent natural hazards, such as floods, droughts, earthquakes, and tsunamis, allowing them to take the necessary measures to minimise the potential loss of life and property (Grasso *et al.*, 2011; Kelman & Glantz, 2014). GIS can be used to develop EWSs that provide real-time information on flood conditions and potential flood risks. This information can be used to alert residents and other stakeholders, allowing for early evacuation and reducing the impact of flood events (Quansah *et al.*, 2010).

In South America, the Peruvian Meteorological and Hydrological Service of Peru (SENAMHI) EWS relies on real-time weather and water level data to monitor potential flood risks in vulnerable areas (Huggel *et al.*, 2015). The system uses GIS mapping and modelling to generate flood hazard maps and to identify at-risk populations and has been successful in reducing the loss of life and property damage during severe weather events (Aguirre *et al.*, 2019).

In Oceania, the Joint Australian Tsunami Warning Centre (JATWC) is an important example of an EWS in the Oceania region. The JATWC operates as a collaboration between the Australian Bureau of Meteorology and Geoscience Australia (Greenslade *et al.*, 2009). The primary responsibility of the JATWC is to detect and issue tsunami warnings for Australia, including its islands and territories (Wilson *et al.*, 2018). The JATWC serves as a 24/7 monitoring and analysis centre, equipped with the capacity to provide timely and accurate information about potential tsunamis in the region (Angove *et al.*, 2019). The JATWC's monitoring activities involve the upgrade and expansion of sea-level and seismic monitoring networks in the Indian and South-

West Pacific Oceans, enabling the centre to gather essential data for detecting and analysing tsunamigenic events (Greenslade *et al.*, 2019).

In addition to its responsibilities in Australia, the JATWC also plays a role in supporting neighbouring countries in the Indian Ocean and the South-West Pacific region (Greenslade *et al.*, 2014). During tsunami events, the JATWC collaborates with neighbouring countries, sharing scientific knowledge and examining the strength of the tsunami before issuing relevant threats and warnings.

In Asia, the International Centre for Integrated Mountain Development (ICIMOD) in the Hindu Kush Himalayan region uses GIS mapping and modelling to generate flood risk maps and to provide early warning alerts to local communities (Tsering *et al.*, 2021). The flood early warning system (FEWS) integrates rainfall data, river level data, and weather forecasts to provide accurate and timely flood warnings (Balsamo *et al.*, 2009; Shrestha *et al.*, 2016). The FEWS is designed to be user-friendly and accessible to local communities, and has been successful in supporting flood response efforts in Afghanistan, India, Nepal, and Pakistan (Shrestha *et al.*, 2015)

In Africa, the Southern African Development Community's (SADC) Regional Remote Sensing Unit (RRSU) has, among other implementations, developed a FEWS that uses satellite imagery, weather data, and GIS mapping to monitor and forecast flood events across the region (Brown *et al.*, 2015). The FEWS provides early warning alerts to relevant government agencies and communities and has been used to support disaster response efforts in countries such as Mozambique and Zimbabwe (Brown *et al.*, 2015). The RRSU also provides capacity building and technical assistance to member countries to help them develop their own EWS and improve their disaster preparedness and response capabilities (Cooper & Gavin, 2005).



**Figure 2.12: Illustration of an early warning system (The Open University, 2024)**

The fourth way in which GIS is used for in flood management is asset management (Evans *et al.*, 2008). Asset management is an essential component of flood management, as floods can cause significant damage to critical infrastructure and communication networks (Vonk *et al.*, 2020). GIS can be used to manage these critical assets by providing detailed information about their location, condition, and vulnerability to flooding (van Maarseveen, 2018). This information can be used to develop plans to protect critical assets, such as building flood protection structures or relocating infrastructure to areas less prone to flooding (Jonkman *et al.*, 2018). GIS can also be used to prioritise critical assets for protection, based on their importance to the community and the potential impact of flood damage on their operations (Albano *et al.*, 2017). By identifying the most critical assets, urban planners can allocate resources more effectively and ensure that essential services are maintained during flood events (Colenbrander & Barau, 2019; Schinke *et al.*, 2016). In addition to managing critical assets, GIS can also be used to monitor the condition of assets during and after floods (Glas *et al.*, 2017; Haq *et al.*, 2012). For example, sensors can be installed on infrastructure such as bridges and levees to monitor their condition and detect damage caused by flood events (Mane *et al.*, 2019). This information can be used to prioritise repairs and ensure that critical infrastructure is restored as quickly as possible following a flood event (Koursari *et al.*, 2020).

In the Netherlands, a country highly vulnerable to flooding, the government has implemented advanced GIS-based systems to monitor and manage flood risks in real time (Klijn *et al.*, 2015). These systems use data from various sources, including water level sensors, weather forecasts,

and infrastructure status reports, to provide an overall view of flood risks and assets (Jonkman *et al.*, 2018).

The GIS-based flood management systems allow the Dutch water authorities to monitor the condition of critical flood defence infrastructure, such as dykes, pumping stations, and storm surge barriers in real time (Jonkman *et al.*, 2018). For example, the system provides information on the structural integrity of major flood defence structures, that can lead to quick identification of potential weaknesses or damages and allowing for rapid response and prioritisation of repairs or upgrades (Klijn *et al.*, 2015).

By using these GIS-based systems, the Dutch water authorities can make informed decisions during flood events, optimise maintenance schedules, and plan investments in flood protection infrastructure (Koks *et al.*, 2015). This real-time asset management approach has significantly enhanced the capacity to manage flood risks and protect the low-lying areas from the potential impacts of flooding.

The fifth way in which GIS is used for in flood management is ERP (Wood, 2000). ERP refers to the development and implementation of procedures, protocols, and strategies aimed at effectively responding to an emergency (Feng & Cui, 2021). The primary goal of ERP is to protect people, assets, and the environment during and after a crisis (Alexander, 2015). GIS can be used to support emergency response efforts, including search and rescue operations, evacuation planning, and the distribution of aid and supplies (Goodchild & Glennon, 2010). The integration of GIS with other technologies, such as GPS and mobile devices, can support real-time decision-making during emergency response operations (Goodchild & Glennon, 2010).

In Asia, the Department of Disaster Prevention and Mitigation (DDPM) in Thailand uses GIS for ERP in flood management (Tanwattana, 2021). This usage of GIS includes information on flood-prone areas, evacuation routes, and emergency shelters. GIS is used to generate flood risk maps that help the DDPM to plan for and respond to flood events. The flood risk maps are also used to communicate flood risks to the public and to support community-based disaster risk reduction initiatives (Maier-Knapp, 2015).

GIS has proven to be a valuable tool for enhancing flood management efforts by providing spatial information and enabling data analysis. GIS offers numerous benefits in terms of flood management, including improved flood mapping, flood modelling, EWSs, asset management, and ERP. However, despite its potential benefits, the implementation of GIS in flood management is not without challenges (Aidinidou *et al.*, 2023; Ali *et al.*, 2019; Fotovatikhah *et al.*, 2018).

One of the main challenges of implementing GIS in flood management is the availability and accuracy of data (Hall *et al.*, 2003; Sanyal & Lu, 2004). Flood management requires a large amount of data, including historical flood records, hydrologic data, topographic data, and land-use information (Sood *et al.*, 2018). This data must be accurate and up to date in order to effectively model and predict flood impacts. In many cases, the data necessary for flood management is either not available or not of sufficient quality to support effective decision making (Petersson *et al.*, 2020).

The nature of data challenges can vary depending on the context and region. In some cases, there may be limited data available due to inadequate monitoring infrastructure or political barriers (Mennecke & West, 2001). For instance, in many African countries, there is limited infrastructure for monitoring water levels, river flow rates, and precipitation, which can make it difficult to develop accurate flood models and predictions (Tarpanelli *et al.*, 2023). This can result in communities being caught off guard by floods, which can have devastating consequences (Reynolds *et al.*, 2020). As stated above, political barriers can hinder data collection and sharing, leading to limited data availability (Mennecke & West, 2001). For example, in some regions with political conflicts, like the Gaza Strip, access to data may be restricted, making it difficult to obtain the necessary information for flood management planning (Alastal *et al.*, 2019). This can make it challenging to develop effective flood management strategies, resulting in increased risk to communities and infrastructure (Bernhofen *et al.*, 2022).

In other cases, the available data may be outdated or of poor quality, which can lead to inaccurate flood maps and ineffective flood management strategies (Kundzewicz *et al.*, 2018). One common example of outdated data is using old flood maps that do not reflect changes in land use or development over time (Knowles & Kunreuther, 2014; Thomas & Liechenko, 2011). This can result in inaccurate assessments of flood risk and ineffective flood management strategies (Kundzewicz *et al.*, 2018). For instance, the city of Houston, which experienced devastating flooding after Hurricane Harvey in 2017, is an example of outdated data leading to ineffective flood management strategies (Pralle, 2019). Zhang *et al.* (2018) note that the outdated flood maps were a factor that contributed to the severity of the flooding in Houston in 2017, as the Houston flood maps did not accurately reflect changes in land use and development that had occurred in the region over the previous decades. The outdated maps resulted in inadequate flood management strategies and increased risk to communities and infrastructure.

Additionally, the type of data required for effective flood management can also vary depending on the specific context (Tariq *et al.*, 2020). For example, in urban areas, data on building heights, road networks, and drainage systems may be critical for modelling flood scenarios and developing



evacuation plans (Bulti & Abebe, 2020; Kourtis & Tsihrintzis, 2021; Milojevic-Dupont *et al.*, 2020). One example of an urban area flood management system is the flood control measures implemented by the Tokyo Metropolitan Government in Japan. One notable flood management system in Tokyo is the Metropolitan Area Outer Underground Discharge Channel (MAOUDC). This system consists of a 6.3 km long network of tunnels and cylindrical structures buried underground (Sukmawati & Widana, 2022). It serves as a floodwater cathedral and is designed to redirect and contain floodwater during heavy rainfall or typhoons. The underground channels and discharge tunnels help alleviate the pressure on above-ground drainage systems, preventing widespread flooding in the city (Knuijt, 2022). In rural areas, on the other hand, data on topography, land use, and soil characteristics may be more important for assessing flood risk as there are fewer built-up areas (Rahayu *et al.*, 2023). For example, in Nepal, which is prone to landslides during the monsoon season, researchers have used GIS and remote sensing data to map the landscape and identify areas that are at high risk of landslides (Gautam *et al.*, 2021). This information can be used to develop EWSs and inform land-use planning to reduce the risk of future disasters (Thapa & Adhikari, 2019).

The second challenge that GIS faces is that of integration among different organisations and people. Flood management often requires integration among various stakeholders, including government agencies, private companies, and individuals (Kreibich *et al.*, 2017). This increases the risk of the number of people who are unsure about their job description. This problem, coupled with spatial fragmentation can have a significant negative effect on GIS capability, which may have an impact on the advantages GIS may provide in flood management (Roy *et al.*, 2008). Spatial fragmentation refers to the unequal spatial pattern in the built-up areas of a city (Balbo & Navez-Bouchanine, 1995).

In the USA, flood management is often a collaborative effort between multiple agencies at the federal, state, and local levels (Tyler *et al.*, 2021). For example, the Federal Emergency Management Agency (FEMA) is responsible for developing flood maps and providing financial assistance to communities for flood mitigation and recovery efforts (Kousky & Shabman, 2017). Meanwhile, local governments are often responsible for implementing flood management strategies, such as zoning regulations and infrastructure improvements (Peterson *et al.*, 2020). However, coordination between different agencies can be challenging due to the use of different GIS systems and data formats (Abdeen *et al.*, 2021; Peters, 2018). For example, FEMA's Flood Insurance Rate Maps (FIRMs) use a different data format than the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service River Forecast Centers (RFCs). The reason for this is because FIRMs are designed for long-term flood risk assessment and insurance rate determination, whereas RFCs focus on real-time monitoring and forecasting of

river conditions (Gochis *et al.*, 2018; Maune *et al.*, 2007; McEnery *et al.*, 2005; Tate *et al.*, 2015). This differing data formats can make it difficult for local governments to integrate the flood data from these different sources into their own GIS systems and develop effective flood management strategies (Waterman *et al.*, 2021). Furthermore, there may be differing priorities and objectives between agencies, which can further complicate coordination efforts (Curnin *et al.*, 2015; Gooding *et al.*, 2022). For example, while FEMA's primary focus is on providing financial assistance for flood mitigation and recovery efforts, local governments may also be concerned with protecting infrastructure and ensuring public safety during flood events (Dzigbede *et al.*, 2020; Reese, 2018). These differing priorities and objectives can make it difficult to develop a cohesive and effective flood management strategy that addresses the needs of all stakeholders (Tariq *et al.*, 2020).

The third challenge with implementing GIS in flood management is technical complexity. GIS is a complex technology that requires specialised skills to operate effectively. Implementing GIS in flood management can require significant technical expertise, which can be a challenge for organisations with limited resources (Tariq *et al.*, 2020; Venkataramanan *et al.*, 2020). Furthermore, the time required to understand and teach GIS has been identified as a barrier to GIS use (Göçmen & Ventura, 2010). According to Bernhäuserová (2022), educators' limitation of time to learn and teach GIS not only hampered its inclusion in the school curriculum but has also been troublesome because educators need time to produce teaching material for lessons as well as time for students to comprehend and use GIS technology.

Countries with well-developed technical infrastructure, such as Western European countries, may have more advanced GIS capabilities for flood management (Alfieri *et al.*, 2018). These countries may have access to high-quality data sources, such as LIDAR (Light Detection and Ranging) data, which can be used to create highly detailed flood models (Proestakis *et al.*, 2019; Wedajo, 2017). Additionally, Western European countries have a well-trained workforce with the necessary technical skills to develop and implement GIS models effectively (Falter *et al.*, 2015; Foudi *et al.*, 2015; Morita, 2011; Rojas *et al.*, 2013; Winsemius *et al.*, 2013).

Developing countries, on the other hand, such as many countries in sub-Saharan Africa or South Asia, may face more significant challenges in implementing GIS for flood management (Taleai *et al.*, 2009). These developing countries may have limited technical infrastructure, such as poor internet connectivity or a shortage of computer hardware (Oluwatayo & Ojo, 2018). Additionally, developing countries may have limited data sources available, which can limit the accuracy of flood models (Mansourian & Valadan Zoej, 2008). Developing countries may also have a shortage of trained GIS professionals, which can make it challenging to develop and implement GIS models effectively (Taleai *et al.*, 2009).

Island nations, such as the Maldives or the Bahamas, may face unique challenges in implementing GIS for flood management due to their geography and their high susceptibility to climate change (Betzold, 2015). These countries may have limited land area, which can make it difficult to create accurate topographic maps, therefore requiring a more technical complex flood model (Gosling-Goldsmith *et al.*, 2019). Additionally, island nations are more vulnerable to the effects of sea-level rise, which can make it challenging to predict and manage flooding events (Donner & Webber, 2014).

Coastal regions, such as the Gulf Coast of the US or the Netherlands, may also face unique challenges in implementing GIS for flood management (Bates *et al.*, 2021; Hadipour *et al.*, 2020; Jonkman *et al.*, 2008). These regions may be more susceptible to storm surges and tidal flooding, which can require specialised modelling techniques (Bates *et al.*, 2021; Eilander *et al.*, 2020). Additionally, coastal regions can have complex hydrological and geohydrological systems, which can make it challenging to accurately predict flooding events (Fisher, 2005; Jiao & Post, 2019).

The cost of purchasing, installing, and maintaining GIS software and hardware can be a significant barrier for many organisations in implementing GIS into flood management (Henrico, 2016). In some cases, the cost of acquiring the necessary data and training staff on GIS use can also be a significant financial burden (Longley *et al.*, 2015). The relatively high cost of GIS software and hardware in many countries in sub-Saharan Africa, can make it difficult for organisations to afford and implement GIS technology (Mwange *et al.*, 2018). For example, the cost of ArcGIS software in Tanzania can be as high as \$550 per year, which is a significant expense for many people, seeing as the gross domestic product (GDP) per capita is expected to be \$1 148 by the end of the year of 2024 (Trading Economics, 2024).

The fifth challenge in using GIS for flood management is user acceptance (Canillo & Hernandez, 2021; Chan *et al.*, 2022; Zeng *et al.*, 2021). One of the biggest challenges in implementing GIS in flood management is getting stakeholders and decision makers to understand and accept the technology and its outputs (Goodchild, 2007). This can require significant education and training efforts to ensure that decision makers are able to effectively use GIS in their work (O'Looney, 2000). Below follows some specific regional and contextual examples that illustrate how user acceptance of GIS for flood management can differ.

In some traditional societies, such as some indigenous communities in the Amazon rainforest, there may be a preference for traditional knowledge and practices over new technologies (Schmidt *et al.*, 2021). In these contexts, there may be a need to build trust and demonstrate the benefits of GIS for flood management to gain user acceptance (Pradeep & Wijesekera, 2021). In regions that have experienced a recent flooding event or other disaster, there may be a greater

willingness to adopt new technologies such as GIS for flood management. For example, after Hurricane Katrina in the USA, there was a significant push to adopt new technologies and approaches to flood management (Kates *et al.*, 2006).

In some highly developed urban areas, such as Tokyo or Singapore, there may be a greater willingness to embrace new technologies and approaches to flood management due to a high level of technological literacy and a desire for innovative solutions to urban challenges (Newman *et al.*, 2016). This is in direct contrast with rural areas where, particularly in developing countries, there may be a lack of technical infrastructure and expertise, which can limit user acceptance of GIS for flood management (Panek, 2013). In these contexts, there may be a need to build technical capacity and provide support for GIS implementation (Alzahrani *et al.*, 2021).

The final challenge in using GIS for flood management is crucial to overcome in the context of this study. To effectively address urban flooding, different hydrological and urban stormwater models should be developed on a case-by-case basis (Chen & Feng, 2021; Guo *et al.*, 2021; Mannina & Viviani, 2009). According to Guo *et al.* (2021), careful research must be conducted on which flood-related elements – rainfall, land cover, river networks for example – can be integrated into a model that can be applied to a specific city. Developing hydrological and urban flooding models on a case-by-case basis can be challenging in different regions and contexts due to a variety of factors (Chen *et al.*, 2022; Guo *et al.*, 2021; Nkwunonwo *et al.*, 2020). Below follows some specific examples.

The urban form and density of a city can affect the design and implementation of flooding models (Li *et al.*, 2021; Bruwier *et al.*, 2020). In highly dense urban areas, such as Tokyo or Hong Kong, there may be a need to develop highly specialised models that take into account the unique urban form and land use patterns of the city (Chan *et al.*, 2018; Takagi *et al.*, 2018). Climate variability can also have an effect on the design and implementation of flood management strategies (Jongman, 2018; Khan *et al.*, 2021; Tabari, 2020). In regions with high climate variability, such as some parts of Southeast Asia, there may be a need to develop flooding models that can adapt to changing rainfall patterns and extreme weather events (Kundzewicz *et al.*, 2019; Räsänen & Kumm, 2013). Thirdly, the local infrastructure of a city can affect the design and implementation of flood management strategies (Yereseme *et al.*, 2022; Chocat *et al.*, 2007). In some regions, such as some parts of East Asia, there may be high percentage of impermeable area, which can make it challenging to develop effective flood management strategies (Ana & Bauwens, 2010). Fourthly, it could be said that developing hydrological and urban flooding models that are unique and developed for a specific case can require significant financial resources, which may be a challenge in some regions (Olcese *et al.*, 2022; Peredo *et al.*, 2020). In regions with limited

financial resources, such as some parts of sub-Saharan Africa, there may be a need to prioritise and phase flood management strategies based on available resources (Triki & Faye, 2013).

AG refers to the ability of decision makers to anticipate and address potential future risks and challenges. GIS can play a valuable role in supporting AG efforts by providing decision makers with the information they need to make informed choices about the future. In the concluding section of this part of the literature study, the value of GIS as a tool for AG is discussed.

### **2.3.7 Geographical information systems as a tool for anticipatory governance**

A GIS is a powerful tool that enables individuals and organisations to collect, analyse, and visualise spatial data (Goodchild & Haining, 2004). In the context of AG, GIS can be used to support decision-making processes that anticipate and respond to future risks, uncertainties, and opportunities (McCall & Dunn, 2012). This section of the study looks at specific ways in which GIS can be used as a tool for AG, with different examples cited throughout the discussion to highlight the versatility and usability of GIS, and how it can help decision makers who want to implement AG. This section ties together the concepts of GIS and AG, which is central to the study's approach.

#### **2.3.7.1 Data collection and analysis**

GIS can be used as a tool for AG by collecting and analysing spatial data to identify emerging risks, opportunities, and trends. Spatial data includes information that has a geographic or spatial component, such as maps, satellite images, and sensor data (DeMers, 2008).

The first way in which GIS can be used for data collection and analysis is in the context of climate change. By using GIS to analyse spatial data on temperature, precipitation, and other climate-related factors, decision makers can identify areas that are most vulnerable to the impacts of climate change, such as exacerbated flood prone areas (Shirzaei & Bürgmann, 2018). This can help decision makers to allocate resources and interventions more effectively and efficiently to reduce the risks and impacts of climate change (Burghila *et al.*, 2015).

A practical example of how GIS can be used for data collection and analysis in the context of climate change is by assessing the urban heat island effect. The urban heat island effect refers to the phenomenon where urban areas experience higher temperatures compared to their surrounding rural areas due to human activities and the built environment (Deilami *et al.*, 2018; Xie *et al.*, 2015). GIS can aid in studying and mitigating this effect, as is the case in the USA, Portugal, Bulgaria, and Egypt among others (Abutaleb *et al.*, 2015; Dimitrov *et al.*, 2020; Reis *et al.*, 2022; Xian, 2021).

GIS can be used for data collection in its assessment of the urban heat island effect (Dimitrov *et al.*, 2020). It can incorporate satellite data to capture land surface temperature across urban and rural areas (Purio *et al.*, 2022). This satellite data can provide insights into temperature variations and the intensity of the urban heat island effect (Zhou *et al.*, 2019a). GIS can also integrate land use and land cover data to understand the distribution of impervious surfaces, such as roads, buildings, and pavement, within urban areas (Liping *et al.*, 2018; Zioti *et al.*, 2022). This information on surface imperviousness can help identify areas susceptible to heat accumulation (White-Newsome *et al.*, 2013).

GIS can perform spatial analysis to quantify the temperature differences between urban and rural areas, highlighting the extent of the urban heat island effect (Ayanlade *et al.*, 2021). It can also identify hotspots within cities, where the effect is more pronounced (Hendel *et al.*, 2020). GIS can enable the creation of models and simulations to forecast future scenarios of urban heat island effect based on factors such as population growth, land use changes, and climate projections (Chen *et al.*, 2020; Stehfest *et al.*, 2019).

By employing GIS for data collection and analysis, researchers and decision makers can gain insight into the urban heat island effect and develop strategies to mitigate its adverse impacts on the public.

The second way in which GIS can be used for data collection and analysis is in the context of urban planning. By using GIS to analyse spatial data on population density, land use, and transportation, decision makers can identify areas that are most in need of new infrastructure, services, or housing (Van Maarseveen *et al.*, 2019). This can help decision makers to plan more effectively for future growth and development, and to anticipate and manage emerging challenges such as traffic congestion or urban sprawl (Rahman, 2019).

A practical example of how GIS can be used for data collection and analysis in the context of urban planning is through resource inventory. GIS platforms, particularly when used in conjunction with remote sensors, can significantly reduce the time spent collecting land-use and environmental information (Bandyopadhyay *et al.*, 2009). It can assist in creating zoning maps, which define and regulate the types of land uses allowed on specific parcels of land and establish design and development requirements and guidelines (Nabati *et al.*, 2020). By using spatial analysis techniques, GIS can help identify and analyse various zoning designations and their impact on urban planning (Ramteke *et al.*, 2018). It can aid urban planners with resource inventory as is the case in Nepal, Egypt and India among others (Ramteke *et al.*, 2018; Thilagam & Sivasamy, 2013; Twayana *et al.*, 2021).

Another example of GIS helping urban planners with data collection and data analysis is the use of GIS for three-dimensional (3D) high-resolution scenario building (Sadoun & Al-Hanbali, 2007). This involves employing structure from motion (SfM) photogrammetry modelling to construct detailed 3D models of urban areas (Iheaturu *et al.*, 2022). Such models can be used to visualise and simulate proposed urban developments, allowing urban planners to assess their potential impact on the surrounding environment and infrastructure (Wu, 2021).

Furthermore, GIS can facilitate geological surveying, mapping, and data collection (Chamine *et al.*, 2021; Giardino *et al.*, 2010). Integrated virtual reality (IVR) can be employed to gather geological data, which is then analysed using GIS for tasks such as calculating extracted volumes and producing new maps (Antoniou *et al.*, 2020). This combination of technologies enables urban planners to gain insight into the geological characteristics of an area, informing decisions related to land use and development.

In summary, GIS provides valuable tools for data collection and analysis in urban planning. It aids in resource inventory, zoning map creation, 3D scenario building, and geological surveying, mapping, and analysis. By leveraging GIS, urban planners can help decision makers make more informed decisions and effectively manage urban development.

GIS can also be used for data collection and analysis in the context of public health. By using GIS to analyse spatial data on disease outbreaks, hospital admissions, and other health-related factors, decision makers can identify areas that are most at risk of infectious diseases or other health threats (Kamel Boulos & Geraghty, 2020). This can help decision makers to develop more effective and targeted public health interventions, such as vaccination campaigns or disease surveillance systems (Davenhall & Kinabrew, 2012).

One specific example of a GIS application in public health is disease surveillance and mapping (Musa *et al.*, 2013; Shaw & McGuire, 2017). GIS allows health authorities to collect and analyse data on disease incidence and prevalence, along with relevant demographic and environmental factors, to gain insight into disease patterns and potential risk factors (Franch-Pardo *et al.*, 2020). By mapping the geographic locations of reported cases, GIS can visualise disease clusters and hotspots, helping public health officials identify areas at higher risk and allocate resources accordingly (McLafferty, 2015). For instance, in a study published in 2014, it was found that GIS techniques were used in one-fourth of the reviewed articles related to infectious disease mapping (Lyseen *et al.*, 2014). GIS enables researchers to integrate various data sources such as population density, environmental factors, and socioeconomic indicators, creating a comprehensive picture of disease transmission dynamics (Tatem *et al.*, 2012). This information on transmission dynamics can guide targeted interventions, such as vaccination campaigns or

vector control measures, in areas most susceptible to disease outbreaks (Gandon & Lion, 2021; Guan *et al.*, 2022).

In these different ways, GIS can theoretically be used as a tool of AG in the eThekweni Metropolitan Municipality, offering methodologies to address flood risk through proactive, spatially informed strategies. By synthesising data on climate change, urbanisation, and public health, GIS enables the identification of vulnerabilities and modelling of future scenarios, aligning with AG's emphasis on foresight and adaptive planning.

For climate change adaptation, GIS's analysis of urban heat islands and flood-prone zones could be applied to informal settlements like Quarry Road West, where impervious surfaces intensify thermal extremes and runoff. Integrating satellite temperature data with floodplain mapping may inform theoretical interventions, such as green infrastructure in Durban's CBD or stormwater upgrades in low-lying areas.

In urban planning, GIS's 3D scenario modelling could guide policies for settlements in uMlazi or oThongathi, simulating how housing projects might alter drainage patterns. Participatory GIS methods may also engage communities in risk mapping, theoretically leading to infrastructure investments, such as reinforced riverbanks in the uMngeni catchment.

For public health, GIS's disease surveillance applications could pre-empt outbreaks in flood-affected areas like Inanda, overlaying risk maps with health facility data to identify care gaps and prioritise medical supply stockpiling.

While these above-mentioned applications remain theoretical, they illustrate GIS's potential to enhance AG in the eThekweni Metropolitan Municipality, bridging spatial analysis with governance. Challenges, such as data gaps in informal settlements, highlight the need for collaborative models integrating local knowledge. This framework positions GIS as a tool of AG to theoretically reorient flood management from reactive response to proactive resilience within the eThekweni Metropolitan Municipality.

#### **2.3.7.2 Scenario planning**

GIS can be used as a tool for AG through scenario planning. Scenario planning is a process that involves creating and testing different hypothetical futures based on different assumptions and inputs (Chermack & Lynham, 2002). Scenario planning allows decision makers to explore a range of possible outcomes and to prepare for uncertain or unexpected events (Goodwin & Wright, 2001).



Regarding climate change, GIS can be used to create and test different scenarios that explore the potential effects of climate change on different regions and communities (Ashiq *et al.*, 2010; Matouq *et al.*, 2014). Decision makers can use GIS to model the potential effects of climate-related factors on infrastructure, ecosystems, and human health (Chiabai *et al.*, 2018; Estrada-Peña & Venzal, 2007). By testing different scenarios, decision makers can anticipate and prepare for potential disasters (Ortolano *et al.*, 2017).

In an example of how GIS can create different scenarios, consider when researchers want to understand the potential impact of rising sea levels on coastal communities (Bamber *et al.*, 2019; Li *et al.*, 2009; Maulud & Rafar, 2015; Schuldt *et al.*, 2020). Using GIS, researchers can gather data on the elevation of different regions, the location of communities, and projections for future sea-level rise (Malik & Abdalla, 2016). By integrating this information, GIS software can generate maps that visually represent the potential extent of coastal flooding in different sea-level rise scenarios (Gravelle & Mimura, 2008). For instance, GIS, with the help of machine learning (ML) can simulate how a 100 millimetre rise in sea levels might affect specific coastal regions (Hawchar *et al.*, 2020). GIS can identify vulnerable areas, such as low-lying neighbourhoods, critical infrastructure, or important ecological zones (Lin *et al.*, 2021; Klein *et al.*, 2019). By overlaying demographic data, GIS can also analyse how a rise in sea levels might disproportionately affect certain communities, such as low-income or marginalised groups (Handwerger *et al.*, 2021).

GIS can further facilitate the exploration of adaptation and mitigation strategies of the sea-level rising (Boateng, 2012). For example, researchers can evaluate the effectiveness of building sea walls, implementing land-use planning regulations, or promoting community relocation in response to sea-level rise (Critchley *et al.*, 2021; Bongarts Lebbe *et al.*, 2021). By modelling these scenarios within GIS, decision makers can estimate the potential benefits, costs, and trade-offs associated with different strategies, aiding decision-making processes (Bareth, 2009; Crossland, 2008).

In the context of urban planning, GIS can be used to create and test different scenarios that explore the potential effects of urban growth and development on different regions and communities (Soward & Li, 2021). Decision makers can use GIS to model the potential effects of different land use patterns, transportation systems, and housing policies on infrastructure, ecosystems, and social equity (Shay *et al.*, 2016; Yigitcanlar *et al.*, 2007). By testing different scenarios, decision makers can anticipate and prepare for potential risks, such as traffic congestion, air pollution, or urban sprawl (Karakayaci, 2016; Zhang *et al.*, 2022).

One example of using GIS to explore the potential effects of different rates of urban growth and development is the application of the SLEUTH (slope, land cover, excluded regions, urban land

cover, transportation, and hill shade) urban growth model (Zhou *et al.*, 2019b). The SLEUTH model is a widely used tool for simulating future urban growth patterns and assessing environmental impacts in urban planning (Hossain Shubho & Islam, 2020). The model uses GIS data and scenario analysis techniques to project and analyse different urban growth scenarios under varying development conditions (Saxena & Jat, 2019).

Using the SLEUTH model and GIS, planners can input various parameters such as population growth rates, land use policies, transportation infrastructure, and environmental factors (Alay *et al.*, 2021; Hossain Shubho & Islam, 2020; Li *et al.*, 2018; Mondal *et al.*, 2020). The SLEUTH model then simulates the potential urban growth patterns that may arise under these conditions. By comparing and analysing the results of different scenarios, planners can assess the potential effects of urban growth on factors such as land use changes, habitat fragmentation, transportation networks, and environmental quality. This information can aid in making informed decisions regarding urban development, policy-making, and sustainable planning practices.

GIS therefore plays an important role in urban planning by providing a platform for spatial analysis, scenario testing, and decision making. By leveraging GIS technologies and models like SLEUTH, planners and decision makers can better understand the potential consequences of urban growth and development, allowing decision makers to make informed choices that promote sustainable urban environments.

Lastly, when looking at public health, GIS can be used to create and test different scenarios that explore the potential effects of infectious diseases or other health threats on different regions and communities (Gao *et al.*, 2008; Wang, 2020). Decision makers can use GIS to model the potential effects of different vaccination rates, disease surveillance systems, and health interventions on human health and wellbeing (Phillips *et al.*, 2023). By testing different scenarios, decision makers can anticipate and prepare for potential risks, such as disease outbreaks or pandemics (Ahasan & Hossain, 2021).

For example, during the COVID-19 outbreak, GIS was extensively employed to model and analyse the spread of the virus and its impact on communities (Franch-Pardo *et al.*, 2020). ESRI, a prominent GIS software company, incorporated open-source models like the CHIME (COVID-19 Hospital Impact Model for Epidemics) model into their geospatial toolbox to align the models directly with the data source that drives the models (Wang & Aydin, 2020). The integration of models into GIS enables users to connect to relevant data sources, such as current case information, hospitalisation rates, susceptible populations, and more (Lucky *et al.*, 2022). By adjusting parameters and exploring different scenarios, decision makers can visualise how behaviours, interventions, and various measures affect the course of the disease across different

regions and over time (Lucky *et al.*, 2022). This helps in understanding the potential effects of infectious diseases on communities and supports evidence-based decision making.

In summary, scenario planning, supported by GIS, can theoretically enhance AG in the eThekweni Metropolitan Municipality by modelling diverse flood risk futures, enabling decision-makers to prepare for uncertainties through spatially informed strategies. By integrating climate projections, urban development trends, and public health data, GIS facilitates the creation of actionable scenarios aligned with AG's focus on proactive resilience.

For climate change, GIS can model sea-level rise scenarios impacting the eThekweni Metropolitan Municipality's coastal zones, such as the Durban beachfront or the mangrove ecosystems of the uMdloti River estuary. By overlaying elevation data, demographic maps, and infrastructure layouts, GIS could simulate the inundation risks for low-lying informal settlements like Merebank or the industrial port area. Additionally, GIS could model rainfall variability under different Shared Socioeconomic Pathways (SSPs), such as increased precipitation under SSP5 (high emissions) or reduced rainfall under SSP1 (sustainable development). These scenarios could reveal how changing rainfall patterns might exacerbate or mitigate flood risks in areas like the informal settlements. Theoretical adaptations, such as constructing seawalls, restoring coastal wetlands, or upgrading stormwater systems, might be evaluated for cost-benefit trade-offs, guiding prioritisation of interventions that protect vulnerable communities and critical economic assets.

In urban planning, GIS-driven models like SLEUTH could simulate urban expansion in flood-prone wards such as uMlazi or oThongathi, projecting how population growth and horizontal informal settlement growth might strain stormwater systems. Scenario testing could assess the efficacy of policies like enforced buffer zones along the uMngeni River or investments in permeable surfaces to mitigate runoff. Participatory GIS could theoretically engage residents in co-designing scenarios, ensuring plans reflect local knowledge, for instance, identifying informal drainage pathways in Cato Manor that are absent from formal datasets.

For public health, GIS can model post-flood disease outbreak scenarios, particularly in informal settlements, where contaminated water and poor sanitation heighten cholera risks. By overlaying flood projections with healthcare facility locations and population density maps, scenarios might reveal gaps in emergency response capacity, informing theoretical strategies such as mobile clinic deployments or community-led sanitation campaigns during rainy seasons.

While these applications remain theoretical, they illustrate GIS's potential to enhance AG in eThekweni, bridging spatial analysis with governance. Challenges, such as data gaps in informal settlements or limited stakeholder coordination, highlight the need for collaborative frameworks integrating different decision makers. This framework positions GIS as a tool of AG to theoretically reorient flood management from reactive response to proactive resilience.

### **2.3.7.3 Spatial modelling**

GIS can be used as a tool for AG through spatial modelling. Spatial modelling is a process that involves using spatial data and mathematical algorithms to simulate and predict spatial patterns and processes (O'Sullivan & Unwin, 2010). Spatial modelling allows decision makers to test different scenarios and predict the potential outcomes of different interventions or policies (Wang *et al.*, 2021).

In the context of natural disasters, GIS can be used to simulate and predict the potential impacts of natural hazards, such as earthquakes or floods (van Westen, 2013). Decision makers can use GIS to model the potential effects of different hazard scenarios on infrastructure, ecosystems, and human populations, and to identify areas that are most at risk (Fekete *et al.*, 2021; Rezvani *et al.*, 2023). By using spatial modelling, decision makers can anticipate and prepare for potential risks, such as landslides, building collapses, or floods (Feng *et al.*, 2023; Zêzere *et al.*, 2014).

Spatial modelling systems employ a variety of mathematical algorithms and models to enhance the accuracy and reliability of predictions. One widely used algorithm in GIS for simulating earthquakes is the finite element method (FEM) (Castaldo & Tizzani, 2016). FEM divides the affected region into small elements and analyses the interactions between them based on the principles of structural mechanics (Lysmer & Drake, 1972). This approach allows for the estimation of potential ground movements, strains, and stresses caused by seismic activity.

In the case of hurricanes or tropical cyclones, numerical weather prediction models are commonly employed. The weather research and forecasting (WRF) model is an example of a numerical weather prediction model, widely used for both atmospheric research and operational forecasting applications (Powers *et al.*, 2017). Since its initial release in 2000, the WRF model has become one of the world's most widely used numerical weather prediction models (Powers *et al.*, 2017).

The WRF model incorporates two dynamic cores, a data assimilation system, and a software architecture that supports parallel computation and system extensibility (Skamarock *et al.*, 2019). The WRF model allows researchers and operational forecasters to simulate and forecast atmospheric processes on various spatial and temporal scales (Powers *et al.*, 2017). The model

and other mesoscale models like it, use complex mathematical equations to simulate the behaviour of the atmosphere by dividing the domain into a grid and solving equations at each grid point. These mesoscale models incorporate various data sources such as weather observations and satellite imagery to initialise the model and make predictions (Dudhia, 2014).

For flood prediction, hydrological models are frequently used in GIS (Kourgialas & Karatzas, 2011; Teng *et al.*, 2017). These models simulate the flow of water in river systems, accounting for factors such as rainfall, soil characteristics, topography, and land use. Various mathematical techniques, including the Muskingum-Cunge method, the Manning's equation, and the Hydrologic Engineering Center–River Analysis System (HEC-RAS) model, are employed to calculate water levels, velocities, and flood extents (Chow, 1959; Cunge, 1969; Manning *et al.*, 1890; Tinkler, 1982). These models assist in identifying vulnerable areas and predicting the potential severity of flooding events.

When looking at land use planning, GIS can be used to simulate and predict the potential effects of different land use patterns on ecosystems, biodiversity, and human health (Fagerholm *et al.*, 2016; Mansour *et al.*, 2020). Decision makers can use GIS to model the potential effects of different land use scenarios, such as urbanisation or deforestation, on soil erosion, water quality, and air pollution (Aneesha Satya *et al.*, 2020; Oñate-Valdivieso & Sendra, 2010). By using spatial modelling, decision makers can anticipate and mitigate potential risks, such as habitat loss, soil degradation, or respiratory diseases (AbdelRahman, 2023; Eigenbrod *et al.*, 2008; Salata, 2021). GIS algorithms and models help in analysing the relationships between land use and its effects on ecosystems or biodiversity to name a few. Some commonly used algorithms and models used to explore land use and its effects on the area are as follow.

Cellular Automata (CA) models simulate land use changes based on local interactions among cells within a defined geographic area (Guzman *et al.*, 2020). Each cell represents a specific land use type, and the model updates the land use of each cell based on a set of transition rules (White & Engelen, 2008). These rules consider factors such as proximity to existing land uses, accessibility, suitability, and other relevant parameters (Xu *et al.*, 2023).

Markov Chain Analysis models are stochastic models that predict land use changes based on the probabilities of transitioning from one land use type to another (Sang *et al.*, 2011). These probabilities of land use transition are derived from historical land use data and can be used to project future land use patterns (Kumar *et al.*, 2014). Markov Chain Analysis models assume that land use transitions are influenced by past states (Iacono *et al.*, 2012).

By employing mathematical algorithms and models within GIS, planners and researchers can simulate and predict the potential impacts of different land use patterns on ecosystems, biodiversity, and human health. This helps the decision makers in making informed decisions and designing more sustainable and ecologically friendly land use plans.

Lastly, with regard to energy planning, GIS can be used to simulate and predict the potential effects of different energy scenarios on greenhouse gas emissions, energy consumption, and renewable energy development (Al-Kurdi *et al.*, 2019; Moghadam *et al.*, 2017). Decision makers can use GIS to model the potential effects of different energy policies, such as carbon taxes or feed-in tariffs, on energy demand, supply, and distribution (Eslami *et al.*, 2022; Ferrari *et al.*, 2021). By using spatial modelling, decision makers can anticipate and promote potential opportunities, such as job creation, energy security, or climate mitigation (Martchamadol & Kumar, 2014; Sieber, 2012).

Spatial simulations can help evaluate various factors such as greenhouse gas emissions, energy consumption, and renewable energy development (Liang *et al.*, 2021; Mohammadi & Taylor, 2017; Xiang *et al.*, 2022). The mathematical algorithms and models used in the modelling process can vary depending on the specific analysis and goals (Wess *et al.*, 2021). Here are some commonly used approaches.

Regression models can be employed to establish relationships between energy-related variables and spatial factors (Hsu, 2015). For example, energy consumption can be modelled as a function of population density, income levels, building types, or other relevant parameters (Muzayanah *et al.*, 2022; Vo & Vo, 2021; Güneralp *et al.*, 2017). Regression analysis helps quantify the influence of different factors on energy consumption or renewable energy potential (Zhou *et al.*, 2021c).

Spatial interpolation techniques are used to estimate values at unsampled locations based on known values from sampled locations (Bajjali, 2018; Longley *et al.*, 2015). In energy planning, interpolation methods can be employed to estimate variables such as solar irradiance, wind speed, or temperature across a region (Kumar *et al.*, 2020; Lee, 2022; Ruiz-Arias, 2022). Common interpolation techniques include inverse distance weighting, kriging, and splining (Wu & Hung, 2016).

Optimisation models are used to find the best possible solution given a set of constraints and objectives (Gill *et al.*, 2008). In the context of energy planning, optimisation models can optimise the location and capacity of renewable energy installations or transmission networks to minimise costs, maximise renewable energy generation, or reduce greenhouse gas emissions (Debnath & Mourshed, 2018; Keck *et al.*, 2022; Klemm & Wiese, 2022). Linear programming, mixed-integer

linear programming, or heuristic algorithms like genetic algorithms or particle swarm optimisation are often applied to optimisation models (Cosic *et al.*, 2021; Lauinger *et al.*, 2016; Kokash., 2005).

It could be said that the choice of algorithms and models depends on the specific objectives, data availability, and complexity of the problem at hand. Energy planners can tailor their modelling approaches to specific needs to gain insights and make informed decisions regarding energy scenarios and their effects on greenhouse gas emissions, energy consumption, and renewable energy development.

In each of these three examples, natural disasters, land use planning and energy planning, spatial modelling using GIS can theoretically be used as a tool for AG in the eThekweni Metropolitan Municipality, enabling decision makers to simulate flood risks, evaluate mitigation strategies, and prioritise interventions through data-driven foresight. By integrating spatial data on hydrology, land use, and socio-economic vulnerabilities, GIS transforms theoretical models into actionable insights, aligning with AG's goal of proactive resilience-building.

For natural disaster management, hydrological models such as HEC-RAS could simulate flood extents in eThekweni's uMngeni River catchment, where informal settlements like Quarry Road West and formal developments in Durban's CBD face recurrent inundation risks. By inputting high-resolution topographic data and rainfall projections, GIS could model scenarios of extreme weather events, theoretically identifying critical overflow points in river systems. For instance, simulating the impact of a 1-in-100-year storm could highlight vulnerabilities in drainage infrastructure or the need for elevated evacuation routes in low-lying areas.

In land use planning, Cellular Automata (CA) models could project urban expansion in flood-prone zones such as the uMngeni floodplain, where informal settlements like Cato Manor encroach on ecologically sensitive wetlands. By testing scenarios of regulated versus unplanned growth, GIS might reveal how unchecked informal settlement horizontal expansion could exacerbate surface runoff, overwhelming stormwater systems. Theoretical applications could include modelling the impact of green infrastructure, such as permeable pavements in Durban's CBD or wetland restoration in the uMdloti estuary, on reducing flood risks while preserving biodiversity.

For energy planning, spatial regression models could analyse correlations between energy access in informal settlements and flood resilience. For example, GIS might identify how decentralised solar microgrids in rural outskirts could theoretically power emergency shelters or water pumps during floods, reducing dependency on centralised grids prone to storm damage. Optimisation models could also guide the placement of renewable energy projects, such as solar

farms in non-flood-prone areas like the outer eThekweni region, avoiding conflicts with future flood mitigation zones.

While these applications remain theoretical, they illustrate GIS's potential to bridge spatial modelling with AG in eThekweni. Challenges, such as fragmented land-use data in informal settlements or limited real-time hydrological monitoring, highlight the need for collaborative frameworks. Partnerships with different decision makers could theoretically enhance data accuracy and model validity. Participatory spatial modelling might also engage residents in co-designing scenarios, such as mapping informal drainage channels in Cato Manor absent from municipal records, ensuring AG strategies reflect grassroots realities.

By using GIS's spatial modelling capabilities as a tool for AG, the eThekweni Metropolitan Municipality could theoretically shift from reactive flood response to pre-emptive risk management, balancing ecological preservation, sustainable development, and climate resilience. This approach positions GIS as a useful tool of AG, translating complex spatial data into governance strategies that anticipate and adapt to an uncertain future with regards to flood risk.

#### **2.3.7.4 Risk management**

GIS can be used as a tool for AG through risk management. Risk management is a process that involves identifying potential risks, assessing their likelihood and impact, and developing strategies to mitigate or manage those risks (Culp, 2002). GIS can support risk management by integrating spatial data, analysing patterns and trends, and communicating results to decision makers and stakeholders (Orlando *et al.*, 2005; Rezvani *et al.*, 2023).

When looking at natural disasters, GIS can be used to map and analyse different types of natural hazards, such as floods, landslides, or earthquakes (van Westen, 2013). Decision makers can use GIS to identify areas that are most at risk, based on factors such as elevation, soil type, and past occurrences of the hazard (Osman & Das, 2023). By using GIS, decision makers can develop strategies to mitigate or manage potential risks, such as building codes, EWSSs, or evacuation plans (Coppock, 1995; Singh *et al.*, 2019).

In another example, infrastructure management, GIS can be used to map and analyse critical infrastructure, such as transportation networks, power grids, or water supply systems (Amini, 2019). Decision makers can use GIS to identify areas that are most vulnerable to disruptions or failures, based on factors such as age, condition, or proximity to natural hazards (Hereher, 2020; Lemer, 1998). By using GIS, decision makers can develop strategies to maintain or upgrade



critical infrastructure, such as asset management plans or emergency response protocols (Schultz, 2012).

In the last example, environmental protection, GIS can be used to map and analyse environmental risks, such as pollution or habitat loss (Padmanaban, 2012). Decision makers can use GIS to identify areas that are most at risk, based on factors such as proximity to pollution sources, or habitat fragmentation (Gajos & Sierka, 2012). By using GIS, decision makers can develop strategies to mitigate or manage potential risks such as pollution prevention plans or habitat restoration projects (Yerramilli *et al.*, 2011).

In each of these examples, GIS is used to support risk management by integrating spatial data, analysing patterns and trends, and communicating results to decision makers and stakeholders. By using GIS for risk management, decision makers can anticipate potential risks and develop strategies to mitigate or manage those risks, thereby reducing the potential impact on communities and ecosystems. It is beneficial to delve deeper into how GIS can enhance decision-making processes. Specifically, exploring how GIS can be integrated into decision-making frameworks such as sustainable development frameworks, cost-benefit analysis, or MCDA would provide valuable insights.

Sustainable development frameworks aim to balance economic, social, and environmental considerations in decision making (Broman & Robèrt, 2017; Grainger-Brown & Malekpour, 2019; Spangenberg, 2002). GIS can help integrate spatial data related to land use, natural resources, population distribution, and environmental factors into sustainable development frameworks (Griggs *et al.*, 2014, Zhou *et al.*, 2021b). Integration of GIS into sustainable development frameworks allows decision makers to analyse the spatial implications of development choices and make evidence-based decisions backed by GIS data (Scott & Rajabifard, 2017).

Cost-benefit analysis (CBA) in the context of environmental science refers to the economic evaluation of policies and projects that aim to enhance the provision of environmental services or actions (Atkinson & Mourato, 2008). GIS can enhance CBA by incorporating spatial data into the decision-making process (Cerreta & De Toro, 2012). By integrating geospatial information on various factors such as transportation networks, land use, demographics, and environmental characteristics, GIS enables a more comprehensive analysis of costs and benefits associated with different alternatives or scenarios (Grilli *et al.*, 2017; Manyama *et al.*, 2021; Rodrigue *et al.*, 2020). GIS backed environmental CBA helps decision makers assess the potential effects of different options and policies and make more informed choices based on a broader understanding of the spatial context (Fuguit & Wilcox, 1999).

GIS can be integrated into MCDA frameworks to support decision-making processes that involve multiple criteria and spatial considerations (Lim & Lee, 2009; Lokhande, 2017; Osman & Das, 2023; Özkan *et al.*, 2020; Paquette & Lowry, 2012). MCDA involves assessing and ranking alternatives based on multiple dimensions or criteria (Cinelli *et al.*, 2020; Tsakalerou *et al.*, 2022). GIS provides the ability to incorporate spatial data and spatial relationships into the MCDA decision-making process, enabling a more comprehensive evaluation of alternatives (Feick & Hall, 2004; Harper *et al.*, 2019; Malczewski, 1999). By considering spatial attributes, such as proximity, accessibility, and spatial relationships, GIS enhances the accuracy and relevance of decision outcomes in MCDA (Chen, 2014; Malczewski, 2004). GIS-based MCDA allows decision makers to visualise the spatial implications of their choices and understand how different criteria interact across geographic space (Tammi & Kallioli, 2014).

In summary, risk management, supported by GIS, can theoretically enhance AG in the eThekweni Metropolitan Municipality by identifying, assessing, and mitigating flood risks through spatially informed strategies. By integrating spatial data on natural hazards, infrastructure, and environmental vulnerabilities, GIS enables decision makers to anticipate risks and develop targeted interventions, aligning with AG's focus on proactive resilience.

For natural disaster management, GIS can map and analyse flood hazards in the eThekweni Metropolitan Municipality's river systems, identifying high-risk areas like informal settlements in Quarry Road West or industrial zones in Durban's south basin. By overlaying elevation data, soil type maps, and historical flood records, GIS could theoretically predict inundation extents during extreme rainfall events, guiding the placement of early warning systems (EWSs) or evacuation routes in vulnerable communities living in informal settlements. For instance, simulating the impact of a 1-in-100-year flood could highlight critical overflow points in the Palmiet River catchment, informing infrastructure upgrades or community relocation plans.

In infrastructure management, GIS can assess the vulnerability of critical systems, such as stormwater networks, transportation corridors, and power grids, to flood disruptions. For example, GIS could identify ageing stormwater infrastructure in Cato Manor or flood-prone sections of the N2 highway, prioritising upgrades to minimise economic and social impacts. Theoretical applications might include asset management plans for reinforcing drainage systems in KwaMashu or relocating electrical substations in low-lying areas like Merebank.

For environmental protection, GIS can map ecological risks, such as habitat loss in the uMdloti River estuary or pollution from industrial runoff in the Durban harbour. By overlaying flood risk maps with biodiversity data, GIS could identify areas where wetland restoration or pollution control measures might mitigate flood impacts while preserving ecosystems. For instance, modelling the

effects of mangrove restoration in the uMngeni estuary could reveal dual benefits, reducing flood velocities and enhancing biodiversity, and providing a basis for cost-benefit analysis (CBA) in environmental decision-making.

GIS's integration into sustainable development frameworks could further enhance risk management in eThekweni. By incorporating spatial data on land use, population density, and natural resources, GIS enables decision makers to balance economic growth with flood resilience. For example, spatial analysis might reveal how urban expansion in uMlazi could strain stormwater systems, guiding policies to enforce buffer zones or promote green infrastructure.

In cost-benefit analysis (CBA), GIS enhances the evaluation of flood mitigation projects by incorporating spatial factors such as proximity to flood zones, population density, and infrastructure value. For instance, GIS could assess the economic and social benefits of constructing retention ponds in oThongathi versus upgrading drainage systems in Durban's CBD, informing prioritisation of interventions that maximise community resilience.

Finally, GIS's role in multi-criteria decision analysis (MCDA) supports complex trade-offs in flood risk management. By integrating spatial data on flood hazards, socio-economic vulnerabilities, and environmental impacts, GIS enables decision-makers to rank interventions based on multiple criteria, such as cost, feasibility, and equity. For example, MCDA could compare the benefits of relocating informal settlements in Cato Manor versus reinforcing riverbanks in the uMngeni catchment, ensuring decisions reflect both technical and community priorities.

While these applications remain theoretical, they illustrate GIS's potential to bridge risk management with AG in the eThekweni Metropolitan Municipality. Challenges, such as fragmented data in informal settlements or limited stakeholder coordination, highlight the need for collaborative frameworks integrating all the different decision makers. By embedding GIS into risk management, eThekweni could theoretically shift from reactive flood response to pre-emptive resilience, balancing ecological preservation, equitable development, and climate change adaptation. This approach positions GIS as a potential tool of AG, translating complex spatial data into governance strategies that anticipate and adapt to an uncertain future.

#### **2.3.7.5 The limitations of Geographical information systems as a tool for anticipatory governance**

Acknowledging the limitations and challenges associated with the use of GIS in AG is essential to gaining a more nuanced understanding of the role of GIS as a tool for AG and identifying areas for future research and improvement. While GIS offers valuable capabilities for decision making

and planning, it is important to recognise the limitations of GIS as a tool for AG in order to effectively leverage the potential of GIS within the context of AG. This section discusses some key limitations and challenges associated with the use of GIS in AG, highlighting the need for further exploration and advancement.

Data inconsistencies pose a significant challenge to the effectiveness of GIS in supporting AG. These inconsistencies can arise from various sources, such as errors in data collection, inconsistent formats or units, and incomplete or missing data (Kumi-Boateng & Yakubu, 2010). The consequences of data inconsistencies on decision making and the overall credibility of GIS as a tool for AG can be far-reaching (Migliorini *et al.*, 2019).

Data inconsistencies can lead to inaccurate analyses and predictions, ultimately resulting in misguided decisions (Devillers *et al.*, 2010). For instance, if data on a specific geographic area is incomplete or outdated, decision makers may lack a clear understanding of emerging issues or risks, thereby missing opportunities to take proactive measures (Opitz-Stapleton *et al.*, 2019). The reliance on inconsistent or unreliable GIS data can therefore undermine the validity and effectiveness of AG processes.

Furthermore, data inconsistencies create confusion and uncertainty among stakeholders, eroding the credibility of GIS as a decision support tool for AG (Hariri *et al.*, 2019; Machiels *et al.*, 2023). When multiple datasets with conflicting information are used to inform decision making, stakeholders may become sceptical about the accuracy and reliability of GIS (Carroll & Sanchez, 2020). This scepticism can hinder collaboration and consensus-building among stakeholders, impeding the effective implementation of anticipatory measures (Bianchi *et al.*, 2021; Goodman *et al.*, 2020; van de Kerkhof, 2006).

Outdated information can also significantly impact the accuracy and reliability of GIS outputs (Longley *et al.*, 2015). Data can quickly become outdated, failing to reflect the current situation accurately (Griffin, 2015). For instance, in the context of weather forecasting, relying on outdated weather data can lead to inaccurate predictions, potentially jeopardising AG strategies and responses (Burgeno & Joslyn, 2020).

The lack of technical expertise in GIS poses a second significant challenge for organisations aiming to use GIS as a tool for AG. GIS requires specialised skills and knowledge that may not be readily available within an organisation or region (Wilke & Fagen, 2014). Lack of technical expertise can lead to various issues that limit the effectiveness of GIS, including misinterpretation of results, inaccurate data collection, and limitations in GIS analysis. These challenges hinder the ability of GIS to support AG effectively.

Organisations without technical expertise may struggle to accurately interpret the results of GIS analysis (Taleai *et al.*, 2009; Tanser & Le Sueur, 2002; Zerger & Smith, 2003). Inaccurate interpretation of GIS data can result in incorrect assumptions or conclusions about the data, ultimately influencing the decisions made based on that data (Ventura, 1995). For instance, if an organisation misinterprets the results of a GIS analysis concerning the potential impact of climate change on agriculture, they may make decisions based on flawed assumptions (Fekadu *et al.*, 2020). This can lead to ineffective or misguided strategies for AG.

Technical expertise is crucial during the data collection phase of GIS (Goodchild & Li, 2012). Without technical expertise, GIS data may be collected inaccurately, resulting in unreliable and flawed datasets (Porter *et al.*, 2004). Inaccurate data can subsequently produce incorrect results and ultimately lead to flawed decisions (Mezias & Starbuck, 2008). In the context of AG, relying on erroneous data can undermine the effectiveness of proactive decision making and strategic planning (Guston, 2014; Maffei *et al.*, 2020).

The absence of technical expertise in GIS can also impose limitations on the analysis capabilities of organisations (Göçmen & Ventura, 2010). Without the ability to understand and use GIS tools effectively, organisations may struggle to perform complex spatial analysis or modelling (Dangermond & Goodchild, 2020). The inability to perform complex spatial analysis hampers the insights that can be derived from the data, hindering the ability to identify emerging trends, potential risks, and opportunities for AG, because limited analysis capabilities undermine the ability to make well-informed decisions based on comprehensive spatial information (Atta & Fan, 2021; Longley *et al.*, 2015).

Infrastructure is an important aspect of leveraging GIS as a tool for AG. The effective utilisation of GIS necessitates substantial investment in hardware, software, and connectivity to support data management, analysis, and visualisation requirements of organisations (Masser, 2020). However, limited infrastructure in many regions in the third world can impede the accessibility and effectiveness of GIS and therefore its use in AG (Fletcher-Lartey & Caprarelli, 2016). There are several challenges associated with infrastructure that can restrict the effectiveness of GIS as a tool for AG. These challenges are discussed next.

GIS heavily relies on internet connectivity to access and share data (Gong *et al.*, 2017). Unfortunately, in certain regions, especially rural areas, inadequate internet connectivity can hinder the ability to use GIS effectively (Garcia-Mora & Mora-Rivera, 2023; Mennecke & West, 2001). Slow internet speeds and limited bandwidth can impede the uploading and downloading of large datasets, resulting in slower analysis processes and limitations in data sharing with other organisations (Kopeć, 2022). AG often involves collaboration and data sharing among different

organisations, including government agencies, research institutions, and NGOs (Berten & Kranke, 2022; Flyverbom & Garsten, 2021). Slow internet speeds can therefore delay the exchange of critical information and hinder the development of shared insights and responses to emerging challenges via AG.

Access to suitable hardware and software is crucial for organisations to effectively employ GIS (Haklay & Weber, 2008). However, in some regions, especially developing countries, the lack of access to hardware and software can impede the utilisation of GIS. For instance, organisations may struggle to acquire high-quality computers or licensed GIS software, making it challenging to perform complex spatial analysis or modelling (Zhu *et al.*, 2021). AG requires timely identification of emerging challenges and prompt response to mitigate or prepare for them (Quay, 2010). If organisations lack high-quality computers, data processing can be slower, leading to delays in generating insights and taking timely action (Popovič *et al.*, 2018). This can undermine the effectiveness of AG, as important opportunities for early intervention may be missed.

Power outages can pose significant challenges in certain regions, particularly in developing countries (Shah *et al.*, 2023; Meles, 2020). These power outages can adversely affect the ability to use GIS effectively, as computer systems may unexpectedly shut down, leading to data loss and potential hardware damage (Zhai *et al.*, 2021). Power outages can cause extended periods of system downtime, as computers and servers need to be restarted and data systems brought back online (Bello *et al.*, 2021). These delays can affect the timeliness of data analysis and decision making, potentially slowing down AG processes and reducing the ability to respond quickly to emerging situations.

In conclusion to this section of the study, the integration of GIS in decision-making processes has proven to be a valuable tool for anticipating and managing emerging risks and opportunities. Through its ability to combine and analyse multiple sources of knowledge, GIS provides decision makers with a comprehensive understanding of complex spatial relationships and trends. One of the key strengths of GIS is its capacity to engage diverse stakeholders. By incorporating data from various sources and involving different perspectives, GIS facilitates inclusive decision-making processes. This inclusivity helps to ensure that the concerns and needs of various stakeholders are taken into account, leading to more informed and balanced decision-making outcomes.

Additionally, GIS supports adaptive approaches to governance, allowing decision makers to respond and adapt to changing circumstances effectively. By providing real-time data and analysis, GIS enables decision makers to monitor and assess the evolving risks and opportunities,

making timely adjustments to their strategies and plans. This adaptability enhances the resilience of societies, enabling them to better cope with and recover from various challenges.

However, it is important to acknowledge that GIS also has limitations to its implementation as a tool for AG. One of the main challenges is the availability and quality of data. The effectiveness of GIS relies heavily on the accuracy and availability of spatial data, and limitations in data availability or quality can limit its potential impact. Moreover, the complexity of GIS technology and the need for specialised skills to operate and interpret GIS tools may pose barriers to its widespread adoption and use in AG.

Despite these limitations, the benefits offered by GIS in supporting AG and enhancing societal resilience outweigh its drawbacks. GIS remains a valuable tool for decision makers, providing them with valuable insights and enabling them to make informed choices. As technology advances and data availability improves, the potential of GIS is likely to grow even further, making it an increasingly indispensable tool for addressing emerging risks and opportunities in various domains of governance.

### **2.3.8 Conclusion**

This second part of the literature study has examined the concept of a GIS and explored its various dimensions. The definition of GIS as a computer-based tool that captures, stores, analyses, and visualises spatial or geographical data has been established. Throughout the analysis of relevant sources, significant insights have been derived concerning the historical development, components, recorded elements, and spatial data models within GIS. The historical evolution of GIS has been traced, highlighting its origins in computer mapping and subsequent advancements driven by digital technologies. This progression has revolutionised the field, reshaping people's perception and management of geographical information. The capability of GIS to record and analyse various elements of geographical data has been emphasised. These elements include spatial, temporal and attribute information, enabling a comprehensive understanding of geographic phenomena and map-making. Spatial data models have been examined within the context of flood risk, encompassing both vector-based and raster-based approaches. These models play a critical role in the organisation and representation of spatial data, facilitating effective implementation and analysis of GIS.

Furthermore, GIS has proven to be a valuable tool in managing urban disaster risk. By assessing vulnerabilities, predicting hazards, and implementing mitigation strategies, GIS enables effective disaster preparedness and response planning, contributing to resilient urban environments. The use of GIS in flood management has demonstrated its significance. By integrating elevation data,

hydrological models, and land-use information, GIS enables the identification of flood-prone areas, simulation of scenarios, and planning of mitigation measures. It enhances EWSs, aids in evacuation planning, and supports efficient emergency response.

This comprehensive exploration of GIS and its applications directly addresses the research objective "To discuss the use of and utility of GIS in mapping urban flood risk." The analysis has demonstrated that GIS is not only a powerful tool for mapping current flood risks but also for predicting and visualising future scenarios, making it invaluable for urban flood risk management.

Finally, GIS has been recognised as a tool for AG. By integrating diverse data sources, GIS empowers policymakers to anticipate and address future challenges. It facilitates scenario planning, risk assessment, and identification of potential socio-spatial impacts, thereby fostering resilience and sustainability in governance practices.

The next chapter outlines the methodology used to combine these concepts of AG and GIS to map current and future flood risk in the eThekweni Metropolitan Municipality.



## CHAPTER 3 METHODOLOGY

### 3.1 Introduction

Flood risk assessment and mapping have gained importance in recent years due to the growing threat of extreme weather events and the potential for devastating consequences on human settlements and infrastructure. The eThekweni Metropolitan Municipality is characterised by diverse topography and land use patterns. It is susceptible to flooding events that can be exacerbated by factors such as rapid urbanisation and climate change. This study aimed to develop a comprehensive current flood risk map, as well as future flood risk maps in line with the principles of AG. To achieve this a MCDA approach will be applied (see Figure 3.1 top and bottom diagrams).

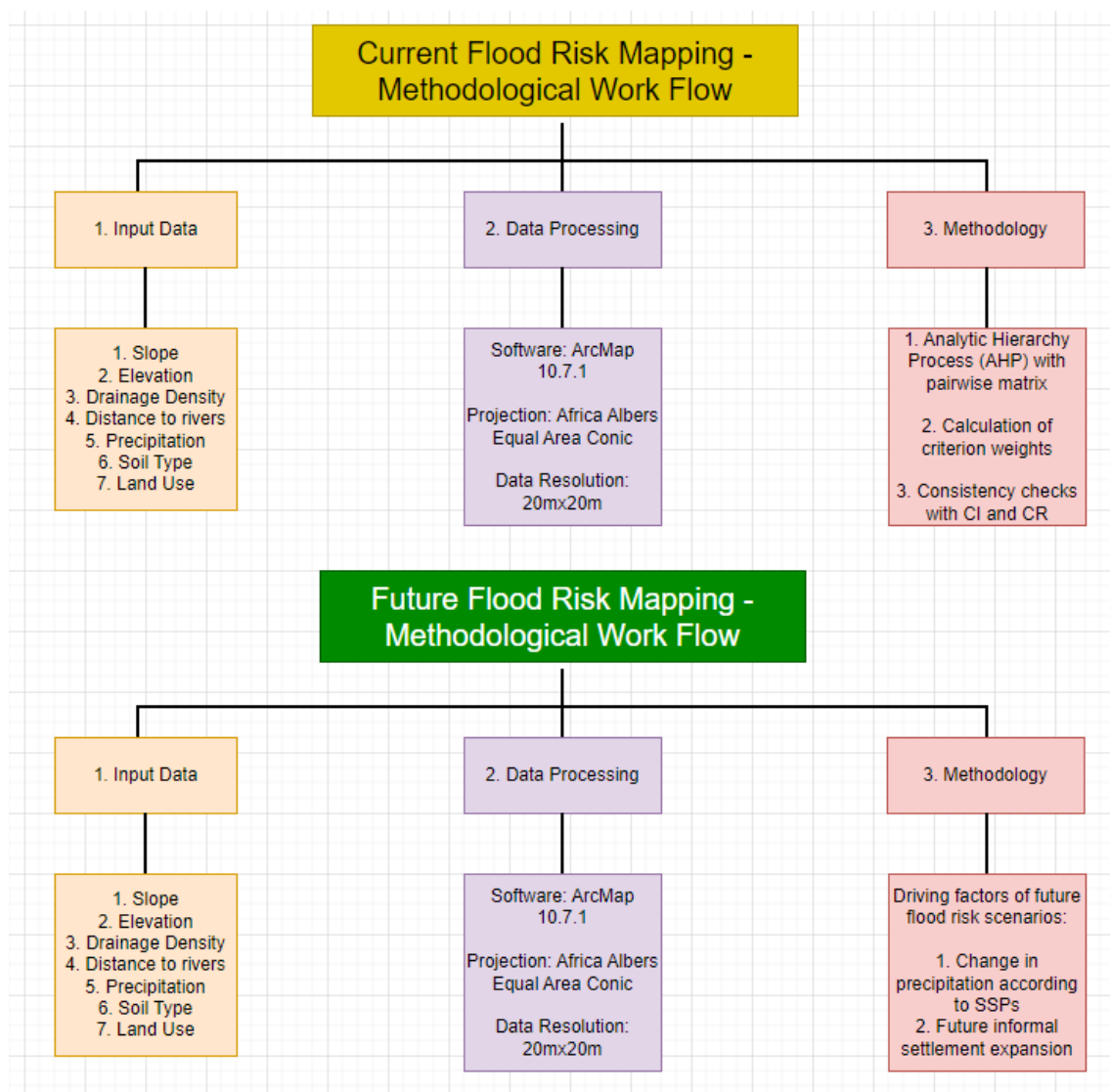


Figure 3.1: The multi-criteria decision analysis approach used during this study

MCDA is a decision-making methodology that helps evaluate scenarios or problems by considering multiple criteria or factors (Belton & Stewart, 2002). It allows decision makers to assess and compare different solutions for a scenario or problem based on a set of predefined criteria (Keeney & Raiffa, 1993). MCDA provides a structured framework for making decisions that involve complex, multi-dimensional considerations, such as creating a flood risk map for metropolitan areas like the eThekweni Metropolitan Municipality. It is a valuable approach to flood risk mapping because it considers the complex interplay of various factors influencing flood risk, including topographical elements, rainfall patterns, land use, and the river network (Hussain *et al.*, 2021; Wondim, 2016). MCDA allows for the systematic weighting and prioritisation of these criteria, ensuring that the most important factors receive appropriate emphasis (Negese *et al.*, 2022; Osman & Das, 2023). Moreover, it offers flexibility by enabling the exploration of different scenarios and trade-offs, facilitating the identification of solutions that balance competing interests, such as minimising flood damage while considering economic costs and environmental impacts in the case of this study (Keeney & Raiffa, 1993).

This chapter outlines the methodology followed to address the fourth research objective, which is "To map the current and potential future areas of the eThekweni Metropolitan Municipality that are vulnerable to flooding events." The approach is twofold, focusing on both current and future flood risk mapping.

This chapter firstly explores a comprehensive approach to creating a current flood risk map for the eThekweni Metropolitan Municipality (see Figure 3.1 top diagram). This study examines seven significant factors contributing to flood risk: land slope, elevation, rainfall patterns, drainage effectiveness, soil type, land use, and distance from rivers, which form the seven criteria for the MCDA of this study. Subsequent sections illustrate the construction of a structured hierarchy of the factors contributing to flood risk and the meticulous pairwise comparison of these factors to determine their relative importance. Furthermore, the chapter delves into the rigorous quality assurance processes inherent to the methodology, including the computation of the CI and the subsequent evaluation of the CR. These assessments serve as a means to ensure the reliability of the findings. Collectively, these methodological steps constitute a robust foundation for the current flood risk mapping process of the eThekweni Metropolitan Municipality.

Secondly, this chapter extends its scope by incorporating AG as a tool for the development of future flood risk maps of the eThekweni Metropolitan Municipality, seeing as incorporating AG into this study enables the creation of multiple future flood risk scenarios that account for different aspects of climate change. The creation of multiple future flood risk scenarios involves exploring changes in precipitation patterns based on different SSPs and changing the input precipitation

data accordingly. Additionally, the multiple future flood risk scenarios investigate the effects of the population growth in informal settlements and the consequent expansion of informal settlements on the future flood risk of the eThekweni Metropolitan Municipality (see Figure 3.1 bottom diagram).

By outlining these methodological approaches, this chapter lays the groundwork for fully addressing the fourth research objective in the results chapter, where the current and potential future flood-vulnerable areas in the eThekweni Metropolitan Municipality are mapped and analysed.

## **3.2 Current flood risk**

### **3.2.1 Mapping contributing factors to current flood risk in eThekweni**

In this section of the study, the current contributing factors to flood risk in the eThekweni Metropolitan Municipality is systematically mapped, encompassing factors such as elevation, slope, rainfall, drainage density, soil type, land use, and distance from rivers. The data used to create these maps were sourced from various datasets as is illustrated below.

### **3.2.2 Data collection**

All the data for this study were collected from secondary sources. As defined by Martins *et al.* (2018), secondary data refers to information collected by a party other than the primary user. This aligns perfectly with this study's requirements since this study depended on data collected by large multinational or national organisations. These entities not only possess the essential resources in terms of manpower and funding but can also conduct extensive data-gathering.

The spot heights and contour data, which played a crucial role in creating the elevation and slope datasets, were sourced from NGI. The SOTER database for South Africa was used to obtain a dataset on the soil types found in the eThekweni Metropolitan Municipality. The river data required for generating datasets related to drainage density and distance to rivers were obtained from the eThekweni Metropolitan Municipality GIS website. Furthermore, the land use dataset was also sourced from the eThekweni Metropolitan Municipality GIS website. Lastly, the study relied on the dataset obtained from the WR2012 for the rainfall data.

The comprehensive collection of data from various sources forms a solid foundation upon which the subsequent data analysis and discussion are based. The first data component to be discussed in more detail relates to elevation.

### **3.2.2.1 Elevation**

Elevation above sea level significantly affect flood vulnerability. Low-lying areas are more prone to inundation during heavy rainfall events or storm surges (Wondim, 2016).

The elevation map (see Figure 3.2) for the eThekweni Metropolitan Municipality was generated using spot heights, contour data, and the Topo to Raster tool in ArcMap 10.7.1. For the study area, a total of 731 spot heights were used to create and validate a 20-metre DEM. The spot heights were systematically selected from various locations across the entirety of the study area, with 80% of the spot heights (585 points) designated for the generation of the DEM, and the remaining 20% (146 points) reserved for the task of DEM validation and accuracy determination. Regarding the contour data, 3 165 contour lines with intervals of 20 metres were used in conjunction with the 585 spot heights to create a 20-metre DEM of the eThekweni Metropolitan Municipality.

The accuracy of the generated DEM was quantified using the root mean square error (RMSE) metric. RMSE serves as an essential indicator of the average discrepancy between the elevation values predicted by the DEM and the actual elevation values derived from the validation dataset (Höhle & Höhle, 2009). The computed RMSE value for the DEM was 2.2.

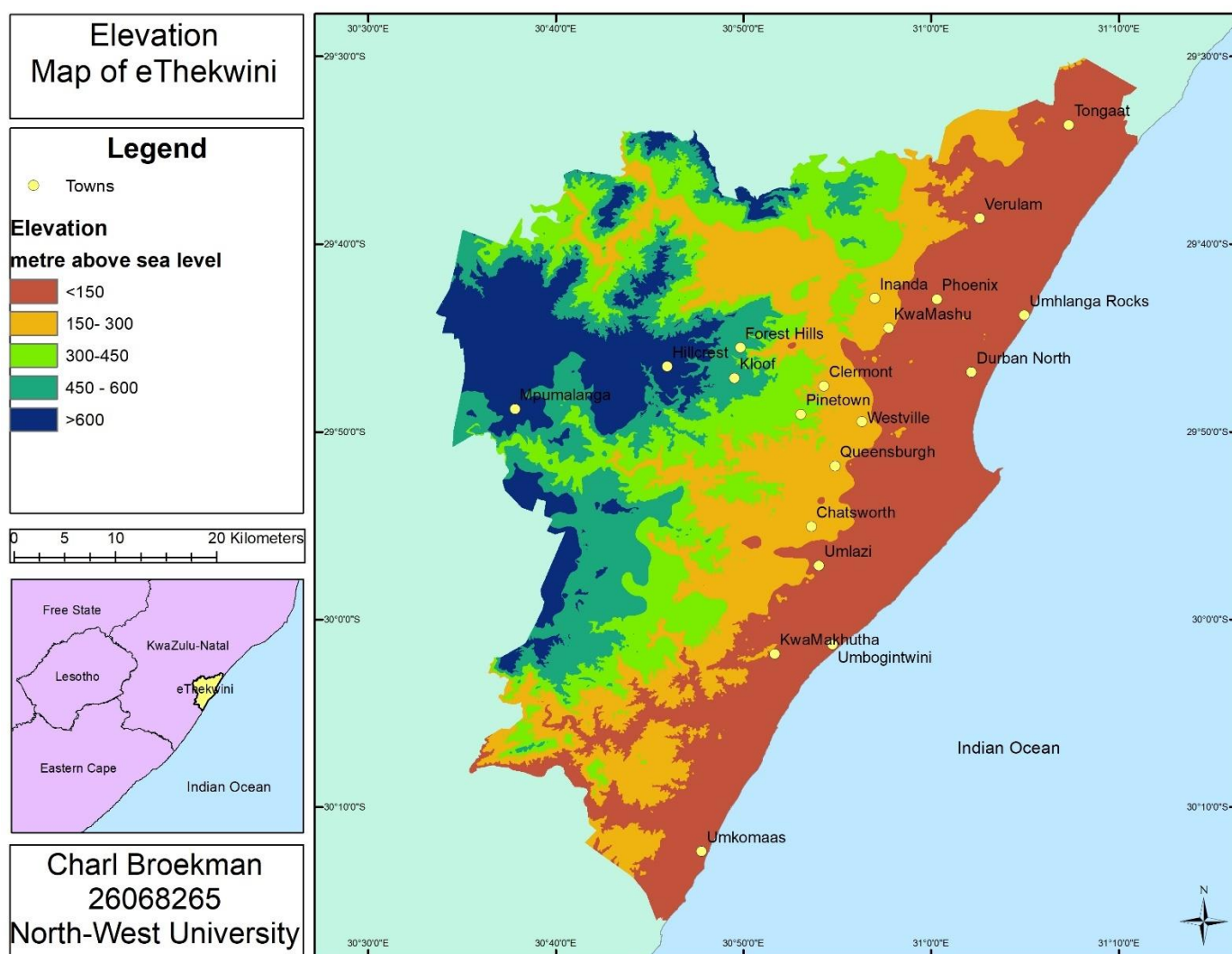


**Figure 3.2: Elevation map of eThekweni (eThekweni Municipality, 2024)**

The elevation of the study area was classified into five classes based on its effect on flood risk: extremely high (less than 150 m), high (150–300 m), moderate (300–450 m), low (450–600 m) and very low (more than 600 m). The selection of intervals was influenced by research from Huřanu *et al.* (2020), Kocsis *et al.* (2022) and Zhong *et al.* (2020). These flood risk studies were selected as a guide to interval selection due to their use of a 150-metre interval and the fact that the elevation ranges in these flood risk studies closely match those of the eThekweni Metropolitan Municipality, ensuring that the flood risk assessment of the eThekweni Metropolitan Municipality is grounded in comparable elevation characteristics for more contextually relevant analysis.

### 3.2.2.2 Slope

Slope, in geographical terms, refers to the degree of inclination or steepness of a feature in relation to the horizontal plane (Hagos *et al.*, 2022). Slope serves as an important indicator of

flood-prone surface areas (Wondim, 2016). The slope of the terrain plays a pivotal role in determining the speed and duration of water flow. On flatter surfaces, water moves more slowly, accumulates over an extended period, and consequently, these areas become more susceptible to flooding (Rincón *et al.*, 2018; Wondim, 2016).

The slope dataset depicted in Figure 3.3 for the eThekweni Metropolitan Municipality was derived using the 20-metre DEM. This DEM, specifically created to meet the requirements of the 'Elevation' input criterion, was employed as the foundational data for the Slope tool in ArcMap 10.7.1.

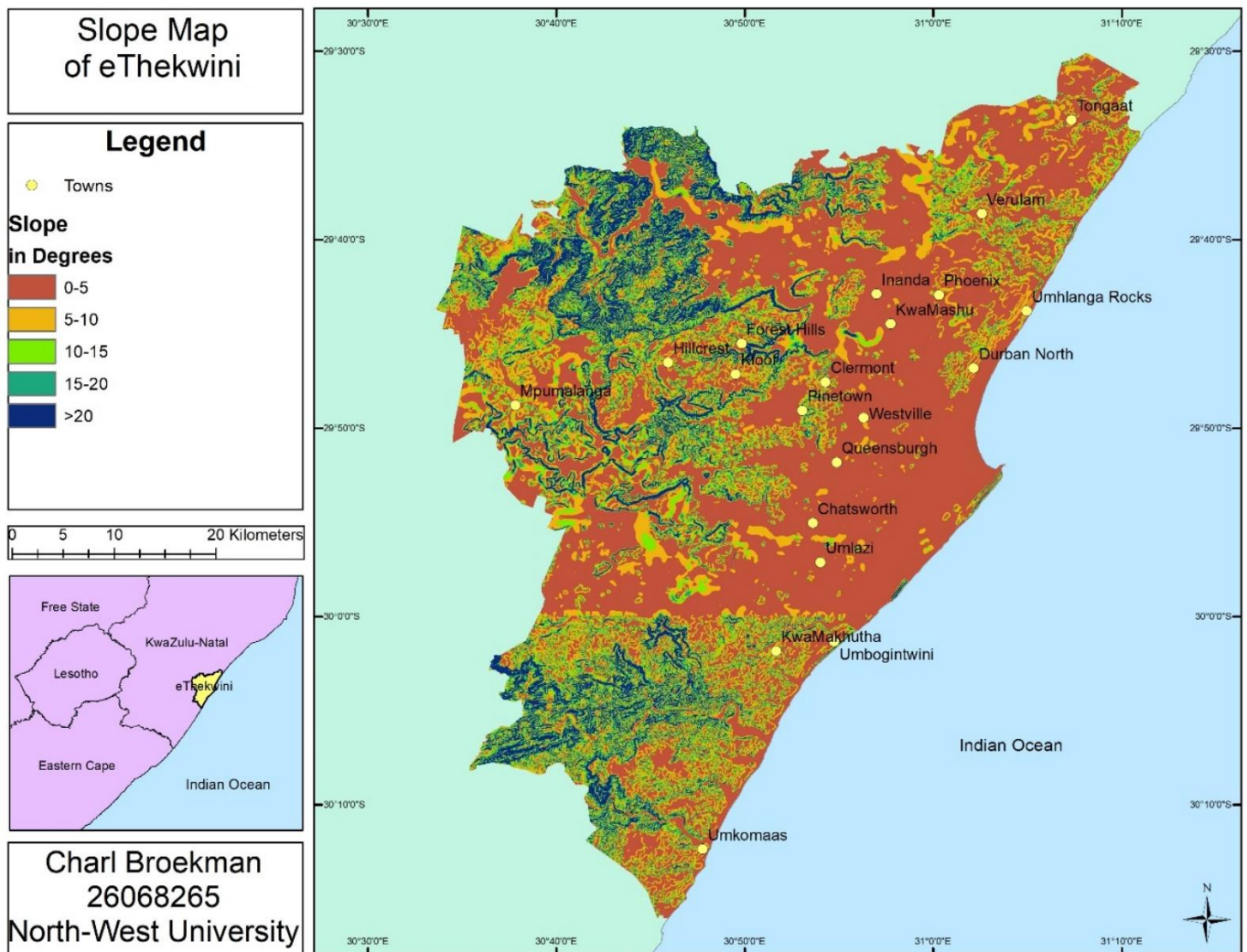


**Figure 3.3: Slope map of eThekweni (eThekweni Municipality, 2024)**

The slope of the study area was classified into five classes based on its effect on flood risk: extremely high (0–5°), high (5–10°), moderate (10–15°), low (15–20°) and very low (more than

20°). This classification scheme aligns with prior research by Olorunfemi *et al.* (2020), Subraelu *et al.* (2023), and Yildiz and Şişman (2022), whose study areas resemble the eThekweni Metropolitan Municipality in terms of slope characteristics, therefore ensuring consistency and comparability with similar flood risk studies.

### 3.2.2.3 Rainfall

Rainfall is a crucial factor in the development of a flood risk map. More specifically, rainfall intensity is a critical determinant of flood events (Hagos *et al.*, 2022). In essence, the greater the amount of rainfall, the higher the potential for generating runoff that can result in flooding. Conversely, when there is less rainfall, the likelihood of flood-producing runoff decreases.

The rainfall map (see Figure 3.4) was created using the mean annual precipitation dataset, using precipitation data from 1920 to 2012, obtained from the WR2012. The WR2012 is the newest study available, with South Africa facing a severe shortage of water-related datasets (Clark, 2020b). The WR2012 dataset was then simply clipped to the eThekweni Metropolitan Municipality using the Clip tool in ArcMap 10.7.1 to display only the rainfall of the eThekweni Metropolitan Municipality.

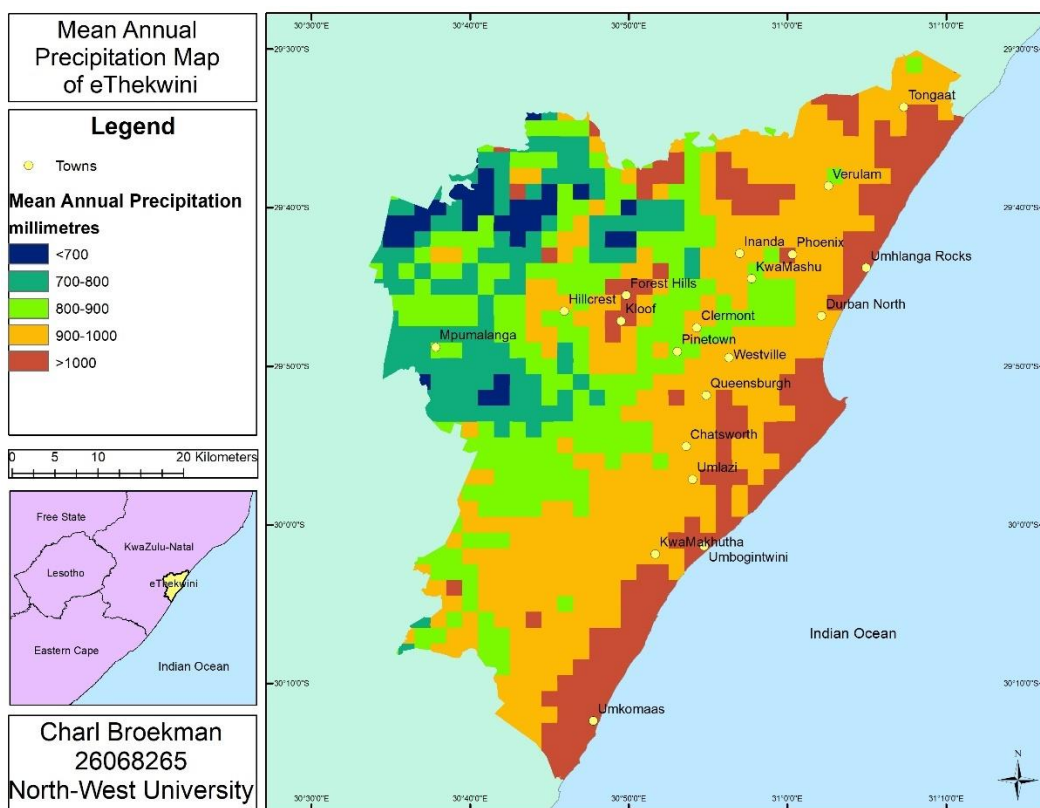


**Figure 3.4: Rainfall map of eThekweni (eThekweni Municipality, 2024)**



The rainfall of the study area was classified into five classes based on its effect on flood risk: extremely high (more than 1000 mm), high (900–1000 mm), moderate (800–900 mm), low (700–800 mm) and very low (less than 700 mm). The classification of rainfall in the study area, with 100 mm intervals, was determined by drawing on the research conducted by Avinash *et al.* (2019), Qin *et al.* (2021), and Rahmati *et al.* (2016). These studies were selected because their rainfall ranges closely align with those found in the eThekweni Metropolitan Municipality, and all the studies used 100 mm intervals, making them highly relevant to this study. Adopting these classifications accounts for the local rainfall conditions and classifies it effectively, facilitating meaningful comparisons and a contextualised analysis.

#### **3.2.2.4 Drainage density**

Drainage density is a significant factor in determining flood risk. It depends on various factors such as slope, bedrock type, and regional and local fracture patterns (Wondim, 2016). Notably, drainage density is inversely related to soil permeability (Hagos *et al.*, 2022). Areas with low soil permeability tend to have higher drainage density, leading to increased runoff from precipitation and vice versa. Therefore, greater drainage density indicates a reduced susceptibility to flooding (Wondim, 2016).

The calculation of drainage density (Dd) involves dividing the combined length of all streams and rivers in a specific area. In this study, the catchment of Mvoti to Umzimkulu, by the total size of that area, can be expressed mathematically as follows (Dragičević *et al.*, 2019).

Drainage Density (Dd) = Total Length of Streams (L) / Area Size (A)

The catchment's hydrological boundary of Mvoti to Umzimkulu was taken from the WR2012 study's GIS base map. The study area's administrative boundary of the eThekweni Metropolitan Municipality falls within the catchment of Mvoti to Umzimkulu's hydrological boundary.

The drainage density map (see Figure 3.5) was created using the eThekweni Metropolitan Municipality GIS website's river dataset and the Line Density tool in ArcMap 10.7.1. The Clip tool was then used to clip the drainage density of the Mvoti to Umzimkulu catchment to the study area of the eThekweni Metropolitan Municipality.



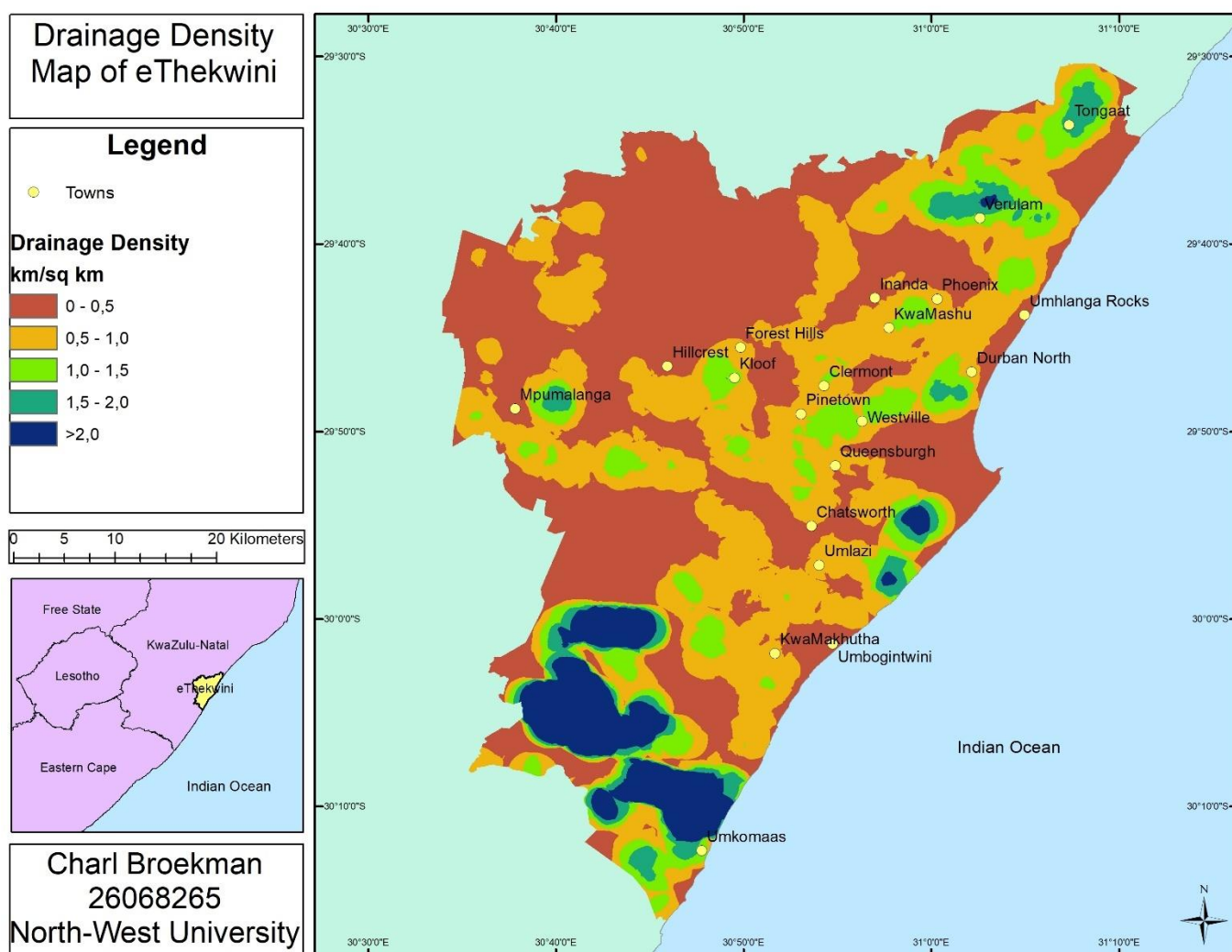


**Figure 3.5: Drainage density map of eThekweni (eThekweni Municipality, 2024)**

The drainage density of the Mvoti to Umzimkulu catchment, and therefore the study area of the eThekweni Metropolitan Municipality, was classified into five classes based on its effect on flood risk: extremely high (0–0.5 km/km<sup>2</sup>), high (0.5–1.0 km/km<sup>2</sup>), moderate (1.0–1.5 km/km<sup>2</sup>), low (1.5–2.0 km/km<sup>2</sup>) and very low (more than 2.0 km/km<sup>2</sup>). The chosen classification intervals of 0.5 km/km<sup>2</sup> were based on the research conducted by Ali *et al.* (2020), Ghanavati *et al.* (2013) and Negese *et al.* (2022). These studies were chosen due to their comparable drainage density ranges and consistent use of 0.5 km/km<sup>2</sup> intervals. This selection ensures that the drainage density map in the current study is comparable to these published works, enhancing the relevance and meaningfulness of this drainage density map of the eThekweni Metropolitan Municipality.

### 3.2.2.5 Soil type

Soil characteristics influence water absorption and retention, directly affecting flood susceptibility (Hagos *et al.*, 2022). Different soil types have varying permeability and water-holding capacities

(Wondim, 2016). A thorough analysis of soil types will aid in identifying areas where water infiltration is limited, increasing the potential for surface runoff and flooding (Morgan, 1995).

The soil type map (see Figure 3.6) was created using the dataset obtained from the SOTER database for South Africa. The scale of the data is 1:90 000 and the dataset was compiled in 2008. The Clip tool in ArcMap 10.7.1 was used to display the soil types of the eThekweni Metropolitan Municipality. Nine soil types were subsequently identified.

#### 3.2.2.5.1 Haplic acrisols

Acrisols are soils that fall in the middle of the drainage spectrum. They are generally well-drained with moderate to high permeability (IUSS Working Group WRB, 2022). While they may not have the best drainage compared to other soil types, they are not extremely poor.

#### 3.2.2.5.2 Humic cambisols

Cambisols are soils that have undergone some level of horizon differentiation due to soil-forming processes. This indicates moderate to good drainage potential. Humic cambisols, in particular, contain organic matter that aids in water absorption, placing them in the lower-middle range for drainage (ISRIC, 2023a).

#### 3.2.2.5.3 Eutric fluvisols

Fluvisols are typically found near rivers and floodplains, which increases their potential for flooding (Chekol & Mnalku, 2012). However, the term "eutric" suggests that they have good fertility and some drainage capacity (Kubotera *et al.*, 2020).

#### 3.2.2.5.4 Rhodic ferrasols

Ferrasols are well-drained soils with high permeability. The term "rhodic" indicates a high degree of weathering, which further enhances their drainage capabilities. Well-drained soils like these are less prone to flooding (Klamt & van Reeuwijk, 2000).

#### 3.2.2.5.5 Dystric leptosols

Dystric leptosols are shallow soils with very poor drainage. They are commonly found on steep slopes or rocky areas, making them highly susceptible to flooding due to their limited drainage capacity (Nachtergaele, 2010).

#### 3.2.2.5.6 Lithic leptosols

Lithic leptosols share characteristics with dystic leptosols but are found in rocky environments. Like dystic leptosols, they have very poor drainage and are at a high risk of flooding (Guerra *et al.*, 2005).

#### 3.2.2.5.7 Haplic phaeozems

Phaeozems are generally well-drained soils (Esayas & Ali, 2006). The term "haplic" suggests that they lack strong diagnostic horizon development, indicating decent drainage capabilities (Schad, 2023).

#### 3.2.2.5.8 Dystic regosols

Dystic regosols are characterised by poor drainage. The term "regosol" typically implies a lack of well-defined horizons. These soils have limited drainage capacity, making them prone to flooding (ISRIC, 2023b).

#### 3.2.2.5.9 Eutric regosols

Eutric regosols are somewhat better in terms of drainage compared to dystic regosols due to their eutric properties, which indicates improved fertility and drainage potential. However, they still have limitations in drainage capacity (ISRIC, 2023b).

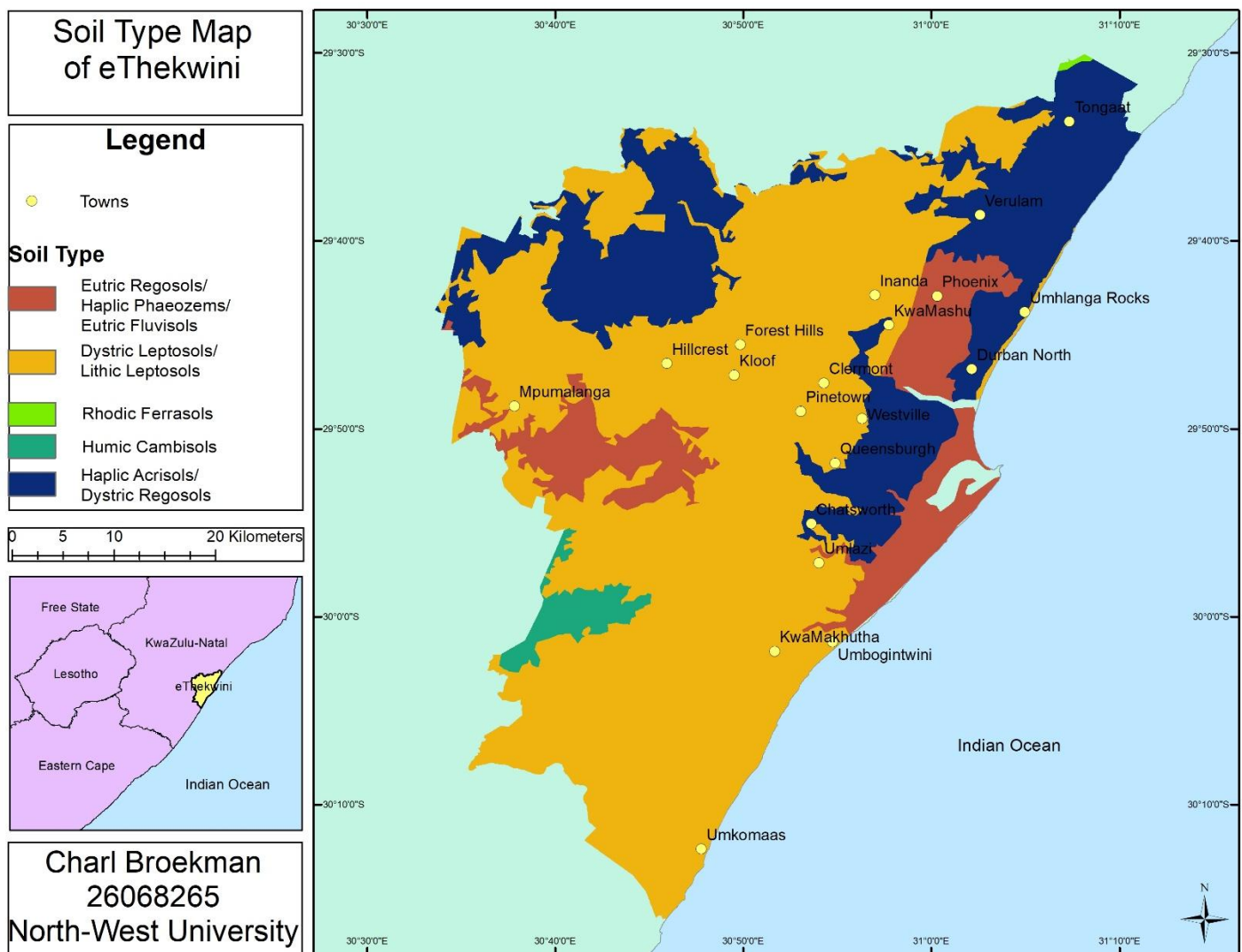


**Figure 3.6: Soil type map of eThekweni (eThekweni Municipality, 2024)**

Taking the above information into consideration, the soil types of the study area were classified into five classes based on their impact on flood risk: extremely high (dystric leptosols and lithic leptosols), high (haplic acrisols and dystric regosols), moderate (eutric regosols, haplic phaeozems and eutric fluvisols), low (humic cambisols) and very low (rhodic ferrasols).

### 3.2.2.6 Land use

Land use classification refers to categorising the Earth's surface into different types based on human and natural characteristics (LaGro, 2005). Land use plays a significant role in determining the number of impermeable surfaces in an area, which in turn can have a substantial effect on water runoff and the risk of flooding (Situngkir *et al.*, 2015). Impermeable surfaces are those that do not allow water to infiltrate into the ground, such as roads, parking lots, buildings, and concrete pavements. These surfaces prevent rainwater from being absorbed by the soil, leading to

increased surface runoff (Davies, 1981). Permeable surfaces also play an important role in shaping the dynamics of water runoff and can help mitigate the risk of flooding. Permeable surfaces are those that allow water to infiltrate into the ground, such as natural vegetation, providing a pathway for rainwater to be absorbed by the soil (Davidsen *et al.*, 2018).

In the assessment of the permeability of land use types, the study relied on the analysis of surface materials. Surface materials play a pivotal role in determining whether a land use category is permeable or impermeable, as they govern the interaction of water with the ground (Sand *et al.*, 2018). Additionally, surface materials have a pronounced impact on runoff coefficients ( $R_v$ ) (Donahue, 2013). Impermeable surfaces exhibit high runoff coefficients, intensifying flood risk. Semi-permeable surfaces fall in between, allowing some infiltration but generating notable runoff. On the other hand, permeable surfaces, characterised by low runoff coefficients, effectively absorb and retain rainfall, ultimately reducing runoff (Donahue, 2013). This led to the selection of runoff coefficients (see Figure 3.7) as a key parameter to determine the relative permeability – and therefore susceptibility to flooding – of all the land use classes in this study.

| Surface Type / Material |                                                                                                                                                            | $R_v$               | $R_v * P_{ptj}$ | Citation |
|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|-----------------|----------|
| Impervious              | Highways                                                                                                                                                   | 0.87<br>(0.35-0.95) | 0.783           | 38       |
|                         | Asphalt, concrete                                                                                                                                          | 0.8                 | 0.72            | 45       |
|                         | Brick, cobblestone                                                                                                                                         | 0.77                | 0.693           | 45       |
| Impervious-Pervious     | High-density neighbourhood commercial development (70% impervious)                                                                                         | 0.69                | 0.621           | 21       |
|                         | Low-density neighbourhood commercial development (50% impervious)                                                                                          | 0.55                | 0.495           | 21       |
| Pervious                | Highly compacted<br>Unpaved parking, driveway, road shoulder; high automobile & human disturbance, poor drainage                                           | 0.50                | 0.45            | 45       |
|                         | Mid-High Compaction<br>Medium density single family development (~26 units/ha) (35% impervious)                                                            | 0.45                | 0.405           | 21       |
|                         | Moderate compaction<br>Low density single family urban development (~13 units/ha)(26% impervious)                                                          | 0.38                | 0.342           | 21       |
|                         | Compacted<br>Unmaintained sports field, park or playground surface; high human disturbance & poor drainage                                                 | 0.35                | 0.315           | 45       |
|                         | Unmaintained<br>Moderate foot traffic & some compaction; foot paths, moderate to poor drainage                                                             | 0.30                | 0.27            | 45       |
|                         | Turf<br>Maintained lawn w/ high foot traffic (e.g., golf course, park, lawn, ballfield)                                                                    | 0.25                | 0.225           | 45       |
|                         | Maintained<br>Landscaped/natural vegetated w/ low foot disturbance/foot traffic                                                                            | 0.20                | 0.18            | 45       |
|                         | Undeveloped<br>Relatively low foot traffic                                                                                                                 | 0.15                | 0.135           | 45       |
|                         | Drainage feature w/ gravel or other coarse-grained material; porous pavement, asphalt, concrete etc w/ subsurface stone reservoir; well-drained sandy soil | 0.10                | 0.09            | 45       |
|                         |                                                                                                                                                            |                     |                 |          |

**Figure 3.7: Runoff coefficients of various land use surface materials (Donahue, 2013)**

The land use map (see Figure 3.8) was created using a dataset obtained from the eThekweni Metropolitan Municipality GIS website and displays the different land uses in the eThekweni

Metropolitan Municipality. The dataset was published in 2022 but reflects the land use information as of 2020, with the exception of the Durban Metropolitan Open Space System (D'MOSS) data, which is from 2018. The dataset is based on Landsat 8 imagery at 30 m resolution. D'MOSS is a network of protected open spaces and green areas managed for conservation, recreation, and ecosystem services, and its boundaries do not change frequently (Roberts *et al.*, 2012). A total of 18 different land uses were identified, as seen in Table 3.1.

**Table 3.1: Land uses in the eThekweni Metropolitan Municipality as of 2022**

| Land use              | Description                                                                                                                                             |
|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|
| D'MOSS                | Green corridors with vegetation and permeable surfaces for water absorption (de Almeida <i>et al.</i> , 2021).                                          |
| Agriculture           | Areas with some imperviousness due to compacted soil but better water infiltration than urban areas (Rose <i>et al.</i> , 2017).                        |
| Airport and tradeport | Extensive paved surfaces, runways, and terminals resulting in very high imperviousness and limited water infiltration (Dougherty <i>et al.</i> , 2004). |
| Business              | Mix of buildings, parking lots, and paved surfaces, leading to significant imperviousness (Pereira <i>et al.</i> , 2019).                               |
| Cemetery              | Open areas with grave plots and pathways, resulting in moderate imperviousness (Żychowski, 2011).                                                       |
| Commercial            | Similar to business areas, with structures, parking, and hardscape contributing to high imperviousness (Sun <i>et al.</i> , 2018).                      |
| Industrial            | Large buildings, storage areas, and parking lots resulting in substantial impervious surfaces (Pereira <i>et al.</i> , 2019).                           |
| Landfill              | Almost entirely covered with materials that prevent water infiltration, resulting in very high imperviousness (Sheng <i>et al.</i> , 2018).             |

|                                      |                                                                                                                                                                                                                    |
|--------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mixed use                            | Combination of various land uses, often with buildings and parking lots, resulting in considerable imperviousness (Sun <i>et al.</i> , 2018).                                                                      |
| Open public spaces                   | Public open spaces like parks with natural features and vegetation allowing for low imperviousness (Brody <i>et al.</i> , 2017).                                                                                   |
| Railway reserve                      | Tracks and some adjacent infrastructure with moderate imperviousness (Alrdadi & Meylan, 2022).                                                                                                                     |
| Recreational                         | Areas like sports fields with some compacted soil and structures but moderate permeability (Dougherty <i>et al.</i> , 2004).                                                                                       |
| Residential                          | Zones with houses, driveways, and paved surfaces contributing to relatively high imperviousness (Sun <i>et al.</i> , 2018). The dataset does not make a distinction between formal and informal residential areas. |
| Rural                                | Lower imperviousness with natural landscapes, vegetation, and open space (Brody <i>et al.</i> , 2017).                                                                                                             |
| Social and civic                     | Areas like community centres with buildings, parking, and some natural vegetation resulting in moderate imperviousness (Pereira <i>et al.</i> , 2019).                                                             |
| Open spaces proposed for development | Public open spaces with natural features and vegetation that may be developed in the future, impacting current permeability (Brody <i>et al.</i> , 2017).                                                          |
| Quarries                             | Very high imperviousness due to excavation and non-permeable materials (Dougherty <i>et al.</i> , 2004).                                                                                                           |
| Utilities and services               | Areas with infrastructure, buildings, and paved surfaces, contributing to significant imperviousness (Pereira <i>et al.</i> , 2019).                                                                               |



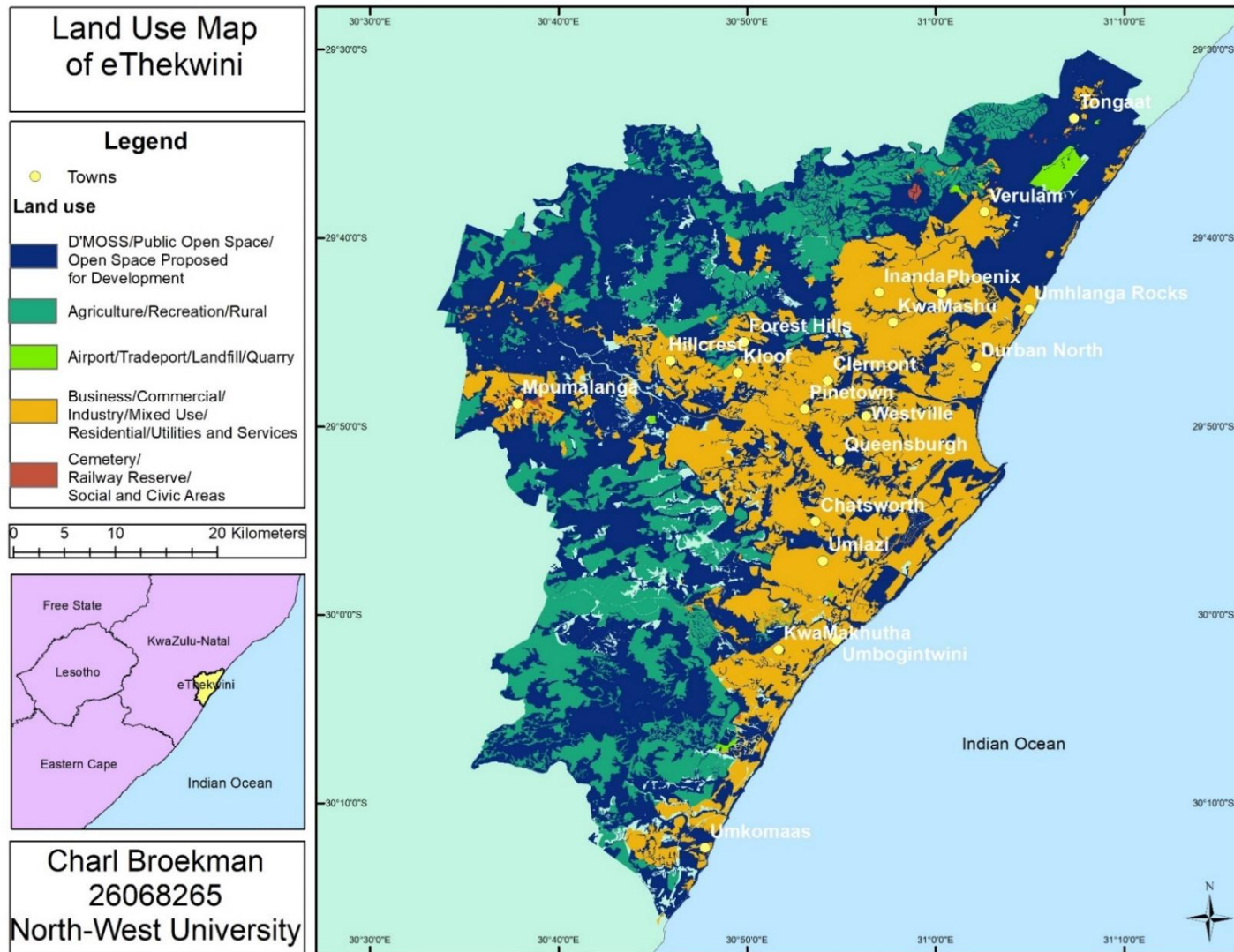


Figure 3.8: Land use map of eThekweni (eThekweni Municipality, 2024)



Taking the above information into consideration, the land use types of the study area were classified into five classes based on their permeability and surface runoff coefficient, as shown in Figure 3.7 (Donahue, 2013), and therefore their impact on flood risk. The land use categories were classified as follows:

Extremely high (Rv 0.77-0.95): Airport/tradeport, landfill, and quarries. Airport/tradeport and landfill typically have surface materials like asphalt and concrete, which have runoff coefficients of 0.8 and 0.77–0.95, respectively, as shown in Figure 3.7. Although quarries are not explicitly listed in the chart, they are characterised by highly compacted surfaces, exposed bedrock, and minimal vegetation cover (Tanaka *et al.*, 2016). These surface characteristics are similar to those of impervious materials like asphalt and concrete. Therefore, quarries were included in the "Extremely high" category, with an estimated runoff coefficient of 0.77–0.95, consistent with the values for asphalt and concrete surfaces.

High (Rv 0.50-0.70): Business, commercial, industrial, mixed use, residential, and utilities and services, which often have a mix of rooftops, driveways, and paved surfaces, corresponding to the runoff coefficients for impervious surfaces in Figure 3.7.

Moderate (Rv 0.35-0.50): Cemeteries, railway reserve, and social/civic areas, characterised by a combination of structures, pathways, and some vegetation, consistent with the runoff coefficients for impervious-pervious surfaces.

Low (Rv 0.15-0.35): Agriculture, recreational, and rural, which generally have more natural landscapes and open spaces, corresponding to the runoff coefficients for maintained and unmaintained turf and landscaped/natural vegetated surfaces.

Very low (Rv 0.05-0.15): D'MOSS, public open spaces, and public spaces proposed for development, dominated by vegetation and permeable surfaces, consistent with the runoff coefficients for maintained and landscaped/natural vegetated surfaces.

These classifications were based on the typical surface materials and characteristics associated with each land use, as described in Table 3.1, and the corresponding runoff coefficients provided in Figure 3.7. Land uses with similar runoff coefficients were grouped together to create the five permeability classes, providing a clear rationale for the categorisation and its relationship to flood risk.

### 3.2.2.7 Distance from rivers

Proximity to rivers is a critical factor in flood vulnerability. Areas closer to rivers are at a higher risk of flooding due to potential riverbank overflow. A critical criterion in generating flood risk maps within the study area can be found in the proximity to rivers dataset.

The distance from rivers map (see Figure 3.9) for the eThekweni Metropolitan Municipality was generated using the dataset of all the major and minor perennial rivers in the eThekweni Metropolitan Municipality. Three inset maps were also made (see Figure 3.10, Figure 3.11 and Figure 3.12) to better showcase the data in the more densely populated areas in the centre of the study area. The data that was used to create the distance from rivers map was obtained from the eThekweni Metropolitan Municipality GIS website. The Euclidian Distance tool in ArcMap 10.7.1 was used to generate the distance buffers around all the rivers in the study area.

The distances from rivers were classified into five classes based on its impact on flood risk: extremely high (0–150 m), high (150–300 m), moderate (300–450 m), low (450–600 m) and very low (more than 600 m). The chosen classification aligns with the research conducted by El-Magd *et al.* (2020) and Mohammed *et al.* (2014), whose study area has a similar area size as the eThekweni Metropolitan Municipality study area. Adopting intervals of 150 metres ensures that the flood risk assessment is tailored to the scale and characteristics of the eThekweni Metropolitan Municipality, thereby promoting a more meaningful and contextually relevant analysis.

Incorporating these seven criteria using a MCDA approach allowed for a comprehensive evaluation of flood risk in the eThekweni Metropolitan Municipality. The selected criteria capture the complex interplay of natural and anthropogenic factors that contribute to flooding, enabling informed decision making for disaster preparedness, urban development, and land-use planning. The following sections of this study detail the methodology for selecting the factors that contribute to flood risk and assigning weights to each input dataset or factor to ultimately produce a current flood risk map for the eThekweni Metropolitan Municipality.

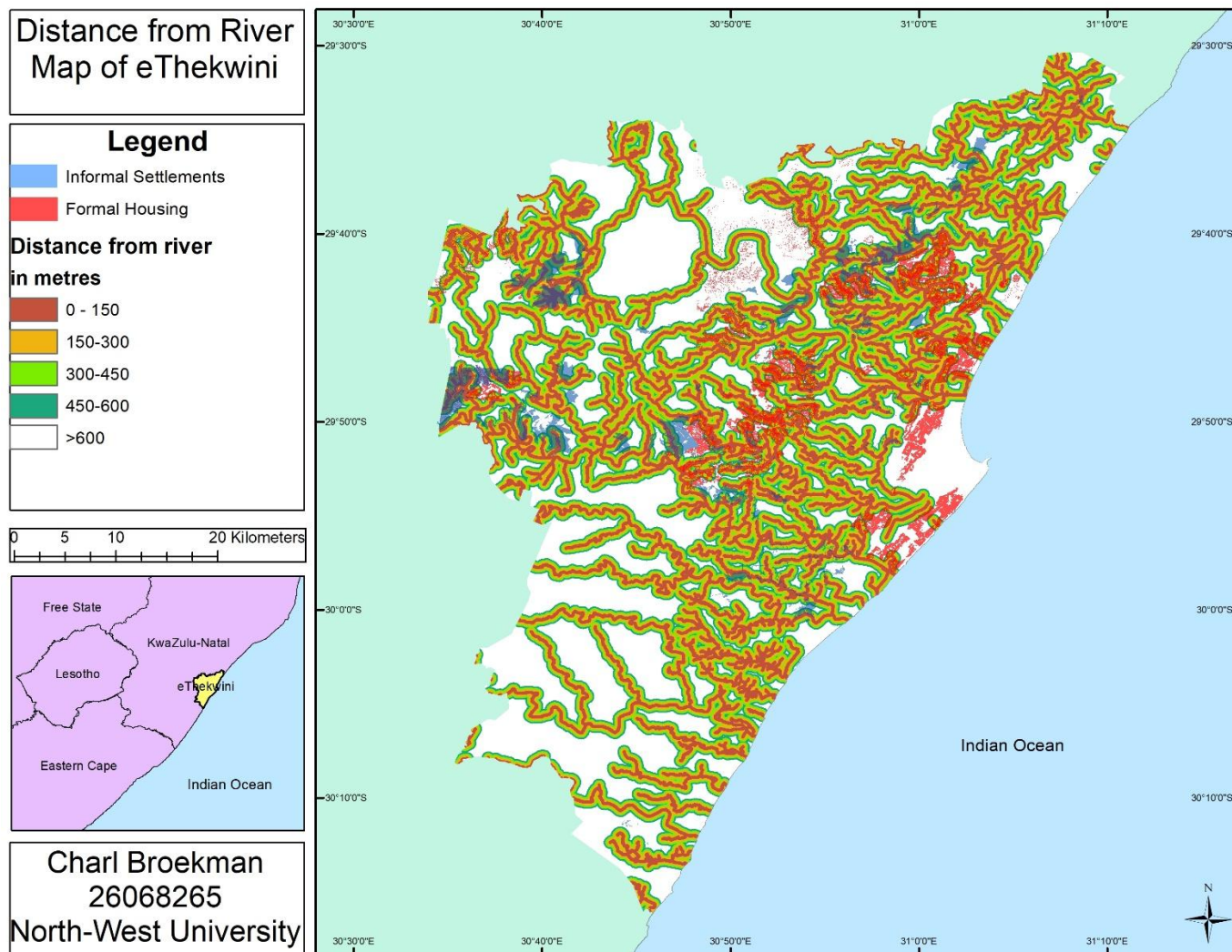


**Figure 3.9:** Distance from rivers map of eThekweni displaying all the informal and formal housing (eThekweni Municipality, 2024)

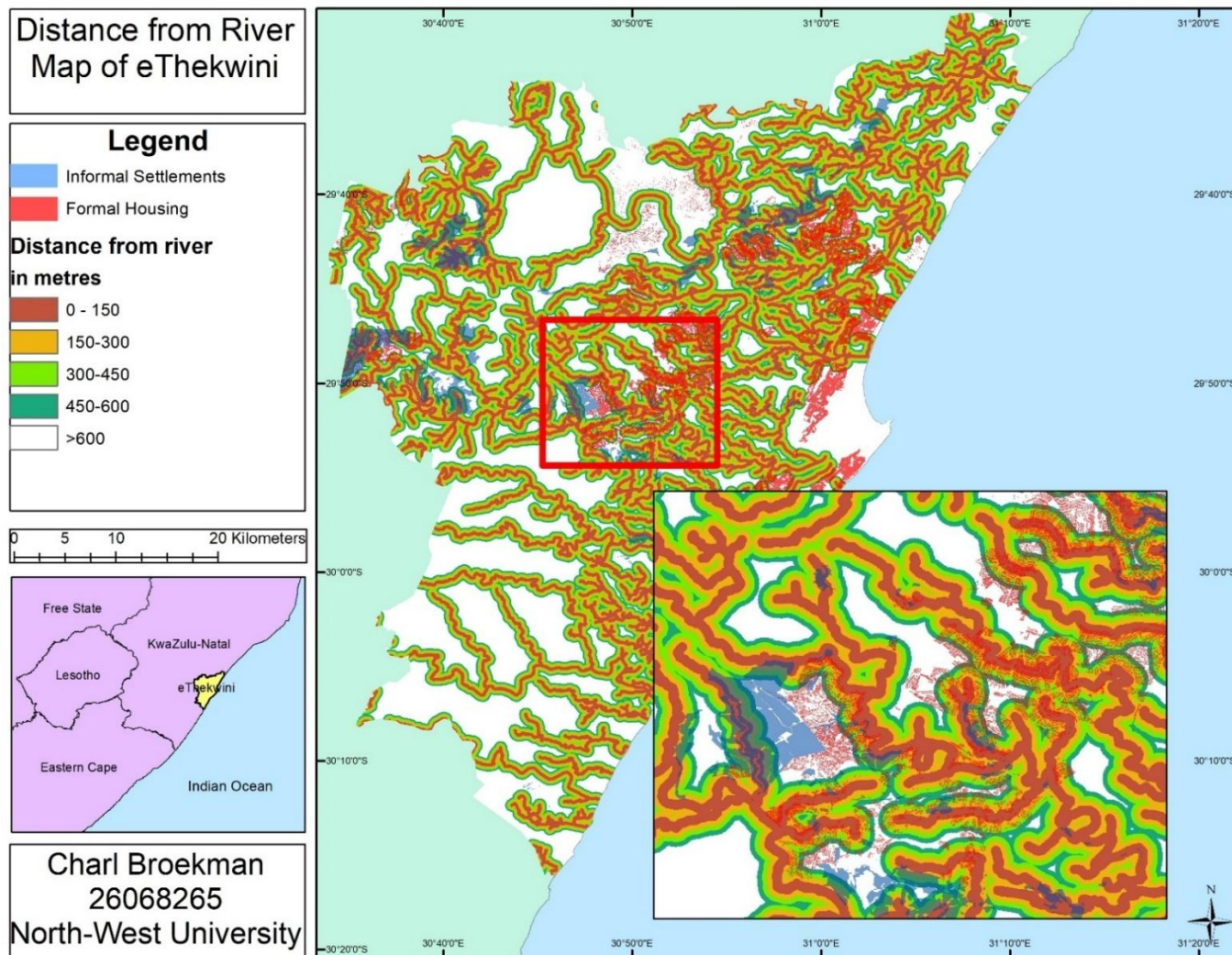


**Figure 3.10:** Distance from rivers inset map number one of eThekwin displaying all the informal and formal housing in the red square (eThekwin Municipality, 2024)



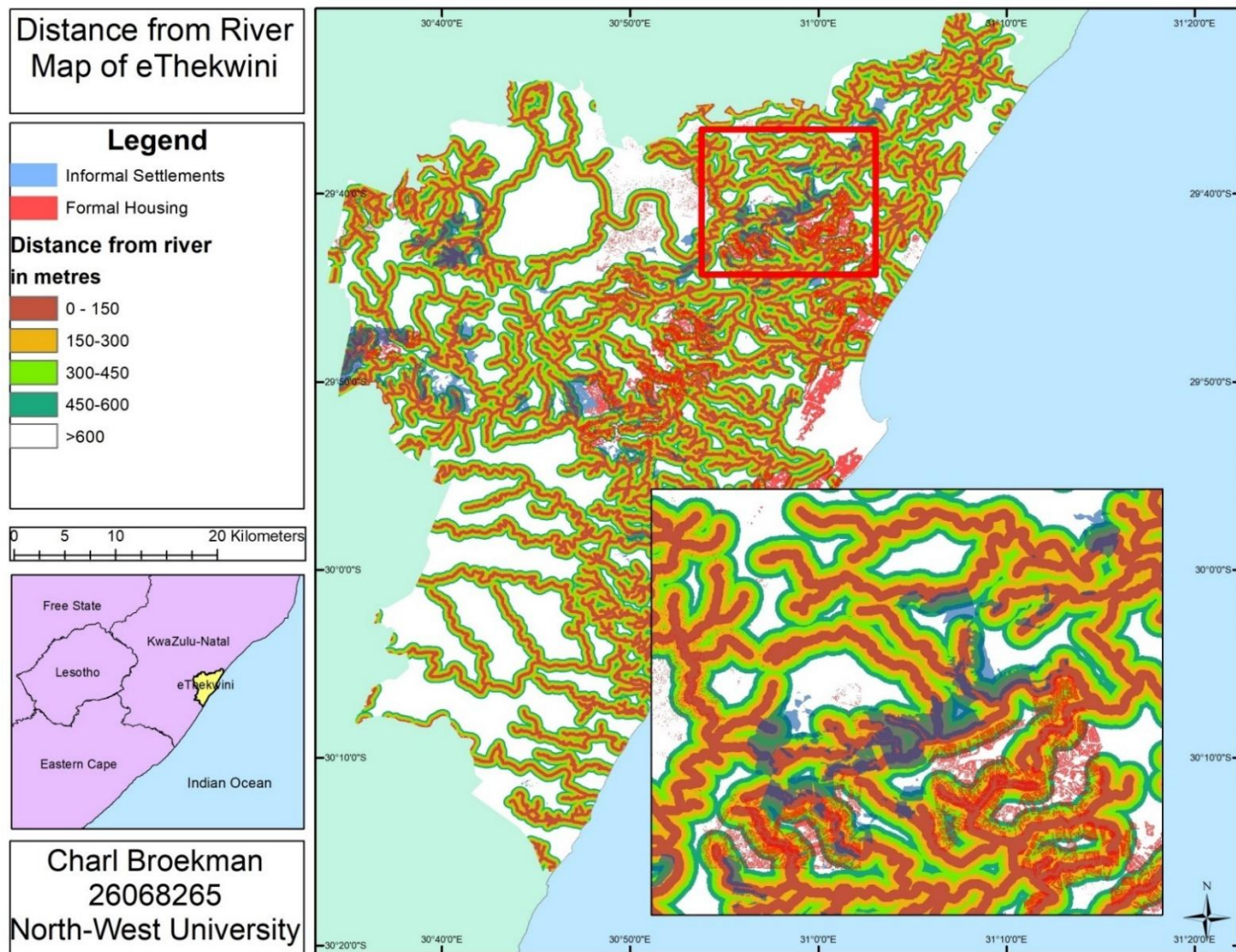


**Figure 3.11:** Distance from rivers inset map number two of eThekwin displaying all the informal and formal housing in the red square (eThekwin Municipality, 2024)

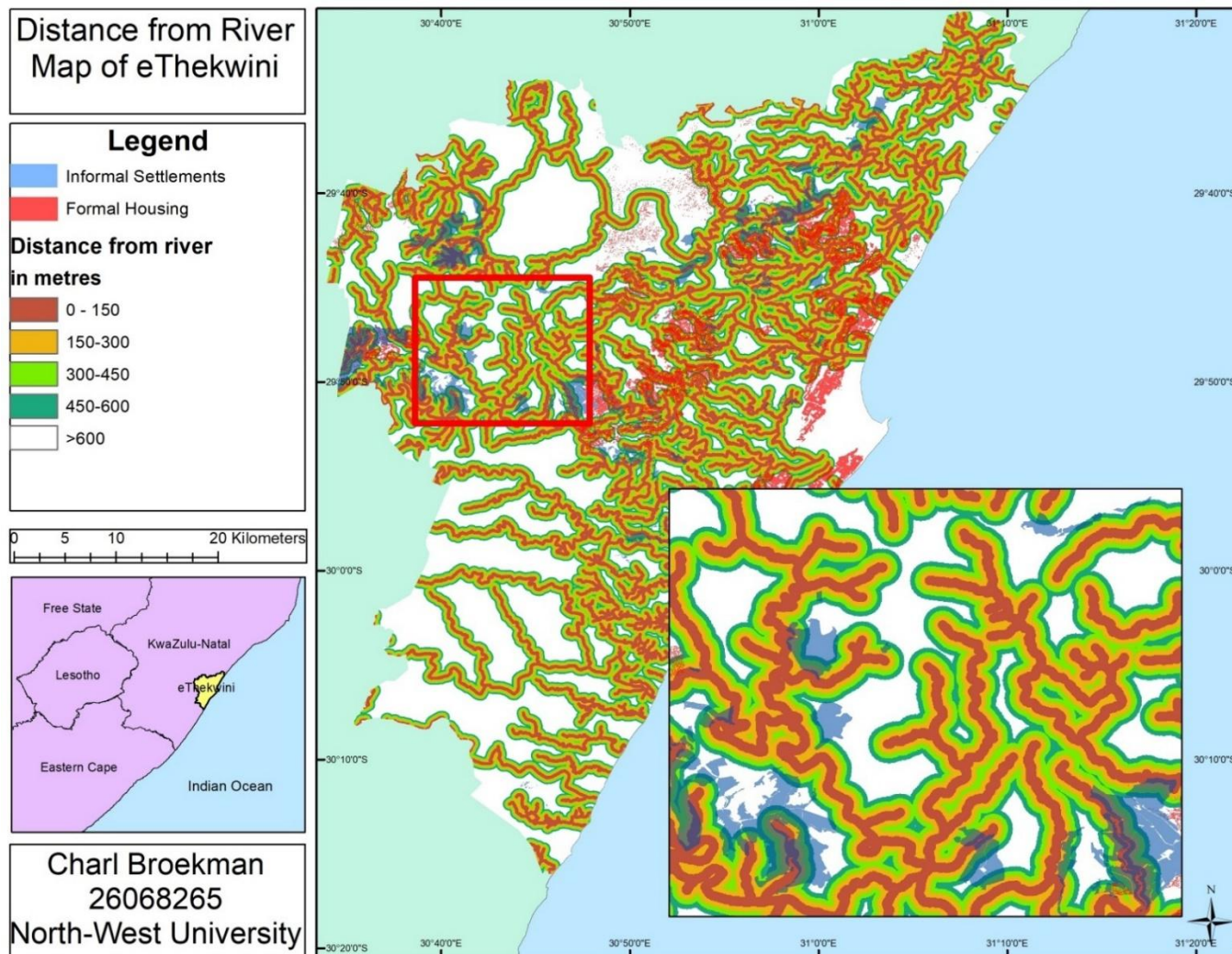


**Figure 3.12: Distance from rivers inset map number three of eThekweni displaying all the informal and formal housing in the red square (eThekweni Municipality, 2024)**

### 3.2.3 Factors that contribute to flood risk

A key challenge in MCDA is merging information from multiple criteria into a single assessment index. To identify variables associated with flooding, the study reviewed various flood risk studies to inform the selection of relevant factors (Ahmed *et al.*, 2019; Blistanova *et al.*, 2016; Danumah *et al.*, 2016; Elsheikh *et al.*, 2015; Gazi *et al.*, 2019; Hagos *et al.*, 2022; Hussain *et al.*, 2021; Jagtrap & Medhe, 2023; Mahmoud & Gan, 2018; Negese *et al.*, 2022; Osman & Das, 2023; Paquette & Lowry, 2012; Pham *et al.*, 2021; Rincón *et al.*, 2018; Rendana *et al.*, 2023; Vojtek & Vojteková, 2019; Wondim, 2016). Ultimately, the studies by Hagos *et al.* (2022) and Rendana *et al.* (2023) were used as a guide for identifying the factors contributing to flood risk. The inclusion of the same seven essential criteria in the studies by Hagos *et al.* (2022) and Rendana *et al.* (2023) for flood risk assessment using MCDA was a compelling reason for choosing these research studies as a guide for identifying the factors contributing to flood risk. The approach by Hagos *et al.* (2022) and Rendana *et al.* (2023) of choosing seven criteria that affect flood risk suggests a comprehensive understanding of flood risk.

These criteria as identified by Hagos *et al.* (2022) and Rendana *et al.* (2023) include slope, elevation, rainfall, drainage density, soil type, land use, and distance from rivers. They are all relevant to real-world flood scenarios, as was demonstrated by the various other flood risk studies that were consulted. Many of the other studies also used some of these criteria as illustrated in Table 3.2.

**Table 3.2: Criterion used in flood risk mapping in the studies consulted**

| Criterion            | Studies                                                                                                                                                                                                                                                           |
|----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Distance from rivers | Hussain <i>et al.</i> (2021), Vojtek and Vojtekova (2019), Rincon <i>et al.</i> (2018), Ahmed <i>et al.</i> (2019), Negese <i>et al.</i> (2022), Osman and Das (2023), Jagtrap and Medhe (2023), Mahmoud and Gan (2018)                                           |
| Elevation            | Hussain <i>et al.</i> (2021), Wondim (2016), Vojtek and Vojtekova (2019), Rincon <i>et al.</i> (2018), Ahmed <i>et al.</i> (2019), Negese <i>et al.</i> (2022), Osman and Das (2023), Paquette and Lowry (2012), Jagtrap and Medhe (2023), Mahmoud and Gan (2018) |
| Rainfall             | Hussain <i>et al.</i> (2021), Rincon <i>et al.</i> (2018), Pham <i>et al.</i> (2021), Jagtrap, and Medhe (2023), Mahmoud and Gan (2018)                                                                                                                           |

|                  |                                                                                                                                                                                                             |
|------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Slope            | Hussain <i>et al.</i> (2021), Wondim (2016), Negese <i>et al.</i> (2022), Gazi <i>et al.</i> (2019), Paquette and Lowry (2012), Pham <i>et al.</i> (2021), Jagtrap and Medhe (2023), Mahmoud and Gan (2018) |
| Land use         | Hussain <i>et al.</i> (2021), Wondim (2016), Negese <i>et al.</i> (2022), Gazi <i>et al.</i> (2019), Paquette and Lowry (2012), Pham <i>et al.</i> (2021), Jagtrap and Medhe (2023), Mahmoud and Gan (2018) |
| Drainage density | Hussain <i>et al.</i> (2021), Wondim (2016), Negese <i>et al.</i> (2022), Osman and Das (2023), Pham <i>et al.</i> (2021), Jagtrap and Medhe (2023), Mahmoud and Gan (2018)                                 |
| Soil type        | Wondim (2016), Vojtek and Vojtekova (2019), Negese <i>et al.</i> (2022), Osman and Das (2023), Pham <i>et al.</i> (2021), Jagtrap and Medhe (2023), Mahmoud and Gan (2018)                                  |

The seven chosen criteria are well-established factors that affect the likelihood and severity of flooding events, as is demonstrated above. Additionally, these seven criteria chosen by Hagos *et al.* (2022) and Rendana *et al.* (2023) typically rely on geospatial and environmental data that is readily available, making data collection more manageable in this study. Accessibility to data is a crucial aspect of conducting practical flood risk assessments, as it affects this study's feasibility for replication or adaptation in the eThekweni Metropolitan Municipality. Furthermore, the choices of criteria by Hagos *et al.* (2022) and Rendana *et al.* (2023) also imply an interdisciplinary perspective, combining insights from geography, hydrology, geology, and land use planning, which can enhance the study's robustness. Lastly, MCDA, as the chosen methodology, allows the integration of these diverse criteria, reflecting the decision-making process of stakeholders and providing a more nuanced understanding of flood risk.

### 3.2.4 Analytic hierarchy process

The analytic hierarchy process (AHP) is a widely recognised decision-making technique that facilitates the systematic evaluation and prioritisation of multiple criteria to make informed decisions (Teknomo, 2006; Vaidya & Kumar, 2006). In this study, AHP was employed to integrate the seven key criteria – slope, elevation, rainfall, drainage density, soil type, land use, and distance from rivers – for the development of a comprehensive flood risk map for the eThekweni Metropolitan Municipality.



### 3.2.4.1 Criteria hierarchy construction

The first step in AHP involves structuring the criteria hierarchy (see Table 3.3). The seven criteria are organised in a hierarchical structure, with the main goal being flood risk mapping. This hierarchical representation allows for a clear understanding of the relationships between criteria and their relative importance.

In constructing a hierarchical representation of the relative importance of the seven input criteria, an extensive number of studies on flood risk mapping were consulted (Ahmed *et al.*, 2019; Blistanova *et al.*, 2016; Danumah *et al.*, 2016; Elsheikh *et al.*, 2015; Gazi *et al.*, 2019; Hagos *et al.*, 2022; Hussain *et al.*, 2021; Jagtrap & Medhe, 2023; Mahmoud & Gan, 2018; Negese *et al.*, 2022; Osman & Das, 2023; Paquette & Lowry, 2012; Pham *et al.*, 2021; Rendana *et al.*, 2023; Rincón *et al.*, 2018; Vojtek & Vojteková, 2019; Wondim, 2016).

Among these studies, five specifically used the seven criteria that were also selected for this study, but they add other criteria that were not selected for this study (Hagos *et al.*, 2022; Jagtrap & Medhe, 2023; Mahmoud & Gan, 2018; Negese *et al.*, 2022; Pham *et al.*, 2021; Rendana *et al.*, 2023). Only two, Hagos *et al.* (2022) and Rendana *et al.* (2023), used exactly the same seven criteria and arrived at a unanimous hierarchy conclusion.

Given the alignment in criteria selection and hierarchy determination between Hagos *et al.* (2022) and Rendana *et al.* (2023), the decision to adopt their hierarchy as the basis for this research is well-founded. The choice is informed by the robustness of their methodology, as evidenced by the convergence of their findings in terms of a hierarchical ranking. Using this shared hierarchy not only builds on the established body of knowledge of flood risk mapping but also ensures consistency and reliability in the analysis of this study.

Therefore, the hierarchical representation of criteria importance in this research study closely follows the same structure proposed by both Hagos *et al.* (2022) and Rendana *et al.* (2023), providing a strong foundation for investigation into flood risk mapping for the eThekweni Metropolitan Municipality.

**Table 3.3: Hierarchy of input criteria in this study**

| Input criteria | Hierarchy |
|----------------|-----------|
| Slope          | 1         |
| Elevation      | 2         |

|                      |   |
|----------------------|---|
| Drainage density     | 3 |
| Distance from rivers | 4 |
| Rainfall             | 5 |
| Soil type            | 6 |
| Land use             | 7 |

### 3.2.4.2 Pairwise comparison

A critical aspect of the AHP is the establishment of pairwise comparisons to assess the relative importance of criteria within a hierarchical structure. AHP is a powerful decision-making method that helps break down complex problems into a structured hierarchy of criteria, sub-criteria, and alternatives (Grzybowski, 2012). To make informed decisions within this hierarchy, numerical values are assigned to represent the relative importance of one criterion over another. The relative importance of one criterion over another was determined with the help of Saaty's scale (see Table 3.4). Also known as the AHP scale, Saaty's scale is a fundamental component of AHP. The scale provides a standardised way to express preferences and judgements when comparing criteria or alternatives (Saaty, 1980). This scale consists of numerical values ranging from 1 to 9, each representing a degree of importance or preference. The scale is designed to capture the extent of importance, allowing researchers to express their subjective judgements consistently and meaningfully (Saaty, 1980).

**Table 3.4: Saaty's AHP scale**

| Intensity of importance | Degree of preference                           | Explanation                                                        |
|-------------------------|------------------------------------------------|--------------------------------------------------------------------|
| 1                       | Equal importance                               | Two activities contribute equally to the objective                 |
| 3                       | Moderate importance of one factor over another | Experience and judgement slightly favour one activity over another |
| 5                       | Strong or essential importance                 | Experience and judgement strongly favour one activity over another |

|            |                                                    |                                                                                                  |
|------------|----------------------------------------------------|--------------------------------------------------------------------------------------------------|
| 7          | Very strong importance                             | An activity is strongly favoured, and its dominance is demonstrated in practice                  |
| 9          | Extreme importance                                 | The evidence favouring one activity over another is of the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values between two adjacent judgments | When compromise is needed                                                                        |

**Adapted from Saaty (1980)**

This study's approach to pairwise comparison, as informed by Saaty's scale and guided by the alignment with Hagos *et al.* (2022) and Rendana *et al.* (2023), serves as a cornerstone of the methodological process to flood risk mapping for the eThekweni Metropolitan Municipality.

Hagos *et al.* (2022) used literature reviews, on-site observations, and expert assessments to fill in a pairwise comparison. The pairwise comparison of Hagos *et al.* (2022) can be seen in Figure 3.13.

| Factor             | Slope | Elevation | Drainage density | Proximity to river | Rainfall | Soil texture | Land use |
|--------------------|-------|-----------|------------------|--------------------|----------|--------------|----------|
| Slope              | 1     |           |                  |                    |          |              |          |
| Elevation          | 1/2   | 1         |                  |                    |          |              |          |
| Drainage density   | 1/3   | 1/2       | 1                |                    |          |              |          |
| Proximity to river | 1/3   | 1/3       | 1/2              | 1                  |          |              |          |
| Rainfall           | 1/5   | 1/5       | 1/3              | 1/3                | 1        |              |          |
| Soil texture       | 1/7   | 1/7       | 1/5              | 1/5                | 1/3      | 1            |          |
| Land use           | 1/9   | 1/9       | 1/7              | 1/7                | 1/5      | 1/3          | 1        |

**Figure 3.13: Pairwise comparison of the study by Hagos *et al.* (2022)**

Rendana *et al.* (2023) also used literature reviews, on-site observations, and expert assessments to fill in a pairwise comparison. The pairwise comparison of Rendana *et al.* (2023) can be seen in Figure 3.14.

| Factors           | Slope | Elevation | Drainage density | Distance to river | Precipitation | Soil type | Landuse |
|-------------------|-------|-----------|------------------|-------------------|---------------|-----------|---------|
| Slope             | 1     |           |                  |                   |               |           |         |
| Elevation         | 1/2   | 1         |                  |                   |               |           |         |
| Drainage density  | 1/3   | 1/2       | 1                |                   |               |           |         |
| Distance to river | 1/3   | 1/3       | 1/2              | 1                 |               |           |         |
| Precipitation     | 1/5   | 1/5       | 1/3              | 1/3               | 1             |           |         |
| Soil type         | 1/7   | 1/7       | 1/5              | 1/5               | 1/3           | 1         |         |
| Landuse           | 1/9   | 1/9       | 1/7              | 1/7               | 1/5           | 1/3       | 1       |

**Figure 3.14: Pairwise comparison of the study by Rendana *et al.* (2022)**

Rendana *et al.* (2023) did not conduct a validation of their flood hazard mapping results, leaving the reliability and accuracy of their findings without explicit confirmation. In contrast, Hagos *et al.* (2022) took a proactive approach by conducting a comprehensive validation process for their study area. Through field visits and interviews with local residents, Hagos *et al.* (2022) collected data on historical flood occurrences, aligning this information with the model's output. The validation demonstrated a consistent alignment between predicted and observed outcomes, highlighting the reliability of their flood risk map.

This study's approach to pairwise comparison (see Table 3.5) as guided by the studies of Hagos *et al.* (2022) and Rendana *et al.* (2023) ensures that the pairwise comparison that was established in Table 3.5 accurately reflects the relative importance of each criterion, establishing a robust foundation for this study.

**Table 3.5: Pairwise comparison matrix used in this study**

| <b>Factor</b>       | Slope | Elevation | Drainage density | Distance from river | Rainfall | Soil type | Land use |
|---------------------|-------|-----------|------------------|---------------------|----------|-----------|----------|
| Slope               | 1     |           |                  |                     |          |           |          |
| Elevation           | 1/2   | 1         |                  |                     |          |           |          |
| Drainage density    | 1/3   | 1/2       | 1                |                     |          |           |          |
| Distance from river | 1/3   | 1/3       | 1/2              | 1                   |          |           |          |
| Rainfall            | 1/5   | 1/5       | 1/3              | 1/3                 | 1        |           |          |
| Soil type           | 1/7   | 1/7       | 1/5              | 1/5                 | 1/3      | 1         |          |
| Land use            | 1/9   | 1/9       | 1/7              | 1/7                 | 1/5      | 1/3       | 1        |

The above pairwise comparison matrix plays an important role in determining the relative importance of various criteria within the context of flood risk mapping for the eThekweni Metropolitan Municipality. Each cell in the matrix represents the pairwise comparisons of one criterion against another, with values derived from judgments based on Saaty's scale. It should be noted that when "/" is used in pairwise comparisons between two criteria, it signifies a fractional relationship, denoting the relative importance or preference of one criterion compared to the other. Specifically, it indicates that the criterion on the left side of the "/" is considered to be of lower importance or preference than the criterion on the right side.

The decimal pairwise comparison matrix presented below (Table 3.6) is pivotal to the AHP methodology. Its significance lies in its ability to quantitatively assess the relative importance of each criterion. This assessment is integral to the process of calculating the weights associated with each criterion.

**Table 3.6: Decimal pairwise matrix used in this study**

| <b>Factor</b> | Slope | Elevation | Drainage density | Distance from river | Rainfall | Soil type | Land use |
|---------------|-------|-----------|------------------|---------------------|----------|-----------|----------|
|---------------|-------|-----------|------------------|---------------------|----------|-----------|----------|

|                     |      |      |      |      |      |      |      |
|---------------------|------|------|------|------|------|------|------|
| Slope               | 1.00 | 2.00 | 3.00 | 3.00 | 5.00 | 7.00 | 9.00 |
| Elevation           | 0.50 | 1.00 | 2.00 | 3.00 | 5.00 | 7.00 | 9.00 |
| Drainage density    | 0.33 | 0.50 | 1.00 | 2.00 | 3.00 | 5.00 | 7.00 |
| Distance from river | 0.33 | 0.33 | 0.50 | 1.00 | 3.00 | 5.00 | 7.00 |
| Rainfall            | 0.20 | 0.20 | 0.33 | 0.33 | 1.00 | 3.00 | 5.00 |
| Soil type           | 0.14 | 0.14 | 0.20 | 0.20 | 0.33 | 1.00 | 3.00 |
| Land use            | 0.11 | 0.11 | 0.14 | 0.14 | 0.20 | 0.33 | 1.00 |

### 3.2.5 Calculation of weighted criteria

The decimal pairwise matrix was used to calculate the weights of criteria. The eigenvector method was applied to compute the weights each criterion will carry. The weights quantify the significance of each criterion in relation to the others.

The first step in computing the weight of each criterion involves normalising the decimal pairwise matrix by calculating the total sum each column. Subsequently, every element in a column is divided by its column sum, resulting in a normalised score for each element in the matrix (see Table 3.7).

**Table 3.7: Normalised decimal pairwise matrix**

| <b>Factor</b>       | Slope  | Elevation | Drainage density | Distance from river | Rainfall | Soil type | Land use |
|---------------------|--------|-----------|------------------|---------------------|----------|-----------|----------|
| Slope               | 0.3816 | 0.4665    | 0.4180           | 0.3100              | 0.2852   | 0.2471    | 0.2195   |
| Elevation           | 0.1908 | 0.2332    | 0.2787           | 0.3100              | 0.2852   | 0.2471    | 0.2195   |
| Drainage density    | 0.1272 | 0.1166    | 0.1393           | 0.2067              | 0.1711   | 0.1765    | 0.1707   |
| Distance from river | 0.1272 | 0.0777    | 0.0697           | 0.1033              | 0.1711   | 0.1765    | 0.1707   |
| Rainfall            | 0.0763 | 0.0466    | 0.0464           | 0.0344              | 0.0570   | 0.1059    | 0.1220   |
| Soil type           | 0.0545 | 0.0333    | 0.0279           | 0.0207              | 0.0190   | 0.0353    | 0.0732   |

|          |        |        |        |        |        |        |        |
|----------|--------|--------|--------|--------|--------|--------|--------|
| Land use | 0.0424 | 0.0259 | 0.0199 | 0.0148 | 0.0114 | 0.0118 | 0.0244 |
|----------|--------|--------|--------|--------|--------|--------|--------|

The final step in computing the weight of each criterion involves calculating the geometrical mean of each row of the pairwise matrix. This gives the final weights of each criterion expressed in Table 3.8.

**Table 3.8: Calculated criteria weights**

| Criteria            | Criteria weight | Influence (%) |
|---------------------|-----------------|---------------|
| Slope               | 0.33            | 33            |
| Elevation           | 0.25            | 25            |
| Drainage density    | 0.16            | 16            |
| Distance from river | 0.13            | 13            |
| Rainfall            | 0.07            | 7             |
| Soil type           | 0.04            | 4             |
| Land use            | 0.02            | 2             |

### 3.2.6 Consistency checks

In order to guarantee the dependability of the pairwise comparisons within the study's analysis, consistency checks should be done. These checks are essential for ensuring that the judgements made during the comparison process align seamlessly with the underlying logic and objectives of this study.

One of the key metrics that was employed to conduct these consistency checks is the CI. The CI serves as a quantitative measure that allows researchers to gauge the degree of coherence and harmony in the pairwise comparisons (Grzybowski, 2012). It essentially acts as a litmus test to

assess whether the relationships established between the elements being compared are logically sound and consistent (Grzybowski, 2012).

Furthermore, alongside the CI, this study will also use the CR as another vital tool in the study's evaluation process (see Table 3.9). The CR serves as a relative measure, enabling researchers to gauge the consistency of judgments relative to the size and complexity of our comparison matrix (Chu & Liu, 2002). This metric plays a pivotal role in ensuring that the comparisons are not only consistent but also appropriately balanced within the context of our analysis (Chu & Liu, 2002).

**Table 3.9: Table used for calculation of consistency checks**

| <b>Factor</b>       | Slope  | Elevation | Drainage density | Distance from River | Rainfall | Soil type | Land use | Weighted sum value | Criteria weight | Weighted sum/Criteria weight |
|---------------------|--------|-----------|------------------|---------------------|----------|-----------|----------|--------------------|-----------------|------------------------------|
| Slope               | 0.3816 | 0.4665    | 0.4180           | 0.3100              | 0.2852   | 0.2471    | 0.2195   | 2.3279             | 0.3326          | 6.9991                       |
| Elevation           | 0.1908 | 0.2332    | 0.2787           | 0.3100              | 0.2852   | 0.2471    | 0.2195   | 1.7645             | 0.2521          | 6.9992                       |
| Drainage density    | 0.1272 | 0.1166    | 0.1393           | 0.2067              | 0.1711   | 0.1765    | 0.1707   | 1.1081             | 0.1583          | 7                            |
| Distance from river | 0.1272 | 0.0777    | 0.0697           | 0.1033              | 0.1711   | 0.1765    | 0.1707   | 0.8962             | 0.1280          | 7.0016                       |
| Rainfall            | 0.0763 | 0.0466    | 0.0464           | 0.0344              | 0.0570   | 0.1059    | 0.1220   | 0.4886             | 0.0690          | 7.0812                       |
| Soil type           | 0.0545 | 0.0333    | 0.0279           | 0.0207              | 0.0190   | 0.0353    | 0.0732   | 0.2639             | 0.0377          | 7                            |
| Land use            | 0.0424 | 0.0259    | 0.0199           | 0.0148              | 0.0114   | 0.0118    | 0.0244   | 0.1506             | 0.0215          | 7.0047                       |
|                     |        |           |                  |                     |          |           |          |                    | <b>CI</b>       | 0.0020                       |



|  |           |        |
|--|-----------|--------|
|  | <b>RI</b> | 1.32   |
|  | <b>CR</b> | 0.0011 |

The CI was calculated using the following formula:

$$CI = (\lambda_{\max} - n) / (n - 1)$$

Where:

$\lambda_{\max}$  is the largest eigenvalue of the pairwise comparison matrix.

'n' is the number of criteria or alternatives being compared.

The CR is the ratio of CI to RI:

$$CR = CI / RI$$

Where:

The Random Index (RI) depends on the number of criteria or alternatives (n). Refer to the standard table (Table 3.10) of RI values corresponding to different 'n' values below (Saaty, 1980).

**Table 3.10: Saaty's random index table**

| <b>n</b>  | 1 | 2 | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-----------|---|---|------|------|------|------|------|------|------|------|
| <b>RI</b> | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.46 | 1.49 |

**Adapted from Saaty (1980)**

If CR is less than 0.10 then the judgements are considered consistent, and the pairwise comparisons are deemed reliable (Chu & Liu, 2002). Therefore, it can be said that the pairwise comparisons are deemed to be reliable in this study as the CR was 0.0011.

Having now established a foundation for the current flood risk mapping methodology in the eThekwin Metropolitan Municipality with the analysis of seven key factors and a meticulous application of MCDA, the methodology now transitions to the future flood risk mapping methodology. This next phase incorporated AG as a pivotal tool to develop future flood risk maps,

enabling the exploration of diverse scenarios that consider the impact of climate change, varying precipitation patterns based on SSPs, and the influence of population growth in informal settlements.

### **3.3 Future flood risk**

In this section of the study, AG, a forward-thinking approach that is increasingly recognised as an essential tool in navigating the complexities of a rapidly changing world is used as a tool of GIS to identify future areas that may be vulnerable to flooding in the coming years. This section of the study specifically focuses on Approach 3: Pluralistic futures, societal mobilisation and co-creating alternatives, as identified by Muiderman *et al.* (2020), to guide the methodology of mapping future risk scenarios in the eThekweni Metropolitan Municipality.

The selection of this approach to AG that is focused on pluralistic futures and societal mobilisation, acknowledges the value of creating multiple future flood risk maps. This approach to AG recognises the inherent uncertainty in the future and encourages the exploration of diverse possibilities. By using this approach to AG, this study can develop not only a single, fixed future flood risk map but a range of scenarios that consider different uncertainties, and potential future climate change outcomes. This can lead to a more comprehensive and adaptable approach to flood risk mapping, considering a spectrum of future possibilities and enhancing the resilience of the strategies developed.

The choice of Approach 3: Pluralistic futures, societal mobilisation and co-creating alternatives over the other approaches of AG lies in its capacity to embrace diverse potential future climate change outcomes and uncertainties. By co-creating multiple future scenarios, this approach to AG allows for a more inclusive and robust exploration of potential outcomes. This approach fosters adaptability, enhancing the ability to respond effectively to a range of future conditions.

By highlighting the importance of this AG approach when dealing with flood risk, this section demonstrates how the core principles of Approach 3: Pluralistic futures, societal mobilisation and co-creating alternatives, address the challenges of flood risk and has the potential to reshape the role of GIS with regard to mapping and mitigating flood risks. This transformation, in turn, promises to be a more effective and generating a proactive approach to flood risk management in the eThekweni Metropolitan Municipality.

#### **3.3.1 Driving factors of future flood risk scenarios**

In addressing the complex task of mapping the future flood risk in the eThekweni Metropolitan Municipality, this study adopts a focused approach, as guided by Approach 3: Pluralistic futures,

societal mobilisation, and co-creating alternatives. This approach to AG emphasises the importance of considering a range of factors that could shape future scenarios. Among the multitude of potential factors that could shape future flood risk, this study specifically focuses on two key elements that are particularly relevant to the eThekweni Metropolitan Municipality, as evidenced by the devastating effects of the floods in 2019 and 2022.

Firstly, the potential change in precipitation as a result of climate change is a critical factor. The change in precipitation has already shown its capacity to play a significant role in the severity and frequency of flooding events. The trend of changing precipitation, likely linked to broader climatic changes, poses a continued and escalating threat to the eThekweni Metropolitan Municipality, necessitating urgent consideration in any future flood risk scenario mapping.

Secondly, the urbanisation and expansion of informal areas are equally significant to future flood risk scenarios. This socio-geographical factor has profound implications for how urban spaces react to environmental challenges. In the eThekweni Metropolitan Municipality, rapid urbanisation, coupled with the unplanned and often precarious expansion of informal settlements, has exacerbated the impact of natural disasters like floods. These areas, typically lacking adequate infrastructure and environmental safeguards, are particularly vulnerable to the consequences of changes in precipitation. The interplay between this rapid urban sprawl and changing precipitation patterns has been starkly demonstrated in the recent floods of 2019 and 2022 in the eThekweni Metropolitan Municipality, underscoring the need to incorporate these issues in tandem when considering future flood risk scenarios.

Approach 3: Pluralistic futures, societal mobilisation and co-creating alternatives, offers a comprehensive framework for reimagining how societies prepare for and respond to the ever-increasing threat of flooding. By selecting this approach to AG, this study can explore numerous possibilities that can be used to visualise future flood risks in the present. The key elements of this approach to AG, from multiple diverse and subjective scenarios to the collective imagination and collaboration, all converge to provide a holistic perspective on flood risk management. These principles can be harnessed to craft a forward-thinking strategy for flood risk mapping in the study area of the eThekweni Metropolitan Municipality, looking ahead to approximately 2050. Looking ahead to the year 2050 in the context of flood risk mapping in the eThekweni Metropolitan Municipality is crucial for several reasons, primarily rooted in the alignment with prevailing national and international development policies. The strategic focus on 2050 corresponds with a date widely acknowledged in diverse policy frameworks as a pivotal milestone for sustainable development (Lempert *et al.*, 2019; van Sluisveld *et al.*, 2017). Numerous national and international initiatives, including climate action agendas such as the International Energy

Agency's Net Zero Emissions by 2050 Scenario (NZE Scenario) and urban planning blueprints such as Vision 2050, centre their objectives around the year 2050 (Liang *et al.*, 2023; Mathiesen *et al.*, 2015).

### 3.3.1.1 Changes in precipitation

In the development of a methodology for future flood risk mapping by using the chosen approach to AG in the eThekweni Metropolitan Municipality for the year 2050, a critical aspect of the analysis is the adjustment of rainfall data inputs. The adjustment of rainfall data inputs is done by considering the SSPs (see Figure 3.15), which offer a framework for exploring various future socioeconomic and climate development scenarios (Riahi *et al.*, 2017). Additionally, the methodology incorporates projections from the World Bank that are based on the Coupled Model Intercomparison Project Phase 6 (CMIP6) for the various SSPs, specifically focusing on the projections up to the year 2050 (World Bank, 2023).



**Figure 3.15:** Diagram showing the five shared socioeconomic pathways (O'Neill *et al.*, 2017)

The CMIP6 is an international effort that brings together climate modelling groups from around the world to develop and compare climate models (Eyring *et al.*, 2016). It is at the forefront of

climate science, using state-of-the-art models to provide projections and insights into future climate conditions (Eyring *et al.*, 2016; Pascoe *et al.*, 2020). The World Bank's reliance on CMIP6 for their projections indicates the use of the newest available climate models and data sources, underscoring the credibility of this study's methodology to map the future flood risk of the eThekweni Metropolitan Municipality. The climate projections of the World Bank extend to the middle of the century, making them highly relevant for assessing flood risk in the year 2050. Incorporating the SSPs into the analysis, this study has developed three distinct rainfall scenarios, each tailored to a specific percentile of rainfall data and corresponding SSP. These scenarios provide valuable insights into how different future socioeconomic and climate pathways may influence rainfall patterns and, in turn, flood risk in the eThekweni Metropolitan Municipality.

The three scenarios that were generated for the rainfall data include the 90th percentile of SSP5, the 50th percentile of SSP2, and the 10th percentile of SSP1. The percentiles used in the SSPs scenarios indicate the relative position of a value across a distribution: the 90th percentile in SSP5 represents a high value, the 50th percentile in SSP2 is the middle or median value, and the 10th percentile in SSP1 signifies a low value compared to others in the distribution. Each SSP scenario reflects a unique combination of population growth, economic development, and technological change, which are pivotal factors influencing greenhouse gas emissions and climate change (Riahi *et al.*, 2017). One scenario represents the absolute best-case climate change scenario in terms of rainfall (10th percentile of SSP1), another depicts a middle-of-the-road scenario (50th percentile of SSP2), and the third scenario portrays the absolute worst-case scenario (90th percentile of SSP5). By integrating these scenarios, this study's methodology ensures a comprehensive understanding of how different socioeconomic and climate scenarios, as outlined by the SSPs, might affect rainfall patterns and flood risk in 2050.

The forthcoming discussion presents three distinct scenarios to project future rainfall amounts in the eThekweni Metropolitan Municipality. These scenarios are based on the principles of Approach 3: Pluralistic futures, societal mobilisation and co-creating alternatives for AG, and aim to provide a clear understanding of the region's potential flood risks in the future.

#### 3.3.1.1.1 Scenario 1: Best case

The best-case scenario for the year 2050 using the 10th percentile of SSP1 data is a pathway characterised by lower levels of greenhouse gas emissions and sustainable development practices. In this scenario, a decrease of 65 mm in rainfall is likely to be observed in KwaZulu-Natal when compared to the current rainfall in the eThekweni Metropolitan Municipality (see Figure 3.16) (World Bank, 2023). As can be seen in the comparison between the current rainfall and the possible rainfall in SSP1 in Figure 3.16, the coastal region of the eThekweni Metropolitan

Municipality will have significantly fewer areas that receive in excess of 1000 mm of mean annual precipitation. Similarly, the inland north-western part of the eThekweni Metropolitan Municipality, the areas that receive less than 700 mm and 700–800 mm of mean annual precipitation, will increase.

A decline in 65 mm in mean annual precipitation in the KwaZulu-Natal region, particularly in the eThekweni Metropolitan Municipality area, would generally signify a diminished risk of flooding. This reduction in precipitation implies a decreased likelihood of overwhelming drainage systems that could lead to flooding. With less water entering rivers and other water bodies, the overall runoff would be reduced, making flooding less likely to occur. In the event that flooding does transpire, its intensity would likely be mitigated by the lower volume of water resulting from the decline in rainfall. Essentially, the implications of such a decrease in rainfall is a dual effect of reducing the probability of flooding and potentially lessening the severity of any flooding that might occur.

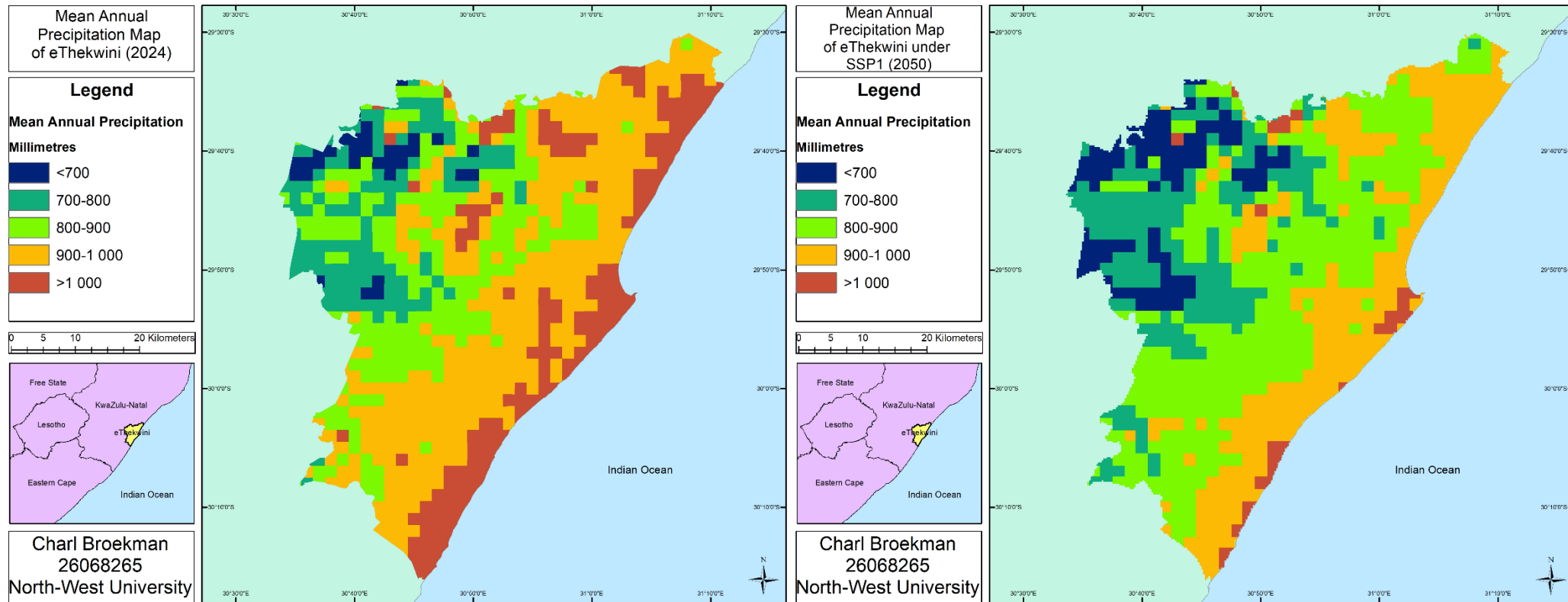


**Figure 3.16: Mean annual precipitation map of eThekweni in Scenario 1: Best Case in comparison with the current precipitation map of eThekweni (eThekweni Municipality, 2024)**

#### 3.3.1.1.2 Scenario 2: Middle of the road

The middle-of-the-road scenario for the year 2050 time period using the 50th percentile of SSP2 data is a pathway characterised by current levels of greenhouse gas emissions and current development practices remaining consistent. In this scenario, an increase of 22 mm in rainfall is likely to be observed in KwaZulu-Natal (see Figure 3.17) (World Bank, 2023). As can be seen from the comparison between the current rainfall and the possible rainfall in SSP2 in Figure 3.17, the coastal region of the eThekweni Metropolitan Municipality will have significantly more areas that receive in excess of 1000 mm of mean annual precipitation, with the coastal region up to 5 km inland possibly receiving in excess of 1000 mm of mean annual precipitation. The central to eastern part of the study area will potentially almost exclusively receive between 900–1000 mm of mean annual precipitation, with the areas that currently receive between 800–900 mm of mean annual precipitation diminishing.

An increase of 22 mm in mean annual precipitation in a coastal region like KwaZulu-Natal, particularly the eThekweni Metropolitan Municipality area, would have implications for the likelihood and intensity of flooding. This additional precipitation means more water would be available to potentially overwhelm drainage systems, rivers, and other water bodies. Consequently, this could lead to an increased likelihood of flooding, as the additional water would contribute to higher runoff levels.

Furthermore, if flooding were to occur under these conditions, it might be more intense than usual. The increased volume of water resulting from the additional 22 mm of rainfall could lead to more severe flooding, with stronger currents and higher water levels. This could result in more significant impacts on infrastructure, agriculture, and communities, especially in areas that are not well-equipped to handle such increases in water levels, such as informal settlements.



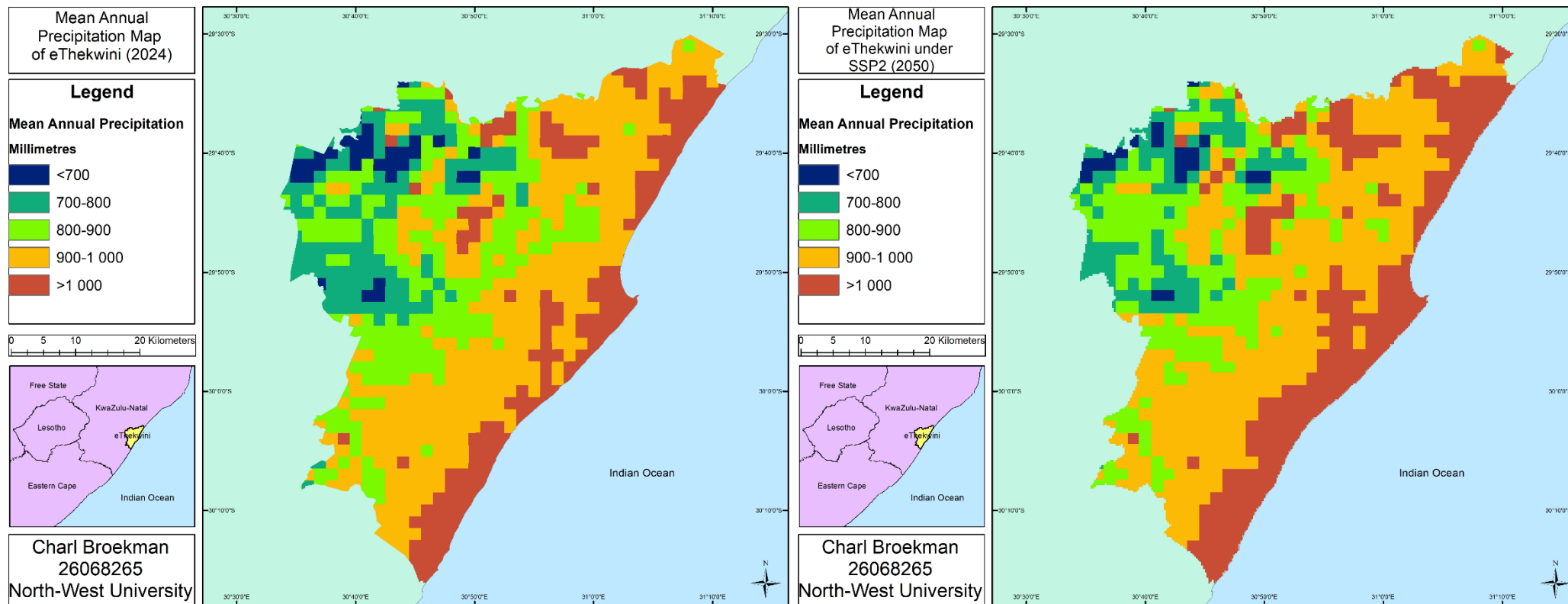


**Figure 3.17: Mean annual precipitation map of eThekweni in Scenario 2: Middle of the road in comparison with the current precipitation map of eThekweni (eThekweni Municipality, 2024)**

#### 3.3.1.1.3 Scenario 3: Worst case

The worst-case scenario for the year 2050 corresponds with the 90th percentile of SSP5, a pathway characterised by low socioeconomic development and no focus on sustainability. In this scenario, a significant increase of 84mm in rainfall is anticipated in KwaZulu-Natal (see Figure 3.18) (World Bank, 2023). As can be seen from the comparison between the current rainfall and the possible rainfall in SSP5 in Figure 3.18, the coastal region of the eThekweni Metropolitan Municipality will have significantly more areas that receive in excess of 1000 mm of mean annual precipitation, with the coastal region, the central-western, and the north-eastern part of the study area almost exclusively receiving in excess of 1000 mm of mean annual precipitation. The north-western inland part of the study area will also potentially gain more areas that receive 800–900 mm and 900–1000 mm, with the north-western inland areas that receive less than 700 mm and 700–800 mm of mean annual precipitation in the future diminishing significantly.

An increase of 84 mm in mean annual precipitation in a coastal region such as KwaZulu-Natal, specifically in the eThekweni Metropolitan Municipality area, would have significant implications for the risk and potential effect of flooding. Such a substantial worst-case increase in precipitation indicates a considerable amount of additional water entering rivers and water bodies, which could lead to a heightened risk of flooding.

The increased volume of rainfall, in this case, would likely overwhelm drainage systems and contribute to a higher likelihood of flooding events. If flooding were to occur, it could be more severe and widespread compared to typical conditions. The potential for increased runoff and rising water levels may pose greater challenges for local infrastructure, agriculture, and communities.

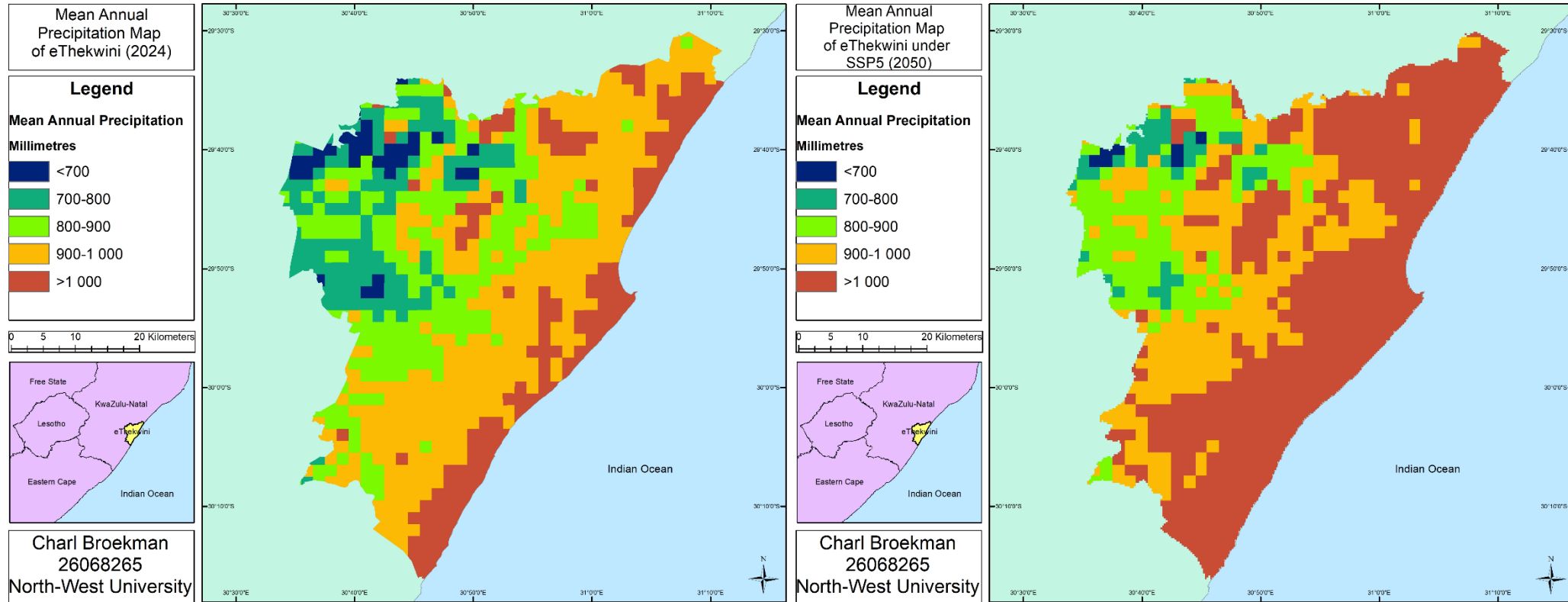


**Figure 3.18: Mean annual precipitation map of eThekweni in Scenario 3: Worst Case in comparison with the current precipitation map of eThekweni (eThekweni Municipality, 2024)**

Another driving factor that influences the development of a methodology for future flood risk mapping, using Approach 3: Pluralistic futures, societal mobilisation and co-creating alternatives, in the eThekweni Metropolitan Municipality for the year 2050, is the growth of the current informal settlements in the eThekweni Metropolitan Municipality. The following section looks at how the current informal settlements in the eThekweni Metropolitan Municipality will have had expanded by the year 2050.

### **3.3.1.2 Future informal settlement expansion**

In the eThekweni Metropolitan Municipality, the expansion of informal settlements is an issue that can be tied to the broader context of urbanisation and socio-economic challenges (Todes *et al.*, 2010; Turok & Borel-Saladin, 2016). The expansion of informal settlements primarily stems from a substantial rural-urban migration and international migration driven by individuals seeking better opportunities and living standards in urban areas (Todes *et al.*, 2010; Huchzermeyer, 2011; Sutherland *et al.*, 2014). The influx of migrants often surpasses the development of adequate urban infrastructure and housing in the eThekweni Metropolitan Municipality, leading to a growth of people living in informal settlements (Huchzermeyer, 2011; Ziblim *et al.*, 2013). The number of people living in informal settlements also grow partly due to difficulties in accessing formal housing, exacerbated by poverty, unemployment, and a scarcity of affordable housing options (Turok & Borel-Saladin, 2016; Marais & Ntema, 2013).

The relationship between the number of people living in an informal settlement and the size of the settlement can be complex and is influenced by various factors (Sutherland *et al.*, 2014; Ziblim *et al.*, 2013). Generally, the size of an informal settlement grows with an increase in population. As more people move into these informal settlement areas, they build more dwellings, leading to an increase in the physical size of the settlement (Marais & Ntema, 2013). However, it is important to note that the relationship isn't always directly proportional. Other factors such as the availability of land, local regulations, and the socio-economic conditions of the residents can also influence the size of the settlement (Sutherland *et al.*, 2014; Todes *et al.*, 2010).

For instance, in densely populated areas, with limited available land, residents might build upwards, creating multi-story dwellings, to accommodate more people without increasing the settlement's size (Marais & Ntema, 2013; Turok & Borel-Saladin, 2016). Conversely, in areas with more available land, residents might spread out more, leading to a larger settlement size even with a smaller population (Marais & Ntema, 2013; Sutherland *et al.*, 2014).

A multi-step methodology was used to predict the potential expansion of informal settlements in the year 2050 in the eThekweni Metropolitan Municipality. This approach incorporated population

data analysis as well as geographical considerations. The primary steps undertaken are as follows:

#### 3.3.1.2.1 Population data analysis

Census data for the years 1996, 2001, 2011, 2016 and 2022 in the eThekweni Metropolitan Municipality were collected and analysed to assess the evolution of the number of households living in informal settlements over time. The historical census data were plotted on a graph (see Figure 3.19), revealing an upward trend. This trendline indicates a potential expansion in the number of households living in informal settlements with the linear regression formula being  $y = 6566.5x - 10\,000\,000$ . To project the expansion of the number of households living in informal settlements in the year 2050, the linear regression formula was used to estimate a total of 489 081 households living in informal settlements. An expansion factor, derived from the historical census data, suggests an anticipated expansion of 154% in the number of households living in informal settlements by 2050.

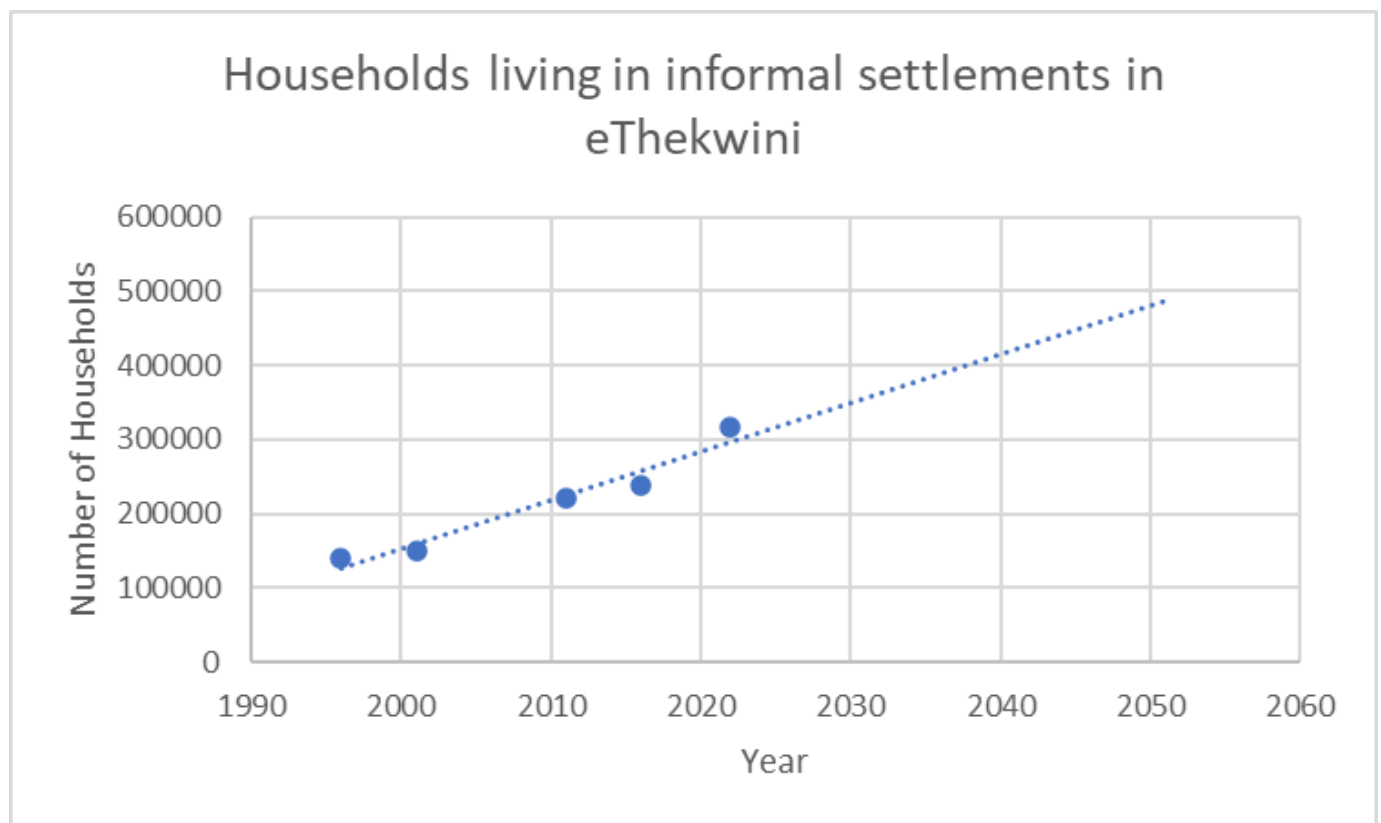


**Figure 3.19: Graph of historical census data plotting the number of households living in informal settlements in eThekweni**

The expansion factor derived from historical census data, predicting a 154% increase in the number of households in informal settlements by 2050, has inherent limitations (Alene, 2022;

Ziblim *et al.*, 2013). Foremost among these is the assumption that observed trends will persist into the future. This assumption may not hold in the face of unforeseen events such as governmental policy changes, economic shifts, or that could alter informal settlement trajectories (Alene, 2022; Huchzermeyer, 2011; Ziblim *et al.*, 2013). Moreover, external factors not accounted for in the calculation, could significantly influence population dynamics (Sutherland *et al.*, 2014; Todes *et al.*, 2010). Natural disasters, political instability, or large-scale economic changes may have unpredictable effects on informal settlement expansion patterns, rendering the projection less reliable (Alene, 2022; Marais & Ntema, 2013; Ziblim *et al.*, 2013). The accuracy of the projection is contingent on the quality and precision of historical census data (Todes *et al.*, 2010). Inaccuracies, inconsistencies, or biases in the data can lead to flawed predictions (Turok & Borel-Saladin, 2016). Informal settlements, being dynamic entities, may not be fully captured by historical data, failing to reflect their adaptability and resilience to changing conditions (Huchzermeyer, 2011; Sutherland *et al.*, 2014). Demographic shifts, such as changes in birth rates, mortality rates, and migration patterns, may not be accurately represented in the historical data, affecting the reliability of the projection (Todes *et al.*, 2010; Ziblim *et al.*, 2013). Furthermore, the spatial variability within informal

settlements may not be adequately considered, with different areas experiencing varying rates of expansion (Marais & Ntema, 2013; Sutherland *et al.*, 2014).

Future policy changes or interventions aimed at addressing informal settlements could alter the anticipated expansion (Huchzermeyer, 2011; Turok & Borel-Saladin, 2016). For instance, successful urban planning initiatives might slow down the growth of informal settlements. Economic conditions, playing a pivotal role in shaping settlement patterns, may evolve in ways not accounted for in the projection (Todes *et al.*, 2010; Ziblim *et al.*, 2013). A lack of sensitivity analysis, testing the effect of variations in assumptions or parameters, also leaves the projection vulnerable to uncertainties (Sutherland *et al.*, 2014). Temporal limitations in historical data may not fully capture recent developments or changes in societal attitudes that could impact informal settlement patterns in the future (Marais & Ntema, 2013; Todes *et al.*, 2010).

Given these limitations, it is important to view this projection not as a definitive forecast, but as a starting point for discussion and further research. Future studies should take a more comprehensive approach, including detailed analysis of current and potential future urban policies, consideration of planned infrastructure developments, integration of socio-economic indicators and their projected changes, spatial analysis to account for varying growth patterns across different areas, and scenario modelling to account for different policy interventions and external factors.

#### 3.3.1.2.2 Geographical considerations

In the assessment of informal settlement expansion in the eThekweni Metropolitan Municipality by 2050, it is important to consider the geographical factors that influence the potential for growth (Sutherland *et al.*, 2014; Todes *et al.*, 2010). The availability of space is a primary determinant in this context. The geographical considerations also include compensating for the non-uniform expansion of these settlements by focusing on those that have the potential for horizontal expansion, using an expansion factor of 154% to project growth (Sutherland *et al.*, 2014; Ziblim *et al.*, 2013).

Where open space exists around an informal settlement, there tends to be horizontal expansion to accommodate an increasing number of households (Huchzermeyer, 2011; Marais & Ntema, 2013). This type of expansion is typically unplanned and dense, occurring more frequently in areas with limited governance. New structures are erected on any available land, leading to a visible increase in the settlement's size (Sutherland *et al.*, 2014; Turok & Borel-Saladin, 2016). In these instances, the projection of settlement growth uses an expansion factor to quantify the expected increase in settlement size, which is determined based on historical household growth and geographical assessments (see Figure 3.20).

Conversely, in areas where space constraints prevent horizontal expansion, settlements may experience a different kind of growth (Marais & Ntema, 2013; Sutherland *et al.*, 2014). In densely populated urban areas where land is at a premium, vertical expansion is a common solution, with residents constructing multi-level dwellings (Marais & Ntema, 2013; Turok & Borel-Saladin, 2016). This methodology, however, recognises that not all settlements have the capacity for horizontal growth due to spatial limitations (Sutherland *et al.*, 2014). In such cases, for the purposes of this study, even with an increase in the number of households, the physical footprint of the settlements remains unchanged (see Figure 3.21). This highlights the importance of incorporating the geographical context into the projection model, acknowledging that the nature of expansion is highly location specific (Todes *et al.*, 2010; Ziblim *et al.*, 2013).

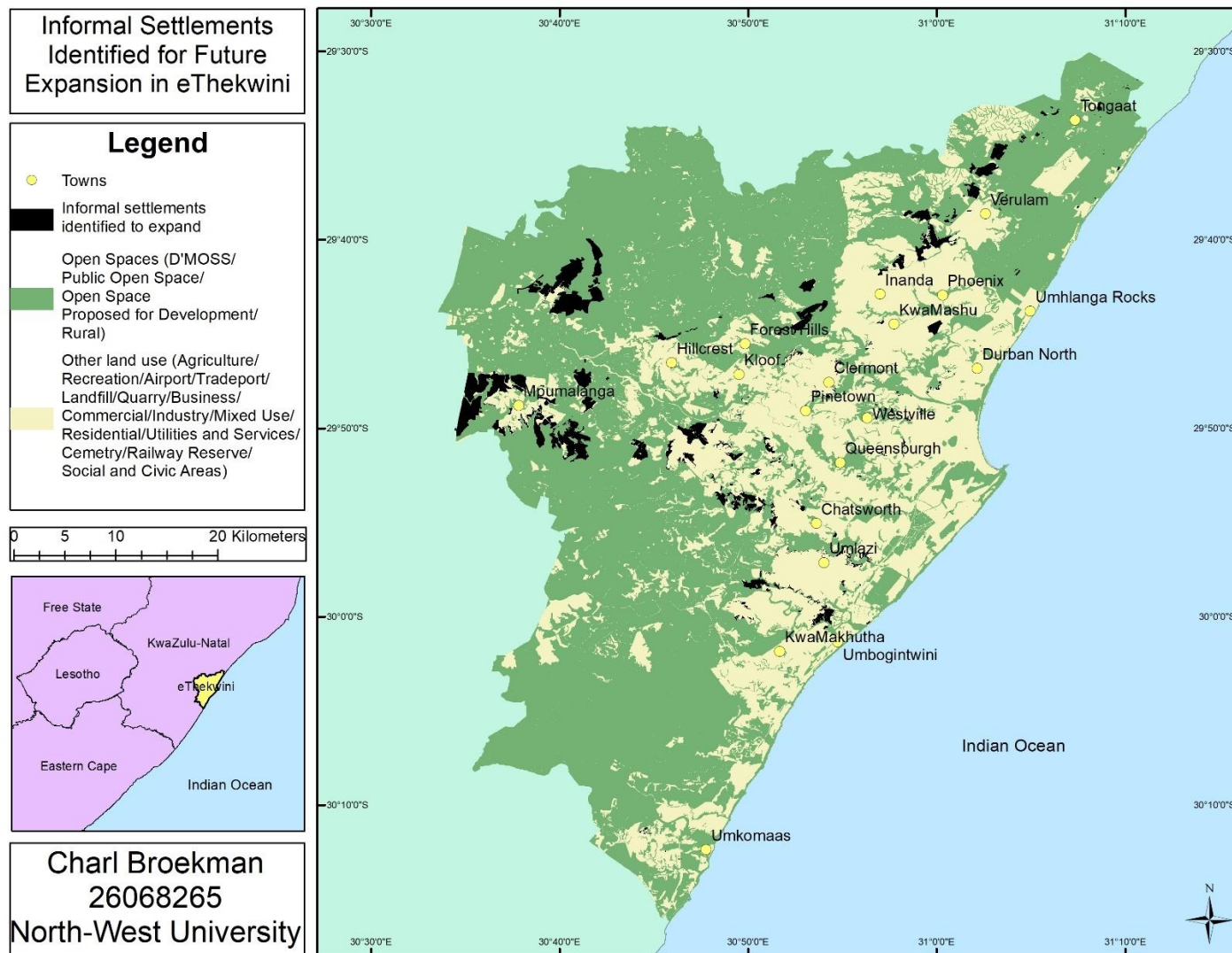


**Figure 3.20: Map of informal settlements identified for future expansion in eThekweni (eThekweni Municipality, 2024)**



The geographical considerations in the methodology, while providing a framework for projecting informal settlement growth, have several limitations that warrant acknowledgement. The binary approach to expansion, which categorises settlements as either having potential for horizontal growth or not, may oversimplify the complex reality of settlement development. This method fails to account for the possibility of mixed growth patterns, where settlements might experience both horizontal and vertical expansion simultaneously. The uniform application of the 154% expansion factor to all settlements with the potential for horizontal growth does not consider local variations in growth rates or differing growth potentials based on unique local factors.

While the methodology recognises vertical growth in space-constrained areas, it does not quantify or project this growth, potentially underestimating the total population increase in these areas. The assumption that current spatial constraints will remain unchanged until 2050 does not account for potential changes in land use, urban planning, or environmental factors that could alter the availability of space for expansion. Moreover, the projection does not factor in the availability or expansion of essential infrastructure and services, which can significantly influence settlement growth patterns.

The methodology's focus on physical space overlooks the influence of socio-economic factors on where and how settlements might expand. Environmental considerations, such as topography, flood-prone areas, or protected lands, which could influence the direction and extent of expansion, are not fully integrated into the model. Furthermore, the approach does not account for broader urban dynamics, such as changes in economic centres or transportation networks, which could significantly affect settlement patterns.

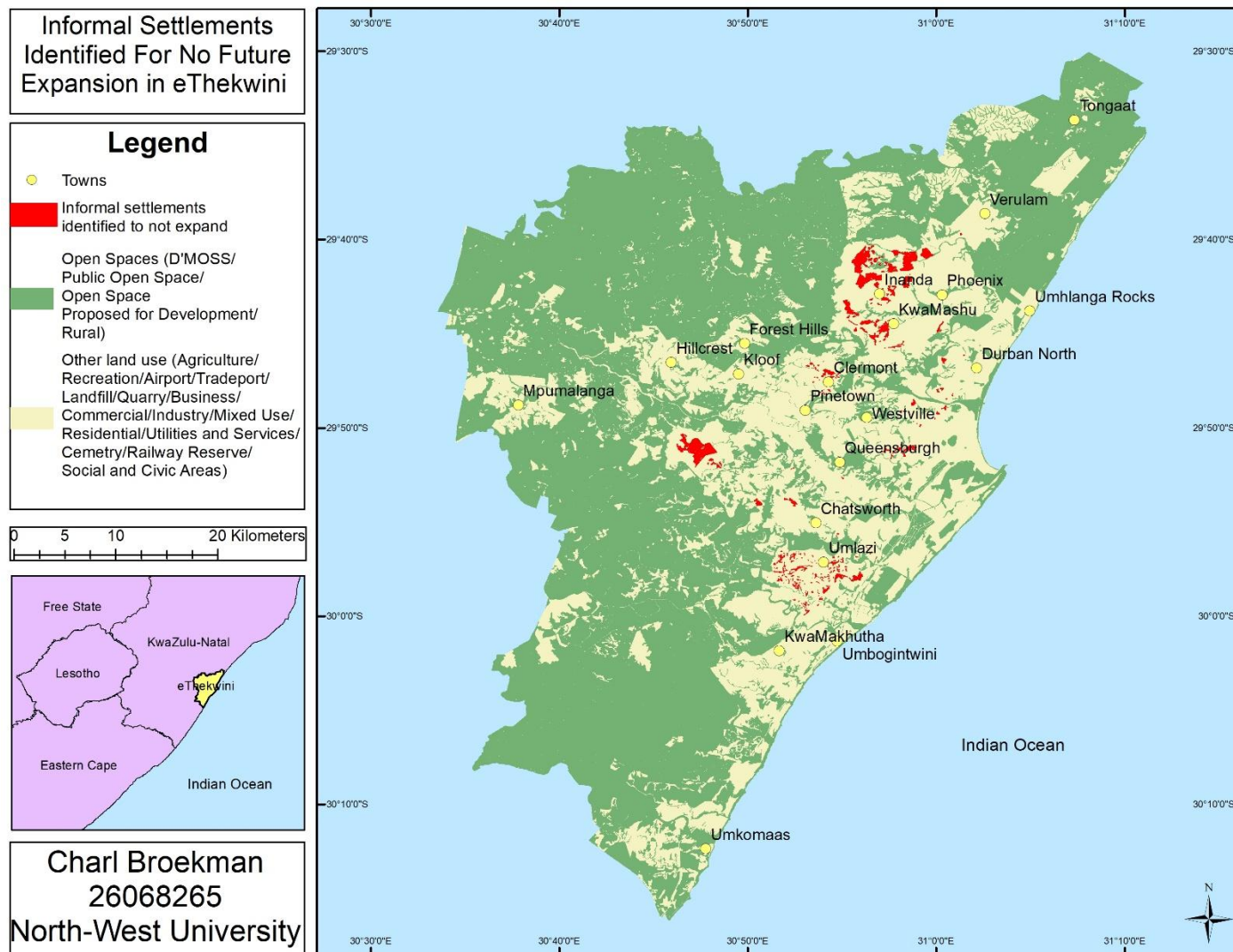


**Figure 3.21: Map of informal settlements identified for no future expansion in eThekweni (eThekweni Municipality, 2024)**

By acknowledging the limitations of both the population data analysis and the geographical considerations and suggesting more complex methods for more comprehensive informal settlement expansion analysis, this study aims to provide a transparent foundation for understanding potential horizontal informal settlement growth in the eThekweni Metropolitan Municipality. The basic methodology used in this study only focuses on the growth of the households and binary geographical considerations to predict the future horizontal size of informal settlements, without accounting for the complex socio-economic, political, and spatial factors that influence informal settlement development.

### **3.3.2 Expansion of informal settlements into open spaces**

Based on the analysis of historical census data and geographical considerations, a projection of the potential expansion of informal settlements in the eThekweni Metropolitan Municipality by the year 2050 was conducted. The historical census data from 1996 to 2022 revealed an upward trend in the number of households living in informal settlements. Using linear regression, it is estimated that by 2050, there could be approximately 489 081 households in informal settlements, representing a 154% increase from the current numbers. However, this expansion is not expected to be uniform across all settlements. The study considered the geographical constraints that limit horizontal expansion in certain areas. Settlements with available open space were identified as having the potential for horizontal growth, and the 154% expansion factor was applied to these areas. Conversely, settlements in densely populated urban areas with limited land availability were recognised as being more likely to experience vertical growth, with limited changes to their physical footprint.

It is again important to note that this approach to the future horizontal expansion of informal settlements represents a simplified method of projecting future informal settlement horizontal size in the eThekweni Metropolitan Municipality. The methodology employs a basic buffering technique based on predicted area requirements and does not incorporate a comprehensive suitability analysis based on socio-economic and biophysical characteristics. Furthermore, the study does not use sophisticated land cover change modelling that would account for incremental changes to urban form. As such, while this approach serves to illustrate a potential future horizontal expansion of informal settlements and stimulates discussion about the future of informal settlements, it should not be interpreted as a high-confidence prediction of future urban form.

The resulting map (Figure 3.22) illustrates the projected expansion of the identified informal settlements in the eThekweni Metropolitan Municipality by 2050, considering both the historical trends and the geographical factors that shape the nature of settlement growth. This visualisation should be understood as an illustrative tool rather than a definitive prediction. It aims to provide

insights into how the informal settlements may horizontally grow and evolve by 2050, but it is subject to the limitations of the simplified methodology.

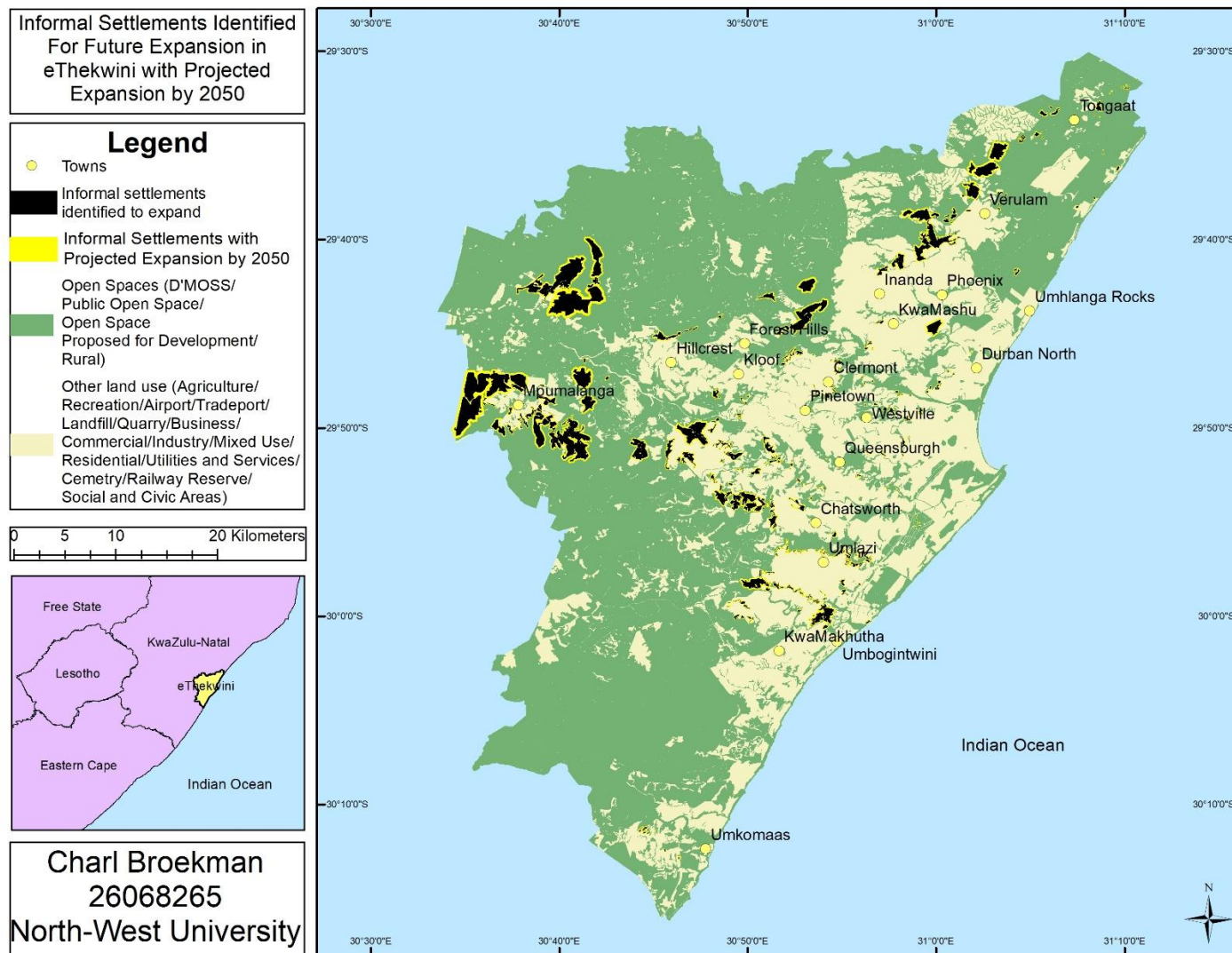


**Figure 3.22: Map of projected expansion of identified informal settlements in eThekweni in the year 2050 (eThekweni Municipality, 2024)**

A final map (Figure 3.23) was created to provide a comprehensive view of the projected informal settlement landscape in the eThekweni Metropolitan Municipality by 2050. This map combines the previously discussed maps of settlements with horizontal expansion potential (Figure 3.22) and those without (Figure 3.21), to present a unified picture of all informal settlements in the study area. The purpose of this consolidated map is to offer a clear and concise overview of the potential scale and distribution of informal settlements in the eThekweni Metropolitan Municipality by 2050. By presenting all informal settlements together, regardless of their projected expansion potential, Figure 3.23 enables the reader to better understand the overall spatial extent and potential challenges associated with the growth of informal settlements.

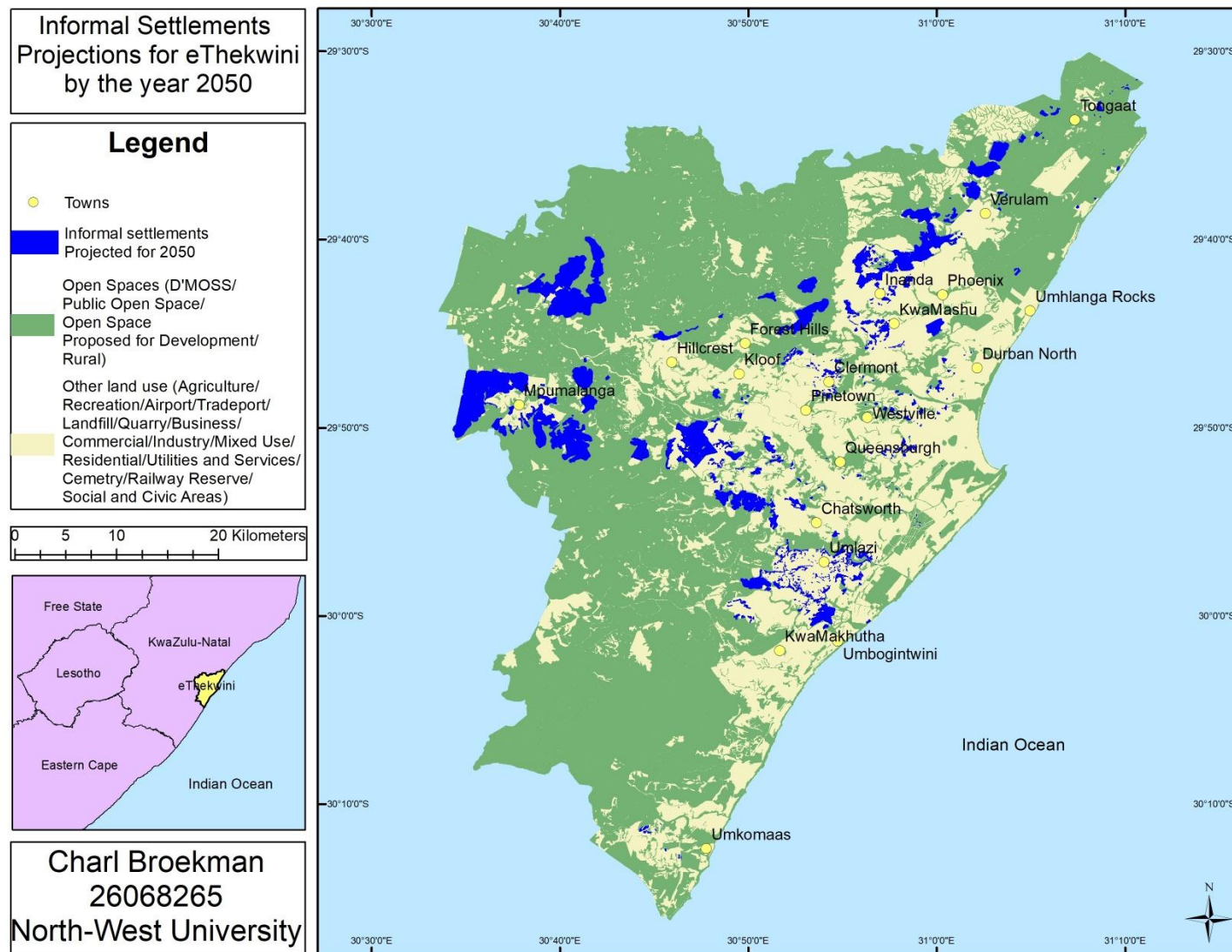


**Figure 3.23: Map of all the projected informal settlements in eThekweni in the year 2050 (eThekweni Municipality, 2024)**



### 3.4 Conclusion

This chapter took a comprehensive approach to creating current and future flood risk maps for the eThekweni Metropolitan Municipality, with a specific focus on identifying informal settlements that are currently or will be vulnerable to flooding in the future. Seven identified criteria contributing to flood risk were considered in creating the current flood risk map: land slope, elevation, rainfall, drainage effectiveness, soil type, land use, and distance from rivers. These criteria formed the basis of this study's MCDA.

A structured hierarchy of these factors was constructed, and their pairwise comparisons were carefully examined to determine their relative importance. Rigorous quality assurance processes were integrated into the methodology, including the CI computation and the CR evaluation. These steps are vital components of the quality assurance effort, ensuring the reliability of the findings.

Extending the scope, this chapter incorporated AG as a tool of GIS for the development of future flood risk maps of the eThekweni Metropolitan Municipality. Using AG within the GIS framework, multiple future flood risk scenarios were created, accounting for different aspects of climate change and uncertainties. This involved exploring changes in precipitation patterns based on different SSPs and adjusting the input precipitation data accordingly. Additionally, the future flood risk scenarios investigated the effects of population growth in informal settlements and the consequent expansion of these settlements on the future flood risk of the eThekweni Metropolitan Municipality.

The creation of these future flood risk maps aligns with the principles of AG, particularly Approach 3: Pluralistic futures, societal mobilisation, and co-creating alternatives. By generating multiple scenarios, this study acknowledges the inherent uncertainty in the future and encourages the exploration of diverse possibilities. This approach fosters adaptability and enhances the ability to respond effectively to a range of future conditions.

Both the current and future flood risk maps were developed with the specific goal of identifying informal settlements that are currently vulnerable to flooding or are likely to become more vulnerable in the future. This targeted approach ensures that the study's findings can directly inform strategies and interventions aimed at enhancing the resilience of these often-marginalised communities.

The methodological steps outlined in this chapter have laid a robust foundation for both current and future flood risk mapping in the eThekweni Metropolitan Municipality, with a clear emphasis on informal settlements. By systematically considering and evaluating key MCDA factors, and by



incorporating AG principles as a tool of GIS to generate future scenarios, valuable insights into the region's complex dynamics of flood risk have emerged. This approach equips decision makers and planners with a solid basis for making informed choices to mitigate flood risks and enhance the resilience of informal settlements, not only for the present but also for the uncertain future.

The methodological approach outlined in this chapter directly addresses the research objective "To map the current and potential future areas of the eThekweni Metropolitan Municipality that are vulnerable to flooding events." By combining MCDA for current flood risk mapping with AG principles for future scenario development, this methodology provides a robust framework for identifying flood-vulnerable areas in the eThekweni Metropolitan Municipality, both in the present and potential future contexts. This comprehensive approach, with its specific focus on informal settlements, ensures that the subsequent results chapter can provide valuable insights for decision makers in their efforts to enhance flood resilience in the eThekweni Metropolitan Municipality.

The next chapter discusses the results of the study, presenting both the current flood risk map and the future flood risk maps, highlighting the informal settlements that are identified as vulnerable to flooding based on the different scenarios developed through the lens of AG.

## CHAPTER 4 RESULTS

### 4.1 Introduction

This chapter discusses the results of the flood risk mapping conducted for the eThekweni Metropolitan Municipality, with a specific focus on identifying informal settlements that are in danger of flooding. Building on the methodological groundwork established in the previous chapter, this results chapter fully achieves the fourth research objective: "To map the current and potential future areas of the eThekweni Metropolitan Municipality that are vulnerable to flooding events."

The study employed a MCDA approach to develop a comprehensive current flood risk map and future flood risk maps in line with the principles of AG. The chapter is divided into two main sections: (1) Current flood risk mapping, and (2) Future flood risk mapping.

In the first section, the results of the current flood risk mapping process are discussed. The study examined seven significant factors contributing to flood risk: land slope, elevation, rainfall patterns, drainage effectiveness, soil type, land use, and distance from rivers. These factors formed the seven criteria for the MCDA that resulted in the current flood risk map. The quality assurance process of the current flood risk map involved validating the current flood risk map by overlaying data from the April 2022 KwaZulu-Natal flooding event and assessing how well the map would have anticipated this actual flood event. The model validation data used were compiled by the United Nations Satellite Centre (UNOSAT) in conjunction with Copernicus, the Earth observation component of the European Union's space programme, from 20 April–4 May 2022. The data collected not only displayed the extent of the flooding but also the extent of landslides and structural damage as a consequence of the flooding. The alignment between the observed flood impacts of the April 2022 flooding and the flood risk map's delineated high and extremely high-risk zones serves as compelling evidence of the map's effectiveness and reliability. The resulting current flood risk map was then used to identify informal settlements that are currently at risk of flooding, highlighting the vulnerability of these communities.

The second section focuses on the incorporation of AG as a tool for the development of future flood risk maps of the eThekweni Metropolitan Municipality. AG enables the creation of multiple future flood risk scenarios that account for different aspects of climate change. The section presents the results of exploring changes in precipitation patterns based on different SSPs and the consequent effects on future flood risk. Additionally, the effect of population growth in informal settlements and the expansion of these settlements on the future flood risk of the eThekweni

Metropolitan Municipality are discussed. The future flood risk maps are then used to identify informal settlements that are likely to be in danger of flooding in the future, emphasising the need for proactive measures to mitigate potential risks.

A key aspect of the analysis involves identifying existing informal settlements that are currently regarded as high risk and will remain high risk in all three future scenarios. These areas can be considered as requiring immediate intervention with a high degree of confidence. The study also provides a gradient, highlighting existing areas that are predicted to be high risk in two scenarios and then finally in just one scenario, allowing for a more nuanced discussion of intervention priorities.

Similarly, the study identifies predicted informal development areas that can be considered high risk in all three future scenarios, then in two scenarios, and finally in just one scenario. The areas consistently predicted to be high risk across all three scenarios should be avoided at all costs for future informal settlement development. This analysis provides important insights for urban planning and risk mitigation strategies.

The results presented in this chapter provide valuable insights into the current and future flood risk of the eThekweni Metropolitan Municipality, with a particular emphasis on the vulnerability of informal settlements. By identifying the informal settlements that are currently and potentially at risk of flooding, this study aims to inform decision makers and support the development of targeted flood risk management strategies to protect these vulnerable communities. The findings serve as a foundation for informed decision making and the development of effective flood risk management strategies for the metropolitan municipality, with a focus on safeguarding informal settlements from the devastating impacts of flooding.

## **4.2 Current flood risk mapping**

The current flood risk map (Figure 4.1) identified areas with different degrees of flood risk and offers valuable insights into the distribution of flood risk across the study area. The flood risk map classifies areas into five distinct risk categories: extremely low, low, moderate, high, and extremely high. These categories offer a comprehensive understanding of flood risk in the eThekweni Metropolitan Municipality.

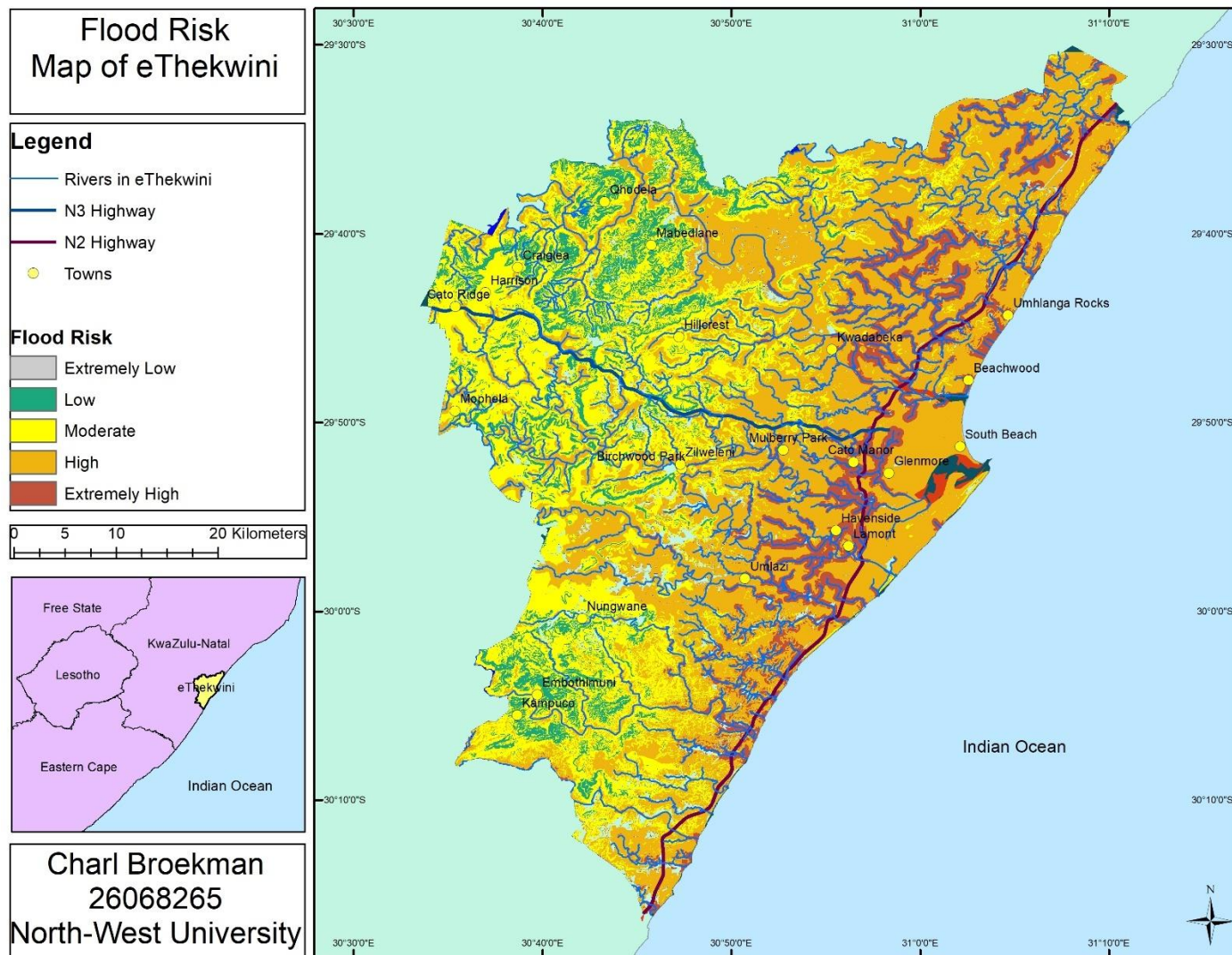


Figure 4.1: Current flood risk map of eThekweni (eThekweni Municipality, 2024)

The areas with extremely low susceptibility to flooding are nearly non-existent, and the few that exist are concentrated in the neighbourhood of Nungwane, specifically in the southwestern part of Nungwane. These areas are characterised by higher elevations, steep slopes, and efficient drainage systems, and were situated inland, a significant distance from the coast. The low-risk areas, characterised by minimal susceptibility to flooding, are scattered sparingly across the flood risk map. The suburbs of Kampuco, Mabedlane, Qhodela and Embothimuni are examples of places that fall into the low-risk areas. These low-risk areas are situated at higher elevations, on steep slopes, and have efficient drainage systems. These areas are also situated inland, relatively far away from the coast.

The moderate-risk areas, characterised by a moderate likelihood of flooding, were scattered across the flood risk map. Suburbs like Cato Ridge, Craiglea, Harrison, Hillcrest and Mophela are examples of places that face moderate risk to flooding in the eThekweni Metropolitan Municipality. These regions are dispersed throughout the eThekweni Metropolitan Municipality, but are mostly located inland, and not along the coast, except in the most southern regions of the study area.

In contrast with the low-risk and moderate-risk areas that are identified, the map highlights several high-risk areas where flood events are likely to be more frequent and severe. Suburbs like Birchwood Park, Glenmore, Kwadabeka, Kwamashu, Mulberry Park, South Beach and Zilweleni are places that lie in the high-risk flooding area. These areas are found to be dispersed throughout the eThekweni Metropolitan Municipality, in the low-lying coastal zone and near riverbanks on relatively gentle slopes, as well as more inland areas.

Lastly, the designation of extremely high-risk areas on the flood risk map signifies zones with the greatest vulnerability to flooding in the eThekweni Metropolitan Municipality. These regions face recurrent and severe flooding, posing a significant threat to both human safety and infrastructure. Suburbs like Beachwood, Cato Manor, Havenside, Lamont, Umhlanga Rocks, as well as the township of Umlazi are located in the extremely high flood risk area. These regions are located almost exclusively in an area 10–15 km from the coastline of the eThekweni Metropolitan Municipality. It is characterised by relatively higher mean annual precipitation, extremely gentle or non-existent slopes, and low elevation.

#### **4.2.1 Model validation**

To validate the accuracy of the eThekweni Metropolitan Municipality flood risk map's predictions, it is essential to establish a strong connection between the map's projections and real-world historical flood events. This validation process entailed overlaying data from the April 2022 KwaZulu-Natal flooding event onto the flood risk map and assessing how well the map would

have anticipated this actual flood event (see Figure 4.2). The model validation data were compiled by UNOSAT in conjunction with Copernicus, the Earth observation component of the European Union's Space programme, from 20 April - 4 May 2022 (UNOSAT, 2022). The data that were collected not only displayed the extent of the flooding, but also the extent of landslides and structural damage as a consequence of the flooding.

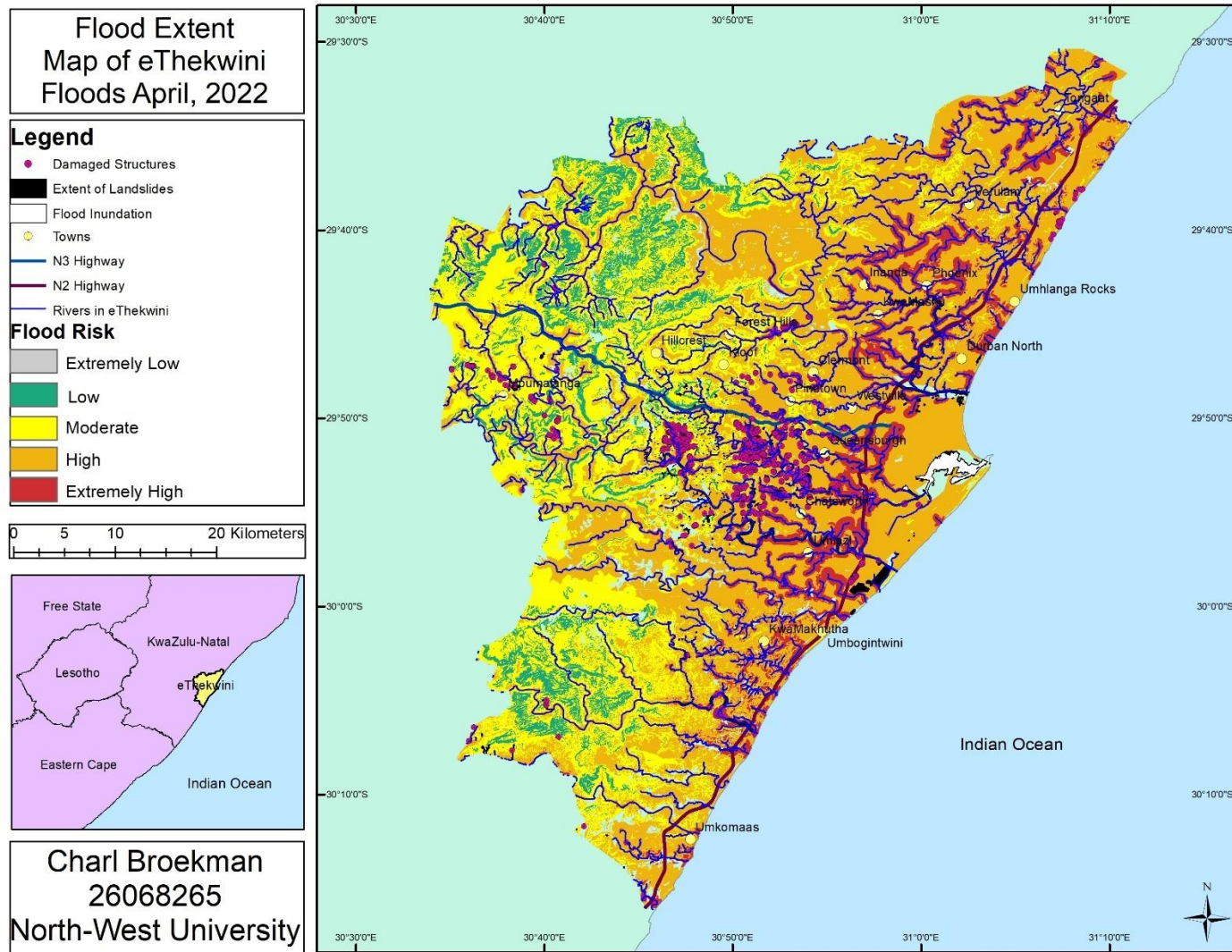


Figure 4.2: Model validation of eThekweni's current flood risk map(eThekweni Municipality, 2024; UNOSAT, 2022)

As can be observed from Figure 4.2, the flooding, landslides, and structural damage that occurred during the 2022 floods were predominantly concentrated in the high and extremely high categories of flood risk as delineated on the map.

As part of the validation process for the flood risk map of the eThekweni Metropolitan Municipality, an analysis was conducted to assess the alignment of the map's predictions with observed damage to 3 851 structures in the April 2022 KwaZulu-Natal flooding event. This validation aims to provide a clear understanding of how well the model's flood risk zones correspond to actual damage, serving as an important step in evaluating the map's accuracy and reliability.

The analysis of structure damage resulting from the April 2022 flooding strongly aligns with the flood risk map's predictions. Particularly noteworthy is the correspondence of observed damage to structures in the April 2022 flooding event to the model's predictions in the high flood risk zone (46.92% or 1 809 of 3 851 damaged structures) and the extremely high flood risk zone (24.32% or 907 of 3 851 damaged structures). Moreover, the model demonstrates accurate prediction capabilities in the moderate flood risk zone (11.92% or 407 of 3 851 damaged structures). The remaining damaged structures of the April 2022 flooding event are located in the low and extremely low flood risk zones (16.84% or 728 of 3 851 damaged structures).

The damaged structures occurring in the low and extremely low flood risk zones can potentially be explained by infrastructure failure, as well as rapid urban development.

Infrastructure can play a crucial role in mitigating or exacerbating flood damage. In some cases, even if an area is designated as a low flood risk zone, poor drainage systems, inadequate dykes, or failing flood control infrastructure can lead to more extensive damage during a flood event. Infrastructure failures can result from factors like poor maintenance, aging infrastructure, or design limitations.

Rapid urbanisation and improper land use planning can increase flood risk. Urban areas that have expanded without adequate flood mitigation measures, could lead to more damage, even in an area that is at low or extremely low risk of flooding. The concentration of population and property in certain areas may also result in higher damage, even if the flood risk is theoretically low.

This alignment between the observed flood impacts of the April 2022 flooding and the flood risk map's delineated high and extremely high-risk zones serves as compelling evidence of the map's effectiveness. It suggests that the map successfully identified areas with a heightened susceptibility to flooding, thereby demonstrating its predictive accuracy of around 70% in anticipating high or extremely high susceptibility to real-world flood events. Such validation



bolsters the flood risk map's credibility and reinforces its usefulness as a valuable tool for flood risk assessment and disaster mitigation in the eThekweni Metropolitan Municipality region.

Having validated the accuracy and reliability of the eThekweni Metropolitan Municipality flood risk map in predicting areas susceptible to flooding, it is now important to examine how this map can be used to identify current informal settlements that face an extremely high threat of flooding in the region.

#### **4.2.2 Mapping current informal settlements in danger of flooding**

The informal settlements are identified by their unique name as officially designated by the eThekweni Metropolitan Municipality. The flood risk analysis presented in Figure 4.3 identifies 289 informal settlements at extremely high risk of flooding. The use of official municipal designations ensures consistency and accuracy in the identification process, aligning with existing administrative frameworks and respecting local context. The current flood risk map reveals 289 informal settlements, housing an estimated 163 000 households, that face an extremely high threat of flooding across various districts within the eThekweni Metropolitan Municipality region, including Inanda, Dassenhoek, Redcliffe, Chatsworth, Durban, Tongaat, Cornubia, Chesterville, Shallcross, Kwamashu, Clermont, Kwandengezi, Westville, Duffs Road, Emona, Ezimbokodweni, Folweni, Golokodo, Durban North, Hazelmere, Isipingo, Klaarwater, Kwadabeka, Lamontville, Ntuzuma, Matabetule, Pinetown, Molweni, Bluff, Queensburgh, Buffelskloof, Newlands, Reservoir Hills, Ottawa, Avoca, Phoenix, Verulam, Umlazi, and Welbedagt.

These areas are characterised by their low-lying coastal locations, featuring low elevations and gentle slopes, which significantly heightens their vulnerability to flooding, particularly during heavy rainfall or storm events. Additionally, their proximity to the coast amplifies their risk to storm surges and coastal erosion. It is noteworthy that the total area of all the informal settlements intersecting with the extremely high flood risk zones amounts to 34.7 km<sup>2</sup>, a substantial figure that underscores the extensive nature of the flood risk faced by these communities.

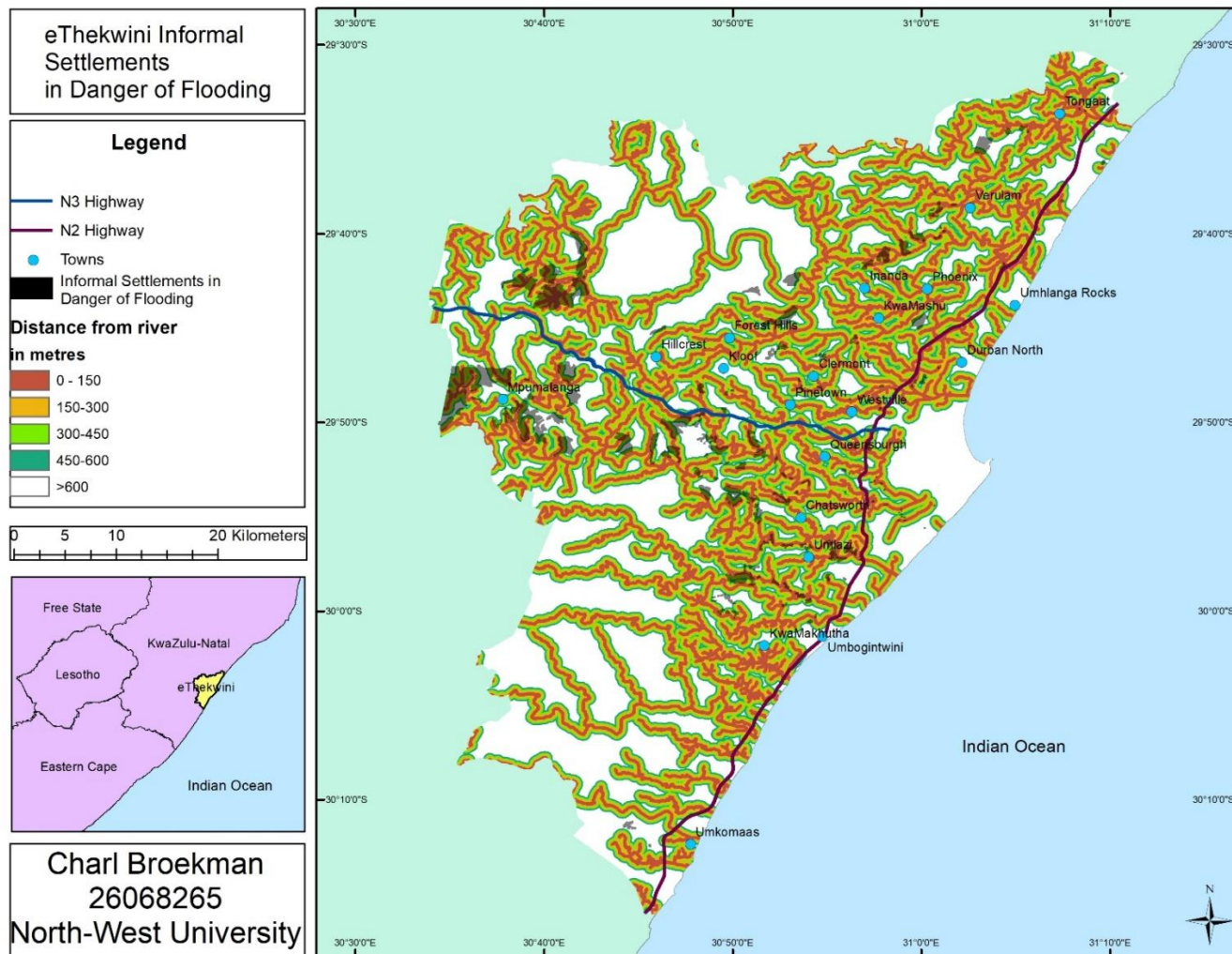


Figure 4.3: Map showing current informal settlements at risk of flooding in eThekwini (eThekwini Municipality, 2024)

The intersection of these 289 informal settlements with extremely high flood-risk areas in the eThekweni Metropolitan Municipality demands immediate attention from policymakers, urban planners, and disaster management authorities. Many of these settlements are likely situated near industrial and commercial areas, potentially providing residents with access to job opportunities while also exposing them to considerable environmental risks, including the threat of flooding.

This critical situation underscores the vulnerability of a substantial portion of the population. Informal settlements often house marginalised and economically disadvantaged communities lacking adequate housing, infrastructure, and resources, making them particularly susceptible to the adverse impacts of flooding, such as loss of life, property damage, and displacement.

Moreover, the presence of informal settlements in these high-risk areas poses severe humanitarian challenges. In the event of a flood, these communities are at risk of facing life-threatening situations, including flash floods and inundation of their dwellings. Therefore, ensuring the safety and well-being of residents in these settlements during flood events should be a top priority.

The considerable size of the affected areas emphasises the urgent need for comprehensive flood risk management strategies and interventions to safeguard the vulnerable populations residing in these informal settlements. While the current flood risk situation in the eThekweni Metropolitan Municipality is alarming, it is important to also consider how this risk may evolve in the future in different scenarios, which is discussed in the next section.

### **4.3 Future flood risk**

The calculated weights (Table 3.8) were again used to create the future flood risk maps for the eThekweni Metropolitan Municipality, with a goal date of 2050. The weighted overlay analysis tool in ArcMap 10.7.1 was used again to spatially depict flood risk levels across the study area in the future flood risk maps. The future flood risk maps identified areas with different degrees of flood risk and offers valuable insights into the distribution of flood risk across the study area. The future flood risk maps classified areas into five distinct risk categories: extremely low, low, moderate, high, and extremely high. Examining these categories reveals potential future flood risk in the eThekweni Metropolitan Municipality. Various flood risk scenarios are discussed below.

#### **4.3.1 Scenario 1: Best case**

In the context of the SSP1 scenario, there are significant changes in flood risk levels (see Figure 4.4 and Figure 4.5). The "extremely low" flood risk category experiences a substantial 420%

increase in area size compared to the current situation, which may lower concerns about certain areas potentially becoming more prone to flooding. The areas with extremely low susceptibility to flooding are, however, still projected to be nearly non-existent, with 0.00911% of the total land area of the eThekweni Metropolitan Municipality represented. The few areas that will potentially exist in 2050 in SSP1 are concentrated in the suburbs of Nungwane, specifically in the southwestern part of Nungwane and Embothimuni. In SSP1 these areas would transition from "low" flood risk category to extremely low risk. Contributing factors to these transitions include geographic characteristics such as higher elevations, steep slopes, and efficient drainage systems, and that they are situated inland, a significant distance from the coast.

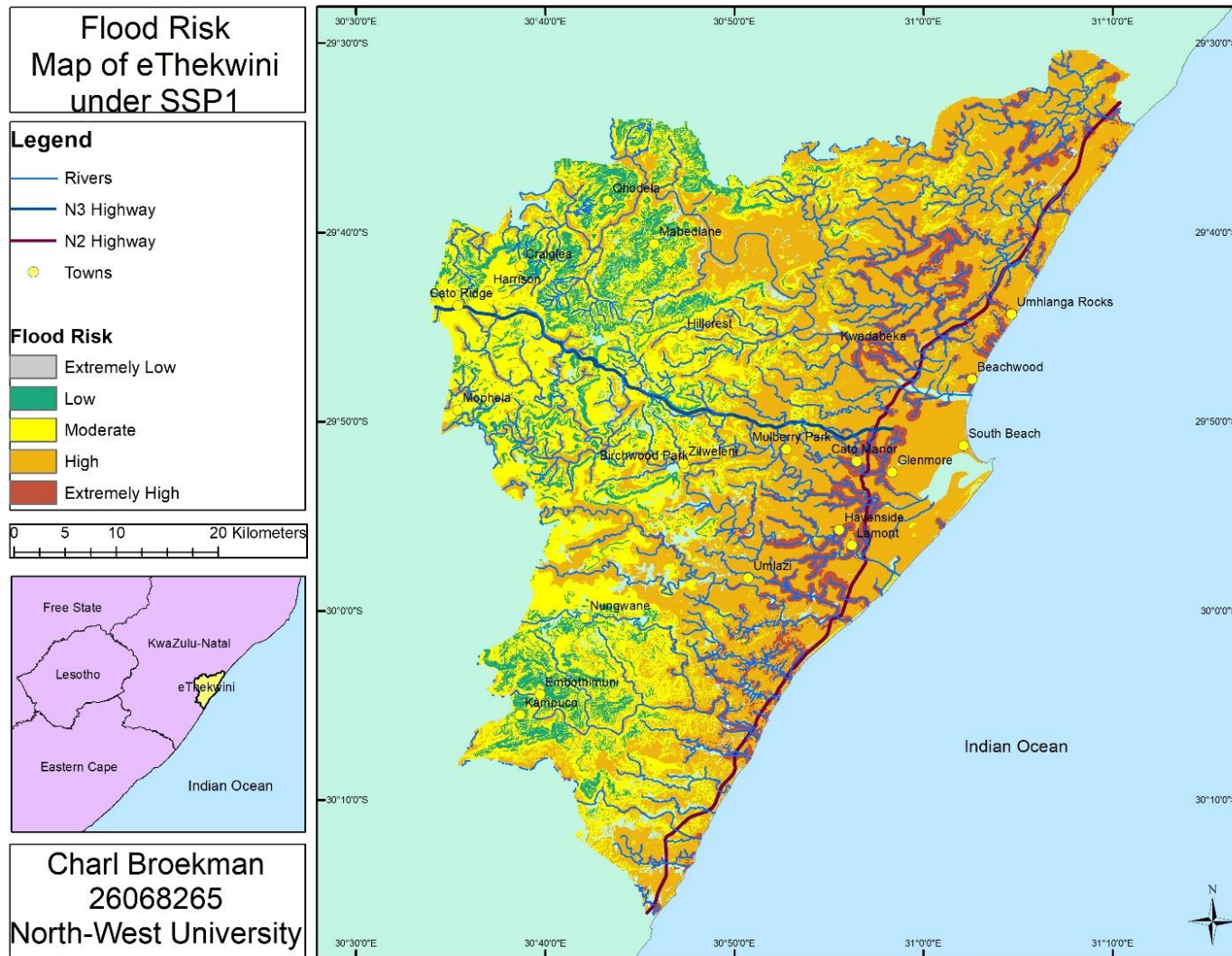
Notably, the data show a decrease in flood risk, with an 11.9% increase in the land area classified as having "low" flood risk. This shift suggests that areas previously in the moderate or high-risk categories have transitioned to the lower risk category, indicating an overall reduction in flooding vulnerability. The low-risk areas, characterised by minimal susceptibility to flooding, are projected to still be scattered sparingly across the flood risk map in SSP1 in the year 2050. The suburbs of Kampuco, Mabedlane and Qhodela are still examples of places that will potentially fall into the low-risk areas in SSP1 in the year 2050. These low-risk areas are situated at higher elevations, on steep slopes, and have efficient drainage systems. These areas are also situated inland, relatively far away from the coast.

For the "moderate" flood risk category, there is a 2.5% increase in area size, which suggests a relatively stable situation or only minor fluctuations in this flood risk category. This lack of significant change may indicate that the flood risk in this category remains similar in the SSP1 scenario. The moderate-risk areas, characterised by a moderate likelihood of flooding, were present across the flood risk map. Suburbs like Cato Ridge, Craiglea, Harrison, Hillcrest and Mophela are still potential examples of places that will face moderate risk to flooding in the eThekweni Metropolitan Municipality in the year 2050 in SSP1. These regions are dispersed throughout the eThekweni Metropolitan Municipality, but are mostly located inland, and not along the coast, except in the most southern regions of the study area.

The "high" flood risk category sees a minor 0.5% increase in area size, which may imply a slight worsening of the flood situation in certain areas. In contrast with the low-risk and moderate-risk areas that are identified, the map highlights several high-risk areas where flood events are likely to be more frequent and severe. Suburbs like Birchwood Park, Glenmore, Kwadabeka, Kwamashu, Mulberry Park, South Beach and Zilweleni are still places that will potentially lie in the high-risk flood area in the year 2050. These areas are found to be dispersed throughout the

eThekweni Metropolitan Municipality, in the low-lying coastal zone and near riverbanks on relatively gentle slopes, as well as more inland areas.

The data indicate a significant reduction in the areas classified as having "extremely high" flood risk, with a 20.7% decrease in the size of these areas in SSP1. This suggests that many regions previously categorised as being at the highest risk of flooding will transition to lower risk categories, primarily shifting into the "high" flood risk classification. The designation of extremely high-risk areas on the future flood risk map signifies zones with the greatest vulnerability to flooding in the eThekweni Metropolitan Municipality. These regions could still face recurrent and severe flooding, posing a significant threat to both human safety and infrastructure. Despite a substantial decrease in the area size of the "extremely high" flood risk category, the suburbs of Beachwood, Cato Manor, Havenside, Lamont, Umhlanga Rocks, as well as the township of Umlazi are located in the extremely high flood risk area, albeit smaller portions of these suburbs as in the case of Umlazi and Havenside. These regions are located almost exclusively on the coastal region of the eThekweni Metropolitan Municipality that is characterised by relatively higher mean annual precipitation, extremely gentle or non-existent slopes, and low elevation.





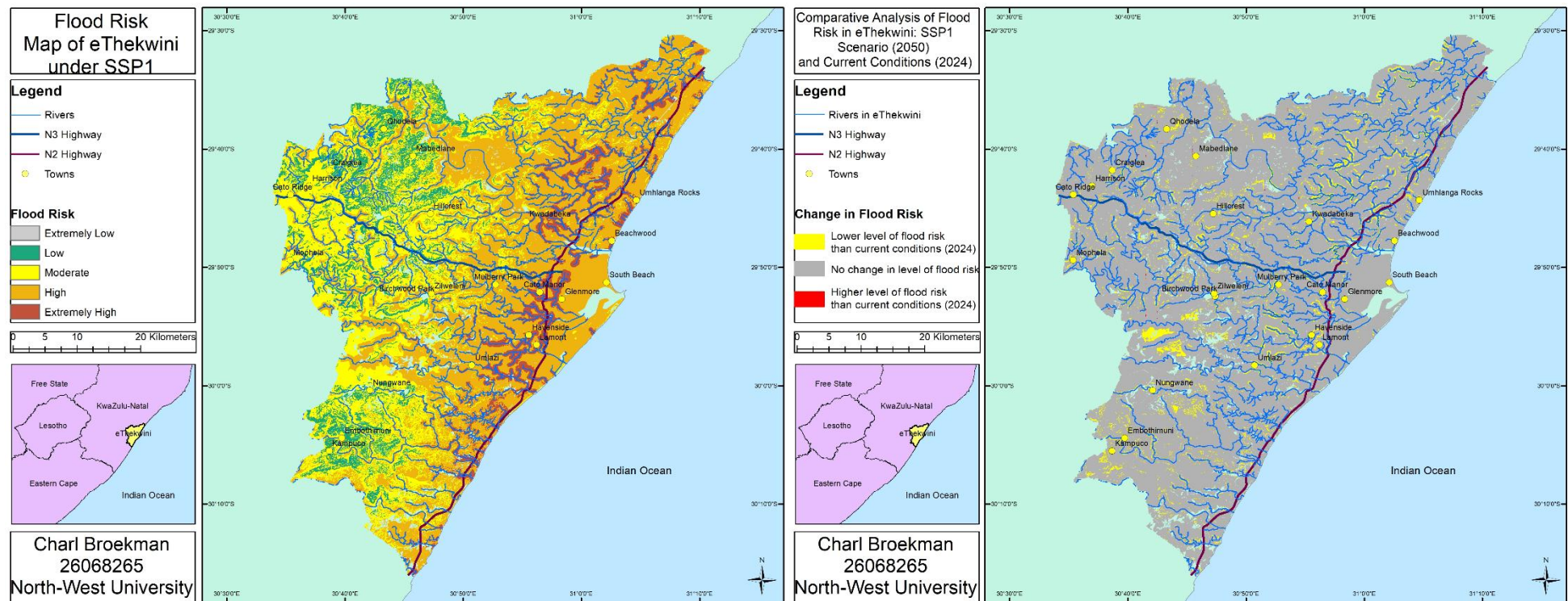


**Figure 4.5: Map showing the future flood risk change in eThekweni in SSP1 in the year 2050 (eThekweni Municipality, 2024)**

#### **4.3.2 Scenario 2: Middle of the road**

In the SSP2 scenario, there are mixed changes in future flood risk (see Figure 4.6 and Figure 4.7). The "extremely low" flood risk category decreases by 18.7% in size, which indicates a reduction in areas with the lowest flood risk. However, the areas with extremely low risk of flooding are still projected to be nearly non-existent, with only 0.001423% of the total land area of the eThekweni Metropolitan Municipality represented. The few areas with extremely low risk of flooding that will potentially exist in 2050 in SSP2 are concentrated in the suburb of Nungwane, specifically in the southwestern part. This area is characterised by higher elevations, steep slopes, and efficient drainage systems, and are situated inland, a significant distance from the coast.

In the "low" flood risk category, there is a 5.1% decrease in size, suggesting an increased risk to flooding and the overall reduction in the size of low-risk areas, which is a negative development for the future. The suburbs of Kampuco, Mabedlane and Qhodela are still examples of places that will potentially fall into the low-risk areas in SSP2 in the year 2050. The suburb of Embothimuni again falls in the "low" risk category in SSP2, the same category it found itself in the current flood risk map. These low-risk areas are situated at higher elevations, on steep slopes, and have efficient drainage systems. These areas are also situated inland, relatively far away from the coast.

In the "moderate" flood risk category, there is a 1% decrease in size, which implies a small reduction in flood risk. The moderate-risk areas, characterised by a moderate likelihood of flooding, are present across the future flood risk map in SSP2. Suburbs like Cato Ridge, Craiglea, Harrison, Hillcrest and Mophela are still potential examples of places that will face moderate risk of flooding in the eThekweni Metropolitan Municipality in the year 2050 in SSP2. These regions are dispersed throughout the eThekweni Metropolitan Municipality, but are mostly located inland, and not along the coast, except in the most southern regions of the study area.

The "high" flood risk category in SSP2 sees a 1.7% decrease, indicating that high flood risk areas in future will stay largely consistent with those in 2023. Suburbs like Birchwood Park, Glenmore, Kwadabeka, Kwamashu, Mulberry Park, South Beach and Zilweleni are still places that will potentially lie in the high-risk flood area in the year 2050 in SSP2. These areas of high flood risk are found to be dispersed throughout the eThekweni Metropolitan Municipality, in the low-lying coastal zone and near riverbanks on relatively gentle slopes, as well as more inland areas.

Importantly, the "extremely high" flood risk category is likely to experience a 7.1% increase in area. This increase may point to a worsening flood situation in SSP2, particularly in the areas with the highest flood risk. The increase in the area size of the "extremely high" flood risk category in



SSP2 will mostly affect the suburbs of Beachwood, Cato Manor, Havenside, Lamont, Umhlanga Rocks, as well as the township of Umlazi. These regions are located almost exclusively on the coastal belt of the eThekweni Metropolitan Municipality, which is characterized by relatively higher mean annual precipitation (which has the potential to rise by 22 mm by the year 2050 in SSP2), extremely gentle or non-existent slopes and low elevation.

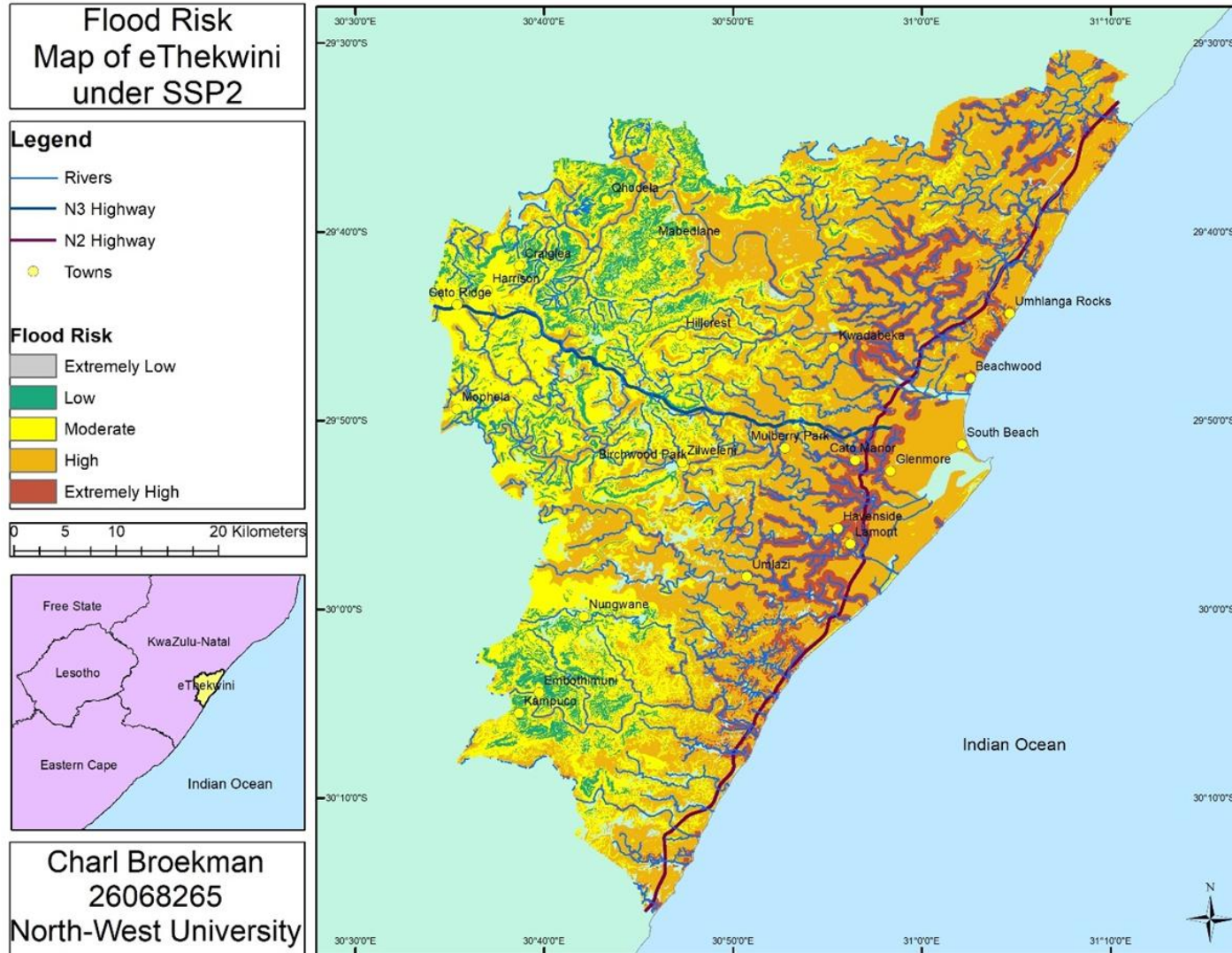


Figure 4.6: Map showing the future flood risk in eThekwinini in SSP2 in the year 2050 (eThekwinini Municipality, 2024)

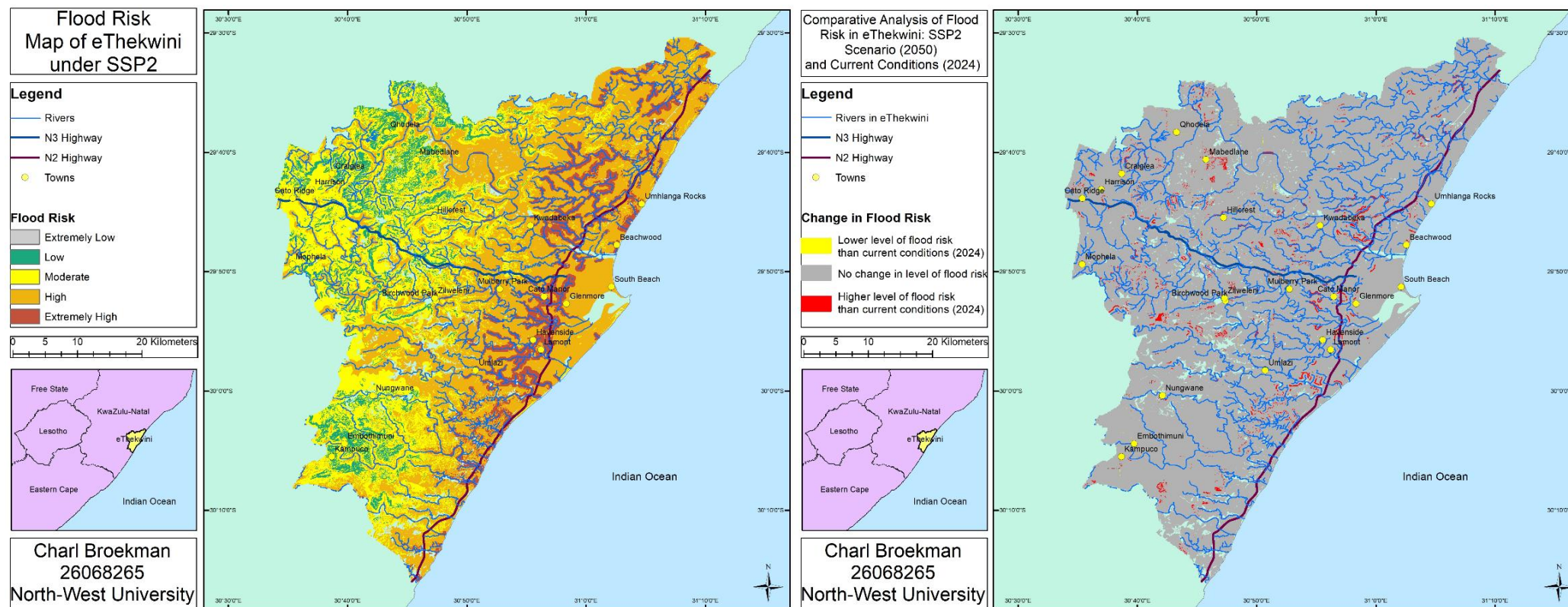


Figure 4.7: Map showing the future flood risk change in eThekweni in SSP2 in the year 2050 (eThekweni Municipality, 2024)

### 4.3.3 Scenario 3: Worst case

The SSP5 scenario shows significant changes in the future flood risk of the eThekweni Metropolitan Municipality (see Figure 4.8 and Figure 4.9). The "extremely low" flood risk category area decreases by 76.6% in area size, implying a substantial reduction in areas with the lowest flood risk. This decrease may indicate a potential increase in flood risk in SSP5. The areas with extremely low risk to flooding are still projected to be nearly non-existent, with now only 0.000376% of the total land area of the eThekweni Metropolitan Municipality represented. The few areas of extremely low risk of flooding that will potentially exist in 2050 in SSP5 are still concentrated in the suburb of Nungwane, specifically in the southern part, and not the southwestern part of the suburbs as is the case in SSP1 and SSP2. This area is characterised by higher elevations, steep slopes, and efficient drainage systems, and are situated inland, a significant distance from the coast.

The "low" flood risk category also experiences a significant decrease of 16.1% in area. This suggests a decrease in areas with low flood risk, which might not be a positive development as it might point to increases in moderate, high and extremely high risk. The suburbs of Kampuco, Mabedlane and Qhodela are still examples of places that will potentially fall into the low-risk areas in SSP5 in the year 2050, albeit smaller portions of these suburbs. These potential future low-risk areas are situated at higher elevations, on steep slopes, and have efficient drainage systems. These areas are also situated inland, relatively far away from the coast.

In this scenario the "moderate" flood risk category sees a 3.2% decrease in size, potentially indicating a slight shift towards the higher categories of flood risk in SSP5. Suburbs like Craiglea, Harrison, Hillcrest and Mophela are still potential examples of places that will face moderate risk to flooding in the eThekweni Metropolitan Municipality in the year 2050 in SSP5, while Cato Ridge will potentially fall into the "high" flood risk category in 2050 in SSP5. The moderate risk regions, however, are dispersed throughout the eThekweni Metropolitan Municipality, but are still mostly be located inland, and not along the coast, except in the most southern regions of the study area.

In the "high" flood risk category, there will be a 2.0% decrease in size. Suburbs like Birchwood Park, Glenmore, Kwadabeka, Kwamashu, Mulberry Park, South Beach and Zilweleni are still places that will potentially lie in the high-risk flooding area in the year 2050 in SSP5, with the addition of Cato Ridge. These areas of high flood risk are found to be potentially dispersed throughout the eThekweni Metropolitan Municipality, in the low-lying coastal zone and near riverbanks on relatively gentle slopes, as well as more inland areas.

Notably, the "Extremely high" flood risk category shows the most significant increase in size at 24.4%, indicating a substantially higher flood risk in SSP5 compared to the current situation, which is a concerning trend. These regions will potentially face recurrent and severe flooding, posing a significant threat to both human safety and infrastructure in the year 2050. This threat is due to a substantial decrease in the area size of the "extremely high" flood risk category. The suburbs of Beachwood, Cato Manor, Havenside, Lamont, Umhlanga Rocks, as well as the township of Umlazi are located in the extremely high flood risk area, and larger portions of these suburbs are involved, as in the case Beachwood and Umhlanga Rocks. These regions are located almost exclusively in the coastal region of the eThekweni Metropolitan Municipality, which is characterized by relatively higher mean annual precipitation, extremely gentle or non-existent slopes, and low elevation.



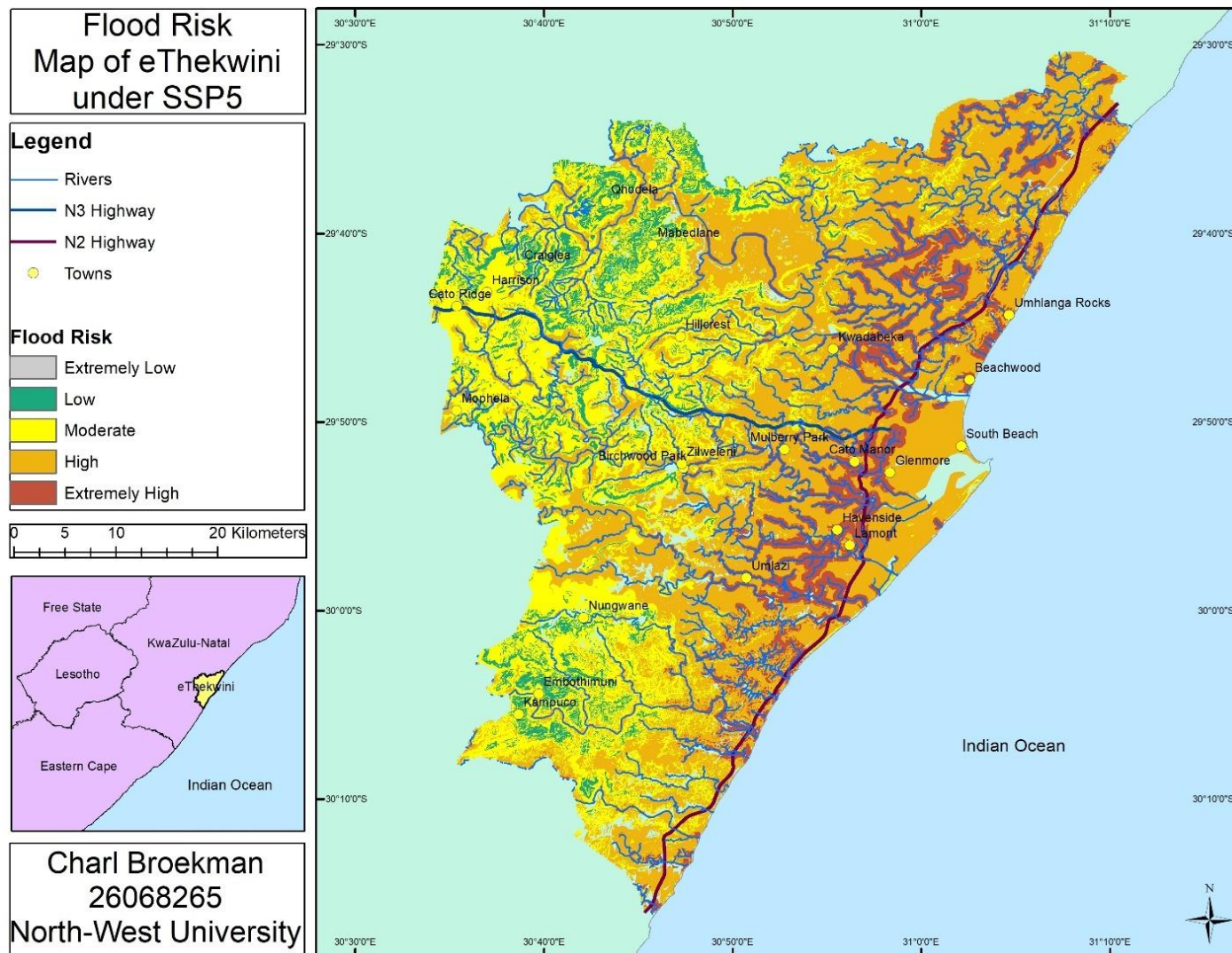


Figure 4.8: Map showing the future flood risk in eThekweni in SSP5 in the year 2050 (eThekweni Municipality, 2024)

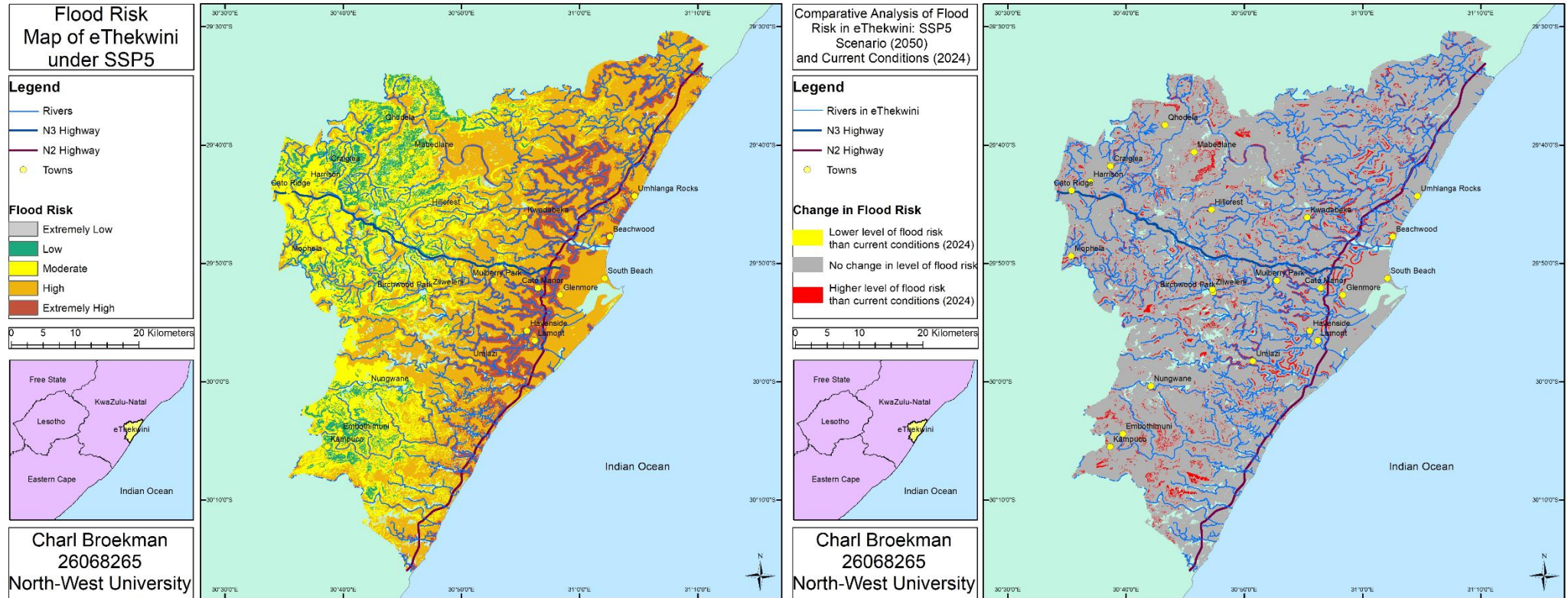


Figure 4.9: Map showing the future flood risk change in eThekweni in SSP5 in the year 2050 (eThekweni Municipality, 2024)

Having examined the potential future flood risk scenarios under different SSPs, the next part of the study focuses on the vulnerability of informal settlements to flooding in the future to identify areas where these settlements may be at risk.

#### **4.4 Mapping future informal settlements at risk of flooding**

A map was created overlaying the existing settlements and the anticipated expansion areas (see Figure 4.10) to visualise the projected changes in informal settlements at risk of flooding by 2050. The map depicts current informal settlements in black and the projected expansion areas in yellow, providing a clear picture of the expected changes and their spatial distribution across the eThekweni Metropolitan Municipality.

##### **4.4.1 Projected changes in informal settlements by 2050**

Figure 4.10 highlights the informal settlements that are projected to expand by 2050, putting more households at risk of extreme flooding. The existing settlement areas are shown in black, while the anticipated expansion areas are depicted in yellow.

Some of the larger informal settlements set to see horizontal growth by 2050 include Kwamashu, RoodeKrans 828/Hazelmere Dam, Malukazi (Lower), Esikhelekehleni 1, Sankotshe, Georgedale, Demat (Damede), Umlazi - CC - CC Esidweni, Mpuma, Ekukhanyeni, and Ebuhleni. These areas are expected to expand by 2050 based on current trends in household statistics and area size, potentially placing an increasing number of households at extreme risk of flooding.

The expansion of informal settlements is not evenly distributed across the eThekweni Metropolitan Municipality. The western and centrally located informal settlements of the eThekweni Metropolitan Municipality are expected to experience more horizontal growth in comparison to the informal settlements located in the southern and northern regions. This uneven pattern shows the need for targeted interventions and resource allocation in these high-growth regions to mitigate the increasing flood risk.



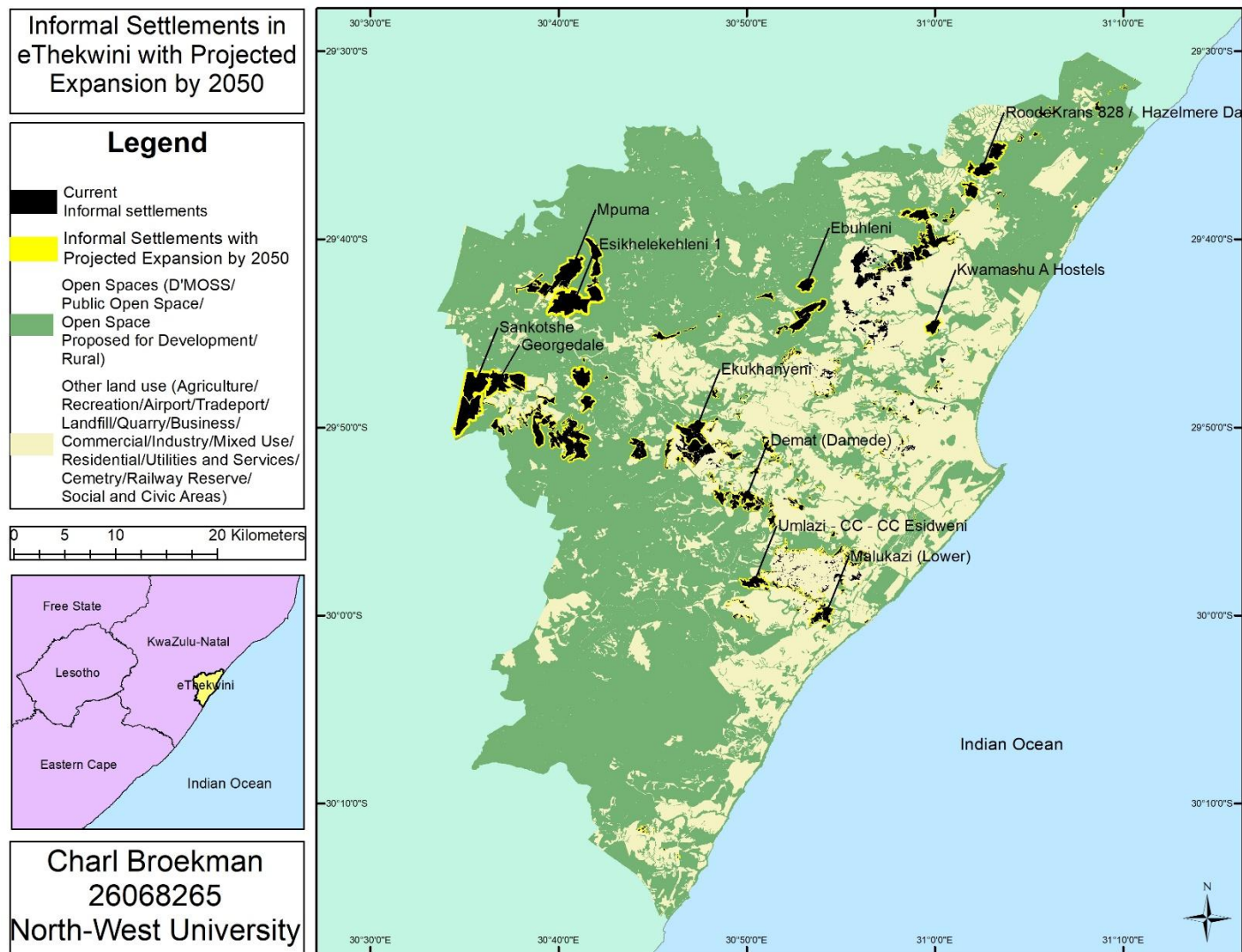


Figure 4.10: Map showing the future expansion of informal settlements in eThekwinini by 2050 (eThekwinini Municipality, 2024)

The above map (see Figure 4.10) also emphasises the urgency of anticipatory planning and adaptation measures to enhance the resilience of these expanding informal settlements. Without addressing this growing vulnerability to flood risk, the people living in the horizontally expanding informal settlements face potentially devastating consequences, including loss of life, property damage, and displacement.

Having established the projected expansion of informal settlements and their potential increased vulnerability to flood risks, it is crucial to consider how these changes might unfold in different climate change scenarios. The analysis thus far has provided a general overview of the potential future horizontal growth in informal settlements across the eThekweni Metropolitan Municipality. However, to gain a more comprehensive understanding of the future flood risks these communities may face, it is necessary to explore specific climate change scenarios and their potential effects on informal settlements. The following sections delve into three distinct scenarios based on different SSPs, each offering unique insights into how climate change and the horizontal growth of informal settlements might interact to shape flood risks in the eThekweni Metropolitan Municipality's informal settlements by 2050.

#### **4.4.2 Scenario 1: Best case**

In the SSP1 scenario, the eThekweni Metropolitan Municipality is projected to experience significant changes in flood risk levels by 2050, with varying impacts across different risk categories (see Figure 4.11). The "extremely low" flood risk category sees a substantial 420% increase in area size, although it still represents only 0.009% of the eThekweni Metropolitan Municipality's total land area, concentrated mainly in areas like southwestern Nungwane and Embothimuni. These areas benefit from higher elevations, steep slopes, and efficient drainage systems. Notably, there's an 11.9% increase in land area classified as "low" risk, indicating an overall reduction in flood vulnerability in areas such as Kampuco, Mabedlane, and Qhodela. The "moderate" risk category shows a slight 2.5% increase, suggesting relative stability, with suburbs like Cato Ridge, Craiglea, and Hillcrest maintaining moderate flood risk. High-risk areas see a minor 0.5% increase, potentially affecting suburbs such as Birchwood Park, Glenmore, and Kwamashu, which are dispersed across low-lying coastal zones and near riverbanks. Significantly, there is a 20.7% decrease in areas classified as "extremely high" risk. However, coastal suburbs like Beachwood, Cato Manor, and parts of Umlazi township remain highly vulnerable due to their low elevation and proximity to the coast. For a visual aid of the changes in flood risk, see Figure 4.11, which illustrates the areas now at higher or lower levels of flood risk compared to the current flood risk situation. The map clearly shows the spatial distribution of risk

level changes, highlighting areas that have transitioned to higher (red) or lower (yellow) flood risk categories across the eThekweni Metropolitan Municipality.

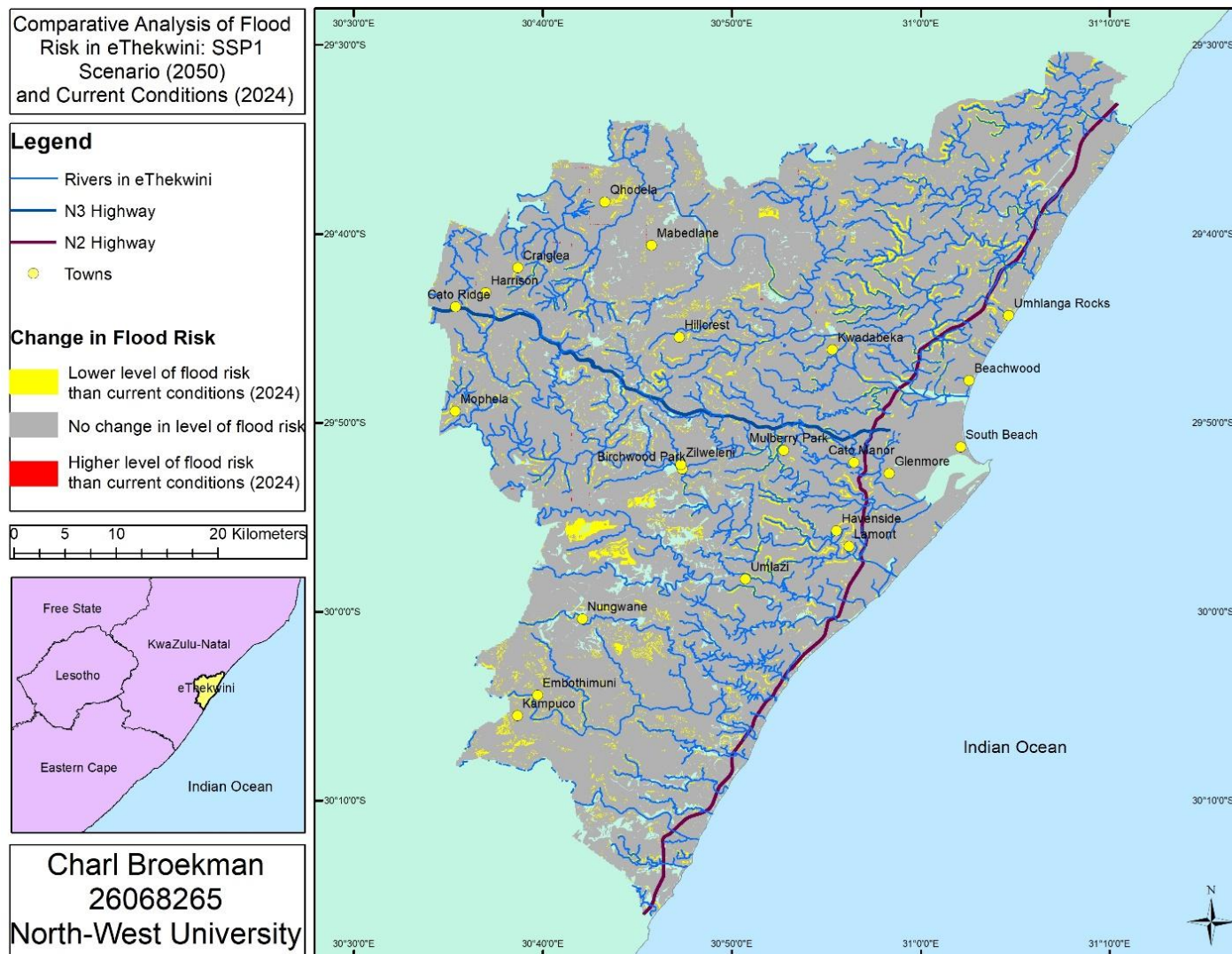


Figure 4.11: Map showing the future flood risk change in eThekweni in SSP1 in the year 2050 (eThekweni Municipality, 2024)

While the overall flood risk in the eThekweni Metropolitan Municipality is projected to improve in SSP1, particularly with the 20.7% reduction in areas classified as "extremely high" risk, the informal settlements, however, will still face increasing challenges related extremely high flood risk despite a general improvement in overall flood risk in SSP1. Currently, 289 informal settlements housing approximately 163 000 households face extremely high flood risk. It is important to note that for future scenarios, including this SSP1 scenario, this study does not predict the exact number of informal settlements that will be at extremely high risk. This is due to the difficulties in forecasting the precise number of settlements that will be in danger in the future. Factors such as potential merging of settlements or changes in settlement patterns make such predictions highly uncertain. Instead, the study focuses on the total area size that will be affected, based on current trends in household size and settlement growth. By 2050, the total area of informal settlements exposed to extremely high flood risk is projected to increase from 34.66 to about 47 km<sup>2</sup> (see Figure 4.12). This increase in vulnerable areas occurs despite a projected decrease in annual rainfall of up to 64 mm per year. The main reason for this is the expected horizontal expansion of informal settlements by a factor of 1.54. As these settlements grow, they are likely to spread into areas with extremely high flood risk. Examples of informal settlements that will potentially be at risk in Scenario 1 in 2050, include Cato Crest and its overspill areas, sections of Umlazi, and the Amawoti settlements. The SSP1 scenario and the projected horizontal growth of the informal settlements highlight the need for targeted interventions and adaptive strategies, especially for the informal settlements of the eThekweni Metropolitan Municipality at extremely high flood risk. While the overall flood risk in the eThekweni Metropolitan Municipality may decrease in SSP1, the horizontal expansion of informal settlements could put more people at risk in 2050. Ongoing reassessment of flood management plans, focusing on protecting informal settlements and improving their resilience, will therefore be important in the future as the year 2050 approaches.



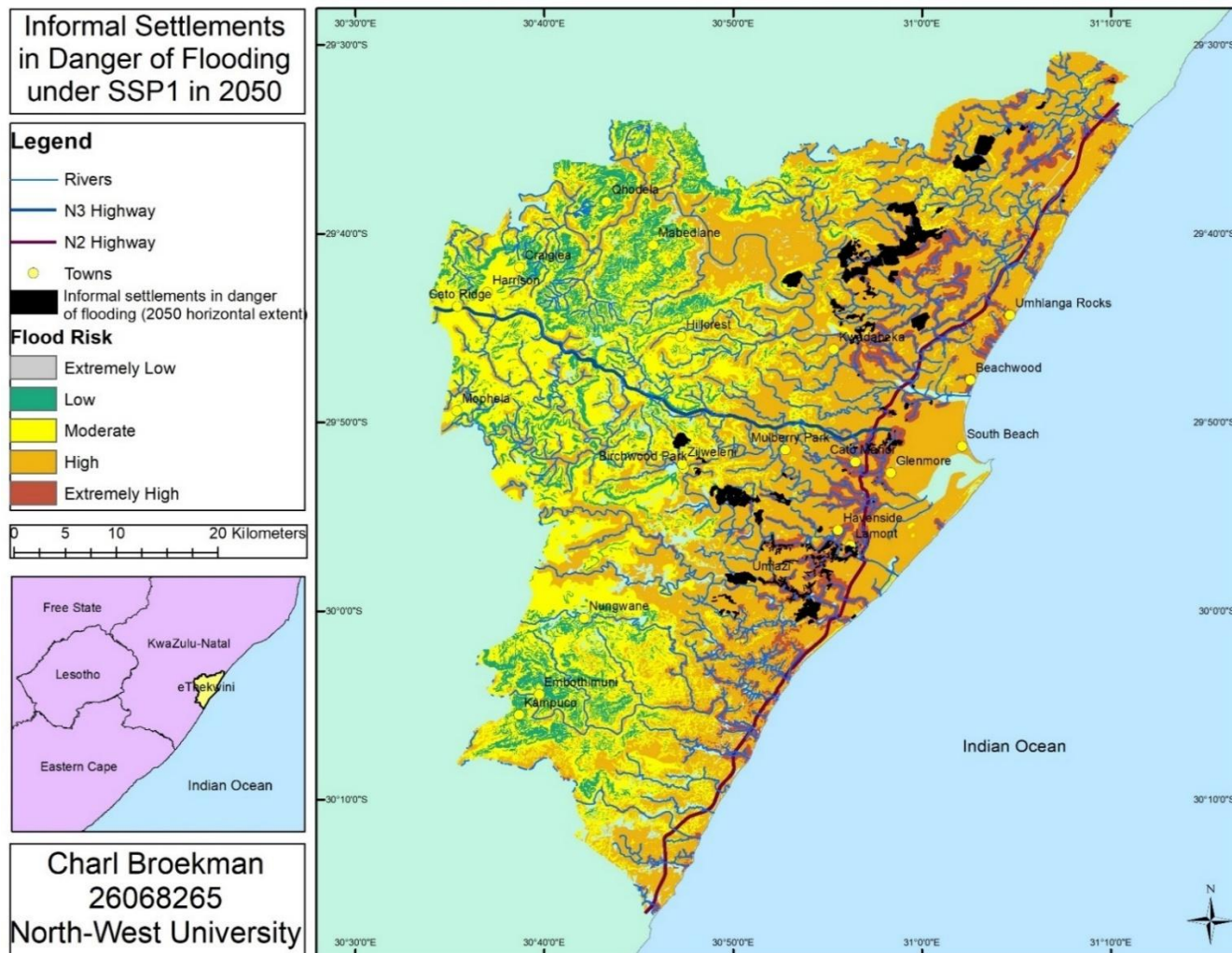


**Figure 4.12: Map showing the future informal settlements at risk of flooding in eThekwinini in SSP1 in the year 2050 (eThekwinini Municipality, 2024)**

#### 4.4.3 Scenario 2: Middle of the road

In the SSP2 scenario, the eThekweni Metropolitan Municipality is projected to experience negative changes in flood risk levels by 2050, with only a move to higher levels of flood risk observed throughout the study area (see Figure 4.13). The "extremely low" flood risk category sees an 18.7% decrease in area size, indicating a reduction in areas with the lowest flood risk. However, these areas remain nearly non-existent, representing only 0.001423% of the eThekweni Metropolitan Municipality's total land area, concentrated mainly in the southwestern part of Nungwane. These areas benefit from higher elevations, steep slopes, efficient drainage systems, and inland locations.

The "low" risk category experiences a 5.1% decrease, suggesting an overall reduction in the size of low-risk areas, which is a concerning development. Areas such as Kampuco, Mabedlane, Qhodela, and Embothimuni are expected to remain in this category. The "moderate" risk category shows a slight 1% decrease, implying a small reduction in flood risk, with suburbs like Cato Ridge, Craiglea, Harrison, Hillcrest, and Mophela maintaining moderate flood risk. High-risk areas see a 1.7% decrease, indicating that high flood risk areas in the future will largely remain consistent with those in 2024, potentially affecting suburbs such as Birchwood Park, Glenmore, Kwadabeka, Kwamashu, Mulberry Park, South Beach, and Zilweleni.

Significantly, there's a 7.1% increase in areas classified as "extremely high" risk, pointing to a worsening flood situation in SSP2, particularly in coastal areas. This increase will affect suburbs like Beachwood, Cato Manor, Havenside, Lamont, Umhlanga Rocks, and the township of Umlazi, which are characterised by higher mean annual precipitation (projected to rise by 22 mm by 2050 in SSP2 throughout the eThekweni Metropolitan Municipality), gentle or non-existent slopes, and low elevation. For a visual representation of these changes, see Figure 4.13, which illustrates the areas now at higher or lower levels of flood risk compared to the current flood risk scenario.

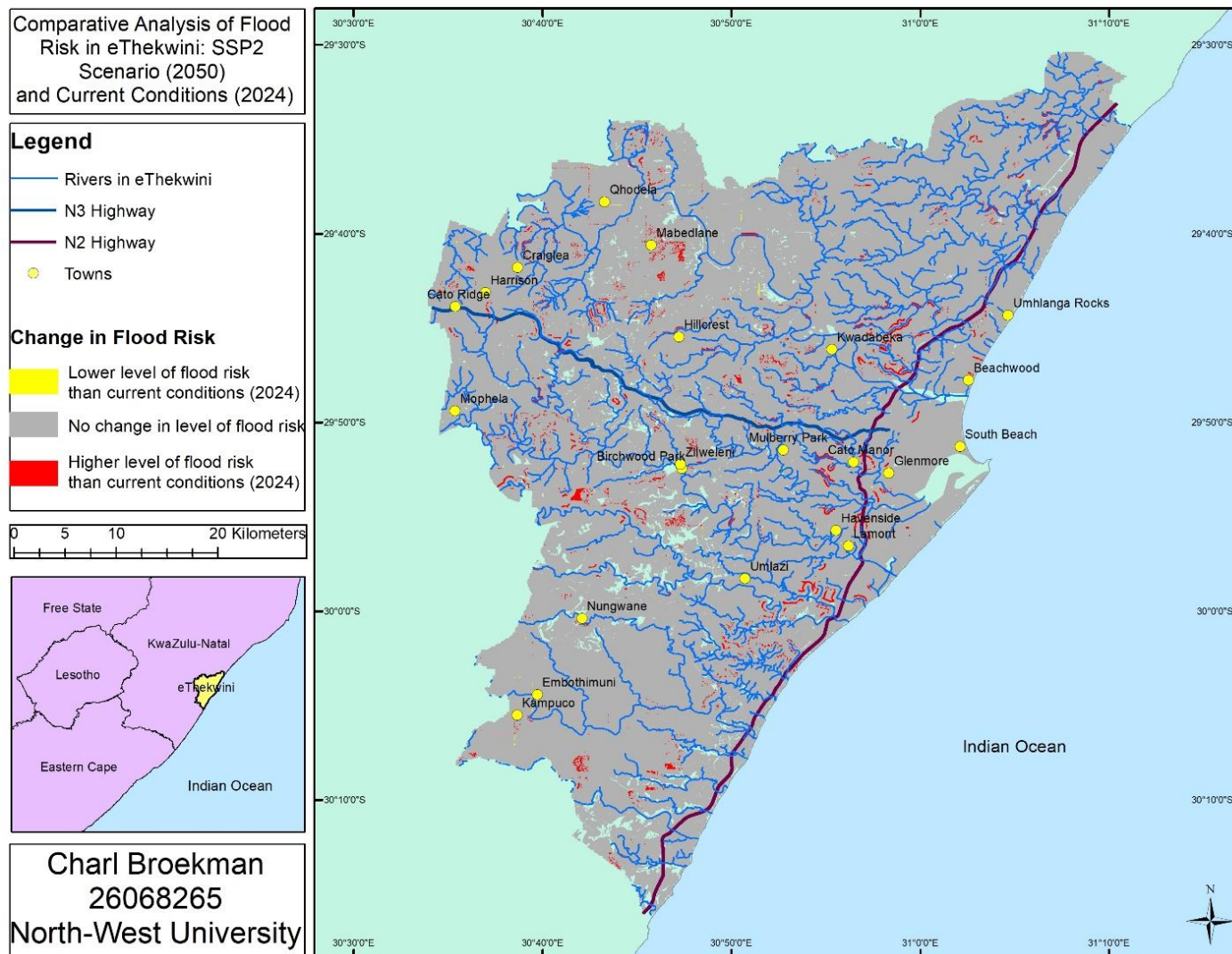


Figure 4.13: Map showing the future flood risk change in eThekweni in SSP2 in the year 2050 (eThekweni Municipality, 2024)



The SSP2 scenario projects an increase in annual rainfall of 22 mm per year by 2050, which will only make the flood risk across the eThekweni Metropolitan Municipality worse than it currently is, with informal settlements facing particularly severe challenges, as shown below. It is important to note that for future scenarios, including this SSP2 scenario, this study does not predict the exact number of informal settlements that will be at extremely high risk. This is due to the significant difficulties in forecasting the precise number of settlements that will be in danger in the future. Factors such as potential merging of settlements or changes in settlement patterns make such predictions highly uncertain. Instead, the study focuses on the total area size that will be affected, based on current trends in household size and settlement growth.

By 2050, the total area of informal settlements exposed to extremely high flood risk is projected to increase to 51.9 km<sup>2</sup> (see Figure 4.14), up from 46.8 km<sup>2</sup> in the SSP1 scenario. This significant increase in vulnerable areas is largely due to the expected horizontal expansion of informal settlements, combined with the projected increase in annual rainfall. Examples of the largest informal settlements that will potentially be at extremely high risk in SSP2 in 2050 include RoodeKrans 828 / Hazelmere Dam, Amatikwe, Kwasumubi / eMahlabathini, Buffelsdraai, and Umlazi - CC - CC Esidweni.

The SSP2 scenario, with its projected increase in rainfall of 22mm by 2050, and the continued horizontal growth of informal settlements, highlights the urgent need for targeted interventions and adaptive strategies. The overall flood risk in the eThekweni Metropolitan Municipality is projected to worsen significantly in SSP2, with a concerning increase in "extremely high" risk areas and no flood risk areas showing improved flood risk conditions in terms of the flood risk categorisation (see Figure 4.13). The expansion of informal settlements into high-risk zones, combined with increased rainfall, could put significantly more people who live in informal settlements at risk by 2050. Ongoing reassessment of flood management plans, with a particular focus on protecting informal settlements and improving their resilience, will be crucial as 2050 approaches. The increased rainfall projected in SSP2 adds an additional layer of complexity to flood risk management in informal settlements, emphasising the need for comprehensive and adaptive urban planning strategies that consider both climate change projections and the dynamic horizontal growth patterns of informal settlements.

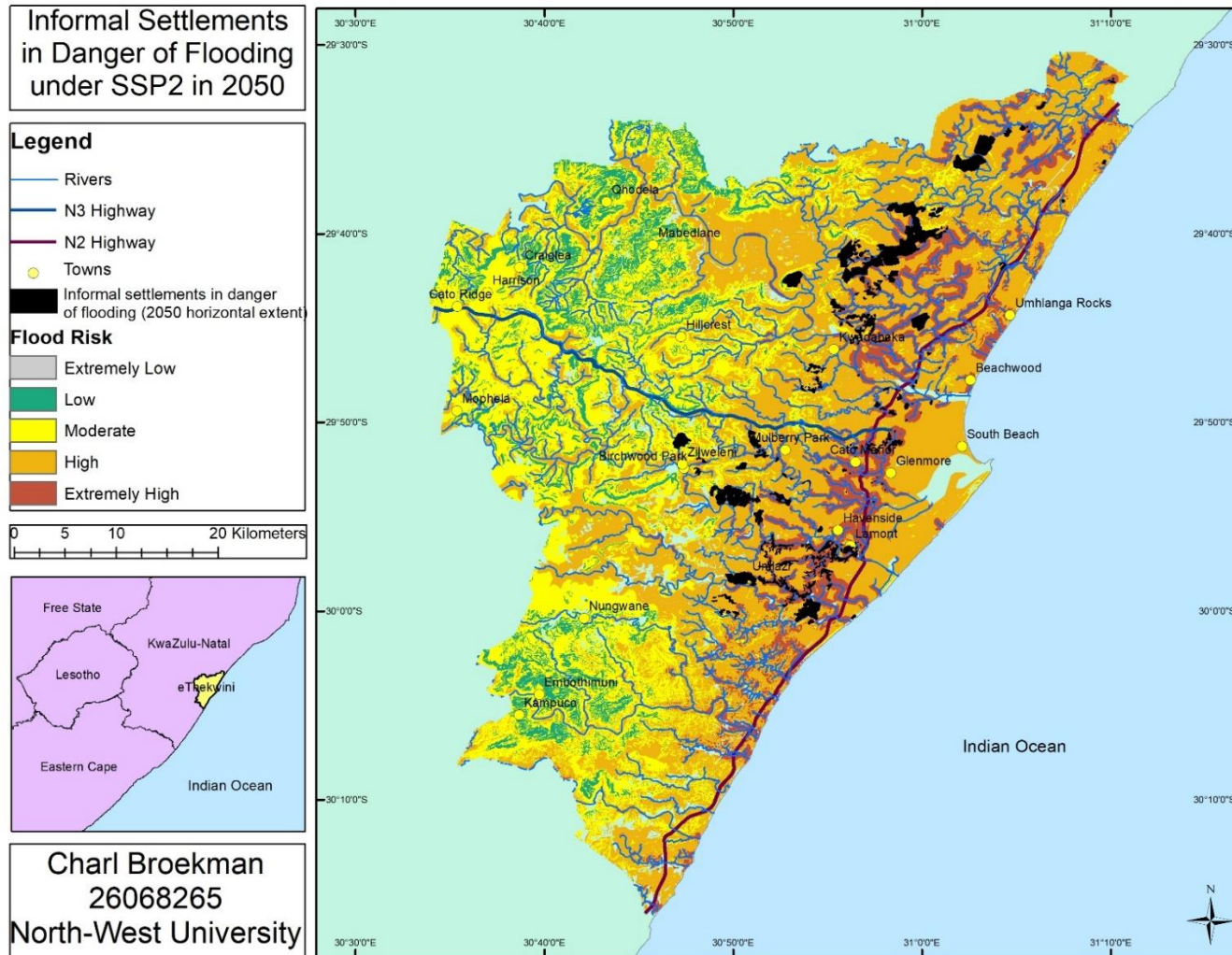


Figure 4.14: Map showing the future informal settlements at risk of flooding in eThekwinini in SSP2 in the year 2050 (eThekwinini Municipality, 2024)

#### 4.4.4 Scenario 3: Worst case

The SSP5 scenario presents a stark negative shift in the eThekweni Metropolitan Municipality's flood risk landscape by 2050, revealing a troubling trend of worsening of flood risk levels experienced in the study area (see Figure 4.15). The areas classified as "extremely low" flood risk shows a great decrease 76.6%, becoming almost negligible at just 0.000376% of the eThekweni Metropolitan Municipality's total land area. These rare low-risk zones are now limited to the southern part of Nungwane, unlike their southwestern location in SSP1 and SSP2 scenarios. This small area of safety is characterised by elevated terrain, sharp or steep slopes, and effective water drainage, situated far from the coastline. The size of the "low" risk category also decreases considerably, dropping by 16.1% in total area size. This decline in area size of the safer areas is a cause for concern, although regions like Kampuco, Mabedlane, and Qhodela still maintain low-risk status, albeit to a lesser extent when looking at the total area size of the "low" risk category. A slight 3.2% reduction in "moderate" risk zones further indicates an upward shift in risk levels, with areas such as Craiglea, Harrison, Hillcrest, and Mophela retaining moderate flood risk, while Cato Ridge potentially escalates to the "high" risk bracket.

The "high" risk category sees a minor 2.0% decrease, including suburbs like Birchwood Park, Glenmore, Kwadabeka, Kwamashu, Mulberry Park, South Beach, Zilweleni, and now possibly Cato Ridge. Most alarmingly, the "extremely high" risk category increases by 24.4% in area size, signalling a great reduction in flood safety. This expansion predominantly affects larger sections of coastal suburbs, including Beachwood, Cato Manor, Havenside, Lamont, Umhlanga Rocks, and Umlazi informal settlement. These vulnerable areas are typified by higher annual rainfall, minimal to no slope, and low-lying terrain. For a visual depiction of these shifts in flood risk categorisation in Scenario 3, refer to Figure 4.15 below, which maps out the evolving flood risk levels in comparison with the current flood risk levels.

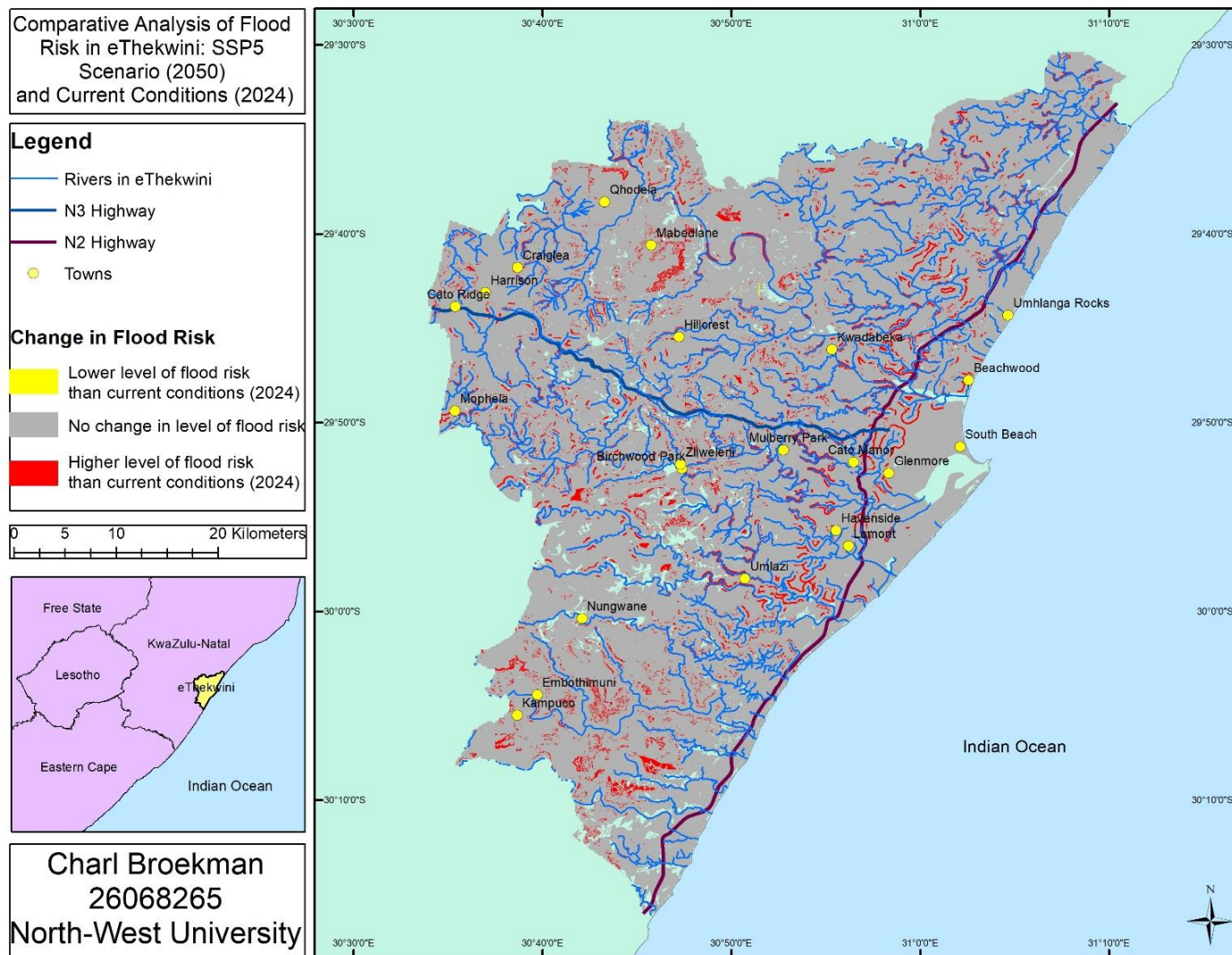


**Figure 4.15: Map showing the future flood risk change in eThekweni in SSP5 in the year 2050 (eThekweni Municipality, 2024)**

The SSP5 scenario (see Figure 4.16) presents the most severe projection for flood risk in the eThekweni Metropolitan Municipality by 2050, with significant implications for informal settlements. In this scenario, the total area of informal settlements intersecting with extremely high-risk flood zones is projected to reach 69.9 km<sup>2</sup>, a substantial increase from both the SSP1 and SSP2 scenarios. This dramatic expansion of vulnerable areas can largely be attributed to the combination of horizontal growth of informal settlements and a projected increase in annual rainfall of 84 mm, the highest among all scenarios considered.

The SSP5 scenario introduces additional areas of concern, with several informal settlements facing extremely high flood risk while they were not similarly affected in the SSP1 or SSP2 scenarios. These newly affected areas, based on their projected horizontal expansion, include various sections of Umlazi such as R6 (West), Z9, Z1, M7/MX14 (Emhlabeni), PX7, DX1 overspill, and KwaMnyandu (13). Additionally, other settlements unique to the SSP5 extremely high-risk category include Jadhu Place, Georgehill Road, Sagu (Sandton phase 3), Dassenhoek - Block G, Redcliff (Canelands/Parkridge), Greylands 82101 TRK Ext, New Germany Road, Umbilo River Valley, Dunstan Garden/Senzokuhle, Lusaka, Esikhelekehleni 1, Sthumba, R.K Khan, Ratna/kwaBridge, KwaCutshwayo (Coffee-Farm phase 2) Ext, and Mpola Phase 2 Ext.

By 2050, in the SSP5 scenario, these informal settlements are projected to face severe and frequent flooding events. The substantial increase in annual rainfall, combined with the expanded area of settlements in high-risk zones, suggests that a significantly larger population will be exposed to extreme flood hazards. This scenario indicates the potential for increased property damage, disruption of livelihoods, and heightened risk to human safety in these areas.

The SSP5 scenario presents a stark picture of potential future flood risks in the eThekweni Metropolitan Municipality, particularly for informal settlements. It highlights the possible consequences of unchecked climate change and unmanaged urban expansion on the most vulnerable communities. The projected outcomes underscore the scale of the challenge that could face the eThekweni Metropolitan Municipality by 2050 with respect to flood risk management, particularly in informal settlements.



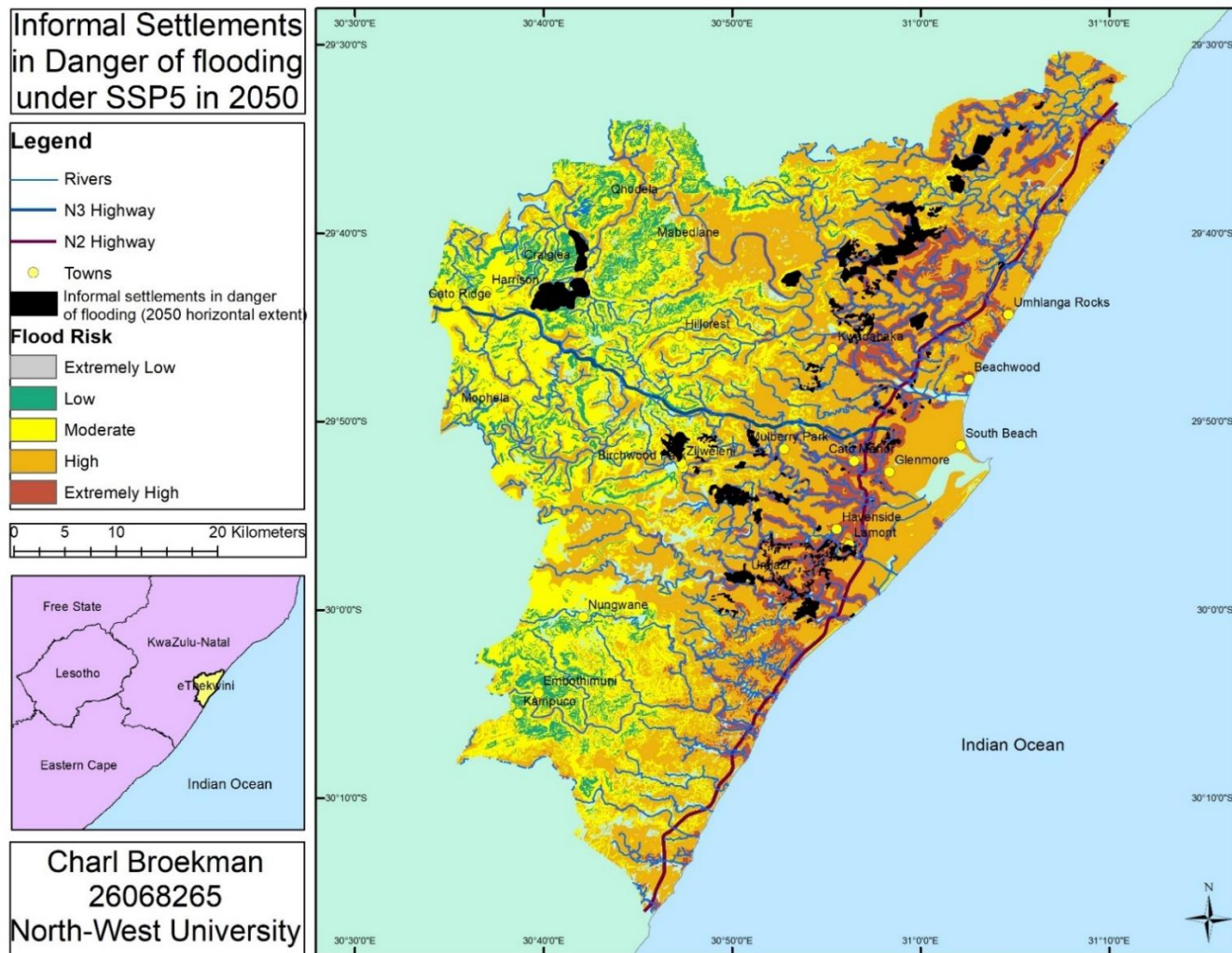


**Figure 4.16: Map showing the future informal settlements at risk of flooding in eThekwinini in SSP5 in the year 2050 (eThekwinini Municipality, 2024)**

#### **4.5 Cross-scenario flood risk analysis: Identifying current informal settlements that need intervention**

In the field of flood risk mapping and management, the ability to identify consistently high-risk areas across multiple future scenarios is important for effective decision making and resource allocation. While individual scenario analyses offer insight into potential future outcomes, a cross-scenario approach provides a better foundation for prioritising interventions with greater certainty. This section combines the results on extremely high flood risk in informal settlements from the three future scenarios and the current scenario to identify informal settlements persistently at risk across the four scenarios in their current horizontal area size and shape. Identifying informal settlements that consistently emerge as extremely high risk across multiple scenarios can provide decision makers with a clearer picture of where immediate action is most urgently needed and what areas should be avoided at all costs.

This section not only improves the results of the single scenario-based predictions but also introduces a gradient of risk certainty, allowing for more targeted intervention by decision makers. The analysis therefore focuses on current informal settlements and their exposure to extremely high flood risk across the current scenario and three future scenarios, creating a better picture of future flood risk in informal settlements.

Of the 289 informal settlements currently at extreme risk of flooding, 230 intersect with extremely high flood zones in all four scenarios (current and three future) in their current horizontal area size and shape. These informal settlements, represented in red on the below map (Figure 4.17), demonstrate persistent extreme flood risk regardless of future rainfall changes according to the SSPs and should be prioritised for immediate intervention. Covering a total current horizontal area of approximately 29.2 km<sup>2</sup>, these affected informal settlements demonstrate the widespread extreme flood risk across the study area. The extensive horizontal area size of the affected informal settlements highlights the urgent need for widespread and comprehensive flood resilience strategies. Importantly, this 29.2 km<sup>2</sup> area is projected to increase substantially by 2050, the focal year of this study's future scenarios. Given prevailing trends in demographic growth and therefore horizontal informal settlement expansion (see Figure 3.19), the importance of proactive and anticipatory planning and intervention strategies to mitigate future flood risks in these 230 informal settlements is clearly demonstrated.





The analysis also identified 59 informal settlements (see Figure 4.17) out of the 289 currently at extremely high flood risk that face extremely high flood risk in three out of the four scenarios examined (the current situation plus future Scenarios 2 and 3). For clarity, it is worth reiterating that this study defines informal settlements according to the eThekweni Metropolitan Municipality's official designation system. The informal settlements, highlighted in orange on the map (see Figure 4.17), show significant potential vulnerability across multiple potential futures, with serious consideration of intervention strategies still needed. While not as critically urgent as the red zones, these areas nonetheless represent a concern for flood risk management in the study area. The current horizontal size of these orange informal settlements is 5.5 km<sup>2</sup>, further illustrating the widespread nature of flood risk in the study area. This area size is also expected to expand by 2050, driven by ongoing population growth in informal settlements. The anticipated horizontal expansion of these vulnerable informal settlements suggests that an increasing number of residents may find themselves exposed to extreme flood risk, again demonstrating the importance of flexible, anticipatory approaches to flood management that can adapt to changing climate conditions over time. It is important to note that among the 289 informal settlements currently at extremely high flood risk, none are projected to be affected in only one or two scenarios. This finding also demonstrates the large flood risk problem in the affected informal settlements.

The gradient of risk across different current and future scenarios illustrated above provides decision makers with a better understanding of flood risk across the eThekweni Metropolitan Municipality's informal settlements. By categorising informal settlements based on their consistent extreme flood risk across multiple scenarios, this approach offers a robust framework for prioritising interventions and allocating resources so that these areas can be avoided. The red zones, at extreme risk in all four scenarios, demand immediate and comprehensive action, while the orange areas, though slightly less critical, still require significant attention and long-term planning to mitigate potential future risks.

While the above cross-scenario analysis of current informal settlements provides important insights into immediate flood risks, it is equally important to consider how these risks may change in the future by the year 2050. As the informal settlements in the eThekweni Metropolitan Municipality continue to horizontally expand and climate patterns shift, the flood risk in informal settlements is likely to change significantly by 2050. To address this, the study now turns to an anticipatory analysis that focuses on the projected horizontal size of informal settlements by 2050 and potential changes in flood risk patterns. This future-oriented cross-scenario analysis builds on the results obtained for current informal settlements and now focuses on the three future scenarios (SSP1, SSP2, and SSP5). By looking at how flood risks can change in the projected horizontally expanded areas of informal settlements, this study aims to provide decision makers

with valuable information for long-term planning and risk mitigation strategies. The results of this approach allow for a more comprehensive understanding of flood risk dynamics in the eThekweni Metropolitan Municipality, bridging the gap between current and future flood risks in informal settlements.

#### **4.6 Cross-scenario flood risk analysis: Identifying future informal settlements that need intervention**

Building on the results for current informal settlements, this section presents the findings of a cross-scenario approach to identify future areas of persistent flood risk across multiple scenarios. These results provide decision makers with a forward-looking perspective on informal settlements that may require intervention or should be avoided for future informal settlement development.

The results of this cross-scenario analysis enhance single scenario-based predictions by presenting a gradient of risk certainty for future informal settlement areas, allowing for more targeted and anticipatory intervention strategies. The analysis reveals the projected horizontal expansion of informal settlements and their exposure to extremely high flood risk across the three future scenarios (SSP1, SSP2, and SSP5), creating a comprehensive picture of potential future flood risks.

The analysis identified areas that intersect with extremely high flooding zones in all three future scenarios. These areas, represented in red on the map (Figure 4.18), demonstrate persistent extreme flood risk across all projected climate change scenarios and should be prioritised for preventive measures or considered as areas to be avoided for future informal settlement development. Covering a total projected horizontal area of approximately 46.8 km<sup>2</sup>, these affected future areas illustrate the potential widespread nature of extreme flood risk across the study area by 2050. This extensive projected area highlights the critical need for proactive flood resilience strategies and careful urban planning.

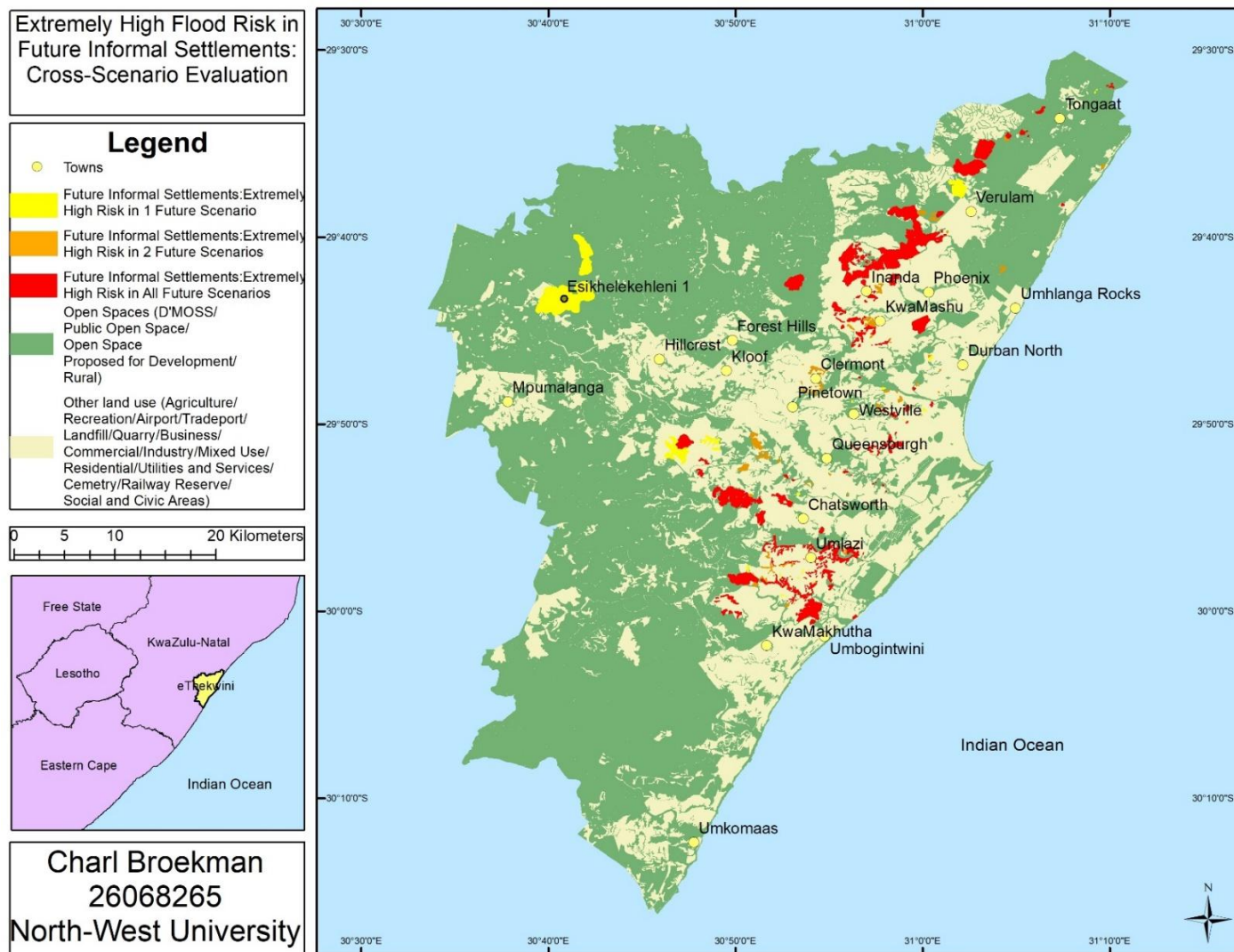


**Figure 4.18: Map showing the cross-scenario flood risk of future informal settlements in eThekweni (eThekweni Municipality, 2024)**

The results in the above map (see Figure 4.18) also identified areas that face extremely high flood risk in two out of the three future scenarios examined (specifically Scenarios 2 and 3). These areas, highlighted in orange on the map, show significant potential vulnerability across multiple potential futures, with serious consideration needed for preventive strategies or alternative development plans for these informal settlements. While not as urgent as the red zones, these areas nonetheless represent a significant concern for future flood risk management in the study area. The projected horizontal size of these orange areas is five km<sup>2</sup>, further illustrating the potential scale of future flood risk in the eThekweni Metropolitan Municipality.

Additionally, informal settlements projected to be at extremely high flood risk in only one of the three future scenarios (Scenario 3) were identified. These areas, marked in yellow on the map, represent potential hotspots that require monitoring and flexible planning approaches to address possible future flood risks. The projected size of these yellow areas is 18 km<sup>2</sup>. It is important to note that this figure is slightly inflated due to one singular currently known informal settlement, Esikhelekehleni, which is projected to horizontally expand to approximately 10 km<sup>2</sup>.

This gradient of risk across different future scenarios provides decision makers with a nuanced understanding of potential flood risks in the eThekweni Metropolitan Municipality's future informal settlement areas. The results offer a robust framework for anticipatory planning, resource allocation, and risk mitigation strategies. The red zones, at extreme risk in all three future scenarios, demand immediate attention in urban development plans, while the orange and yellow areas require careful consideration and flexible approaches to mitigate potential future risks.

These cross-scenario analysis results for future informal settlement areas, combined with the analysis of current settlements, provide a comprehensive view of both present and future flood risks in the eThekweni Metropolitan Municipality. The findings emphasise the importance of adaptive and anticipatory urban planning that considers multiple possible climate futures, ensuring the long-term resilience and sustainability of informal settlements in the face of changing flood risks.

#### **4.7 Conclusion**

This chapter presented the results and discussion of the flood risk assessment and mapping conducted for the eThekweni Metropolitan Municipality, with a specific focus on identifying informal settlements at risk of flooding. Building on the methodological groundwork established in the previous chapter, this study has fully achieved the fourth research objective: "To map the current and potential future areas of the eThekweni Metropolitan Municipality that are vulnerable to flooding events."

The study used a MCDA approach to develop comprehensive current and future flood risk maps using GIS as a tool of AG. This integration of GIS and AG principles allowed for the creation of multiple future flood risk scenarios, enabling a robust and forward-looking analysis of potential flood risks in eThekweni's informal settlements. By aligning with Approach 3: Pluralistic Futures, Societal Mobilisation, and Co-Creating Alternatives, the study emphasised the importance of imagining multiple futures and preparing for different future outcomes, which could result as a consequence of climate change.

The foundation for this approach was established through the literature study, which highlighted the critical role of GIS in managing urban disaster risk and the value of AG in addressing complex, uncertain futures. The literature revealed that GIS is a powerful tool for integrating spatial data, modelling hazards, and visualising risks, making it indispensable for flood risk mapping and scenario planning (Goodchild & Haining, 2004; McCall & Dunn, 2012). Furthermore, the literature on AG, particularly Approach 3: Pluralistic Futures, Societal Mobilisation, and Co-Creating Alternatives, highlighted the importance of creating multiple future scenarios to anticipate and adapt to uncertain conditions, rather than relying on single, deterministic predictions (Muiderman *et al.*, 2020). These insights informed the study's methodology, guiding the use of GIS to model flood risks with the help of MCDA under different SSPs.

The current flood risk map revealed a concerning situation with 289 informal settlements, housing an estimated 163 000 households, facing an extremely high threat of flooding. These settlements, covering an area of 34.7 km<sup>2</sup>, are scattered across various districts within the eThekweni Metropolitan Municipality, predominantly in low-lying coastal areas characterised by low elevations and gentle slopes. The model validation process, using data from the April 2022 KwaZulu-Natal flooding event, demonstrated the accuracy and reliability of the flood risk map. The analysis showed a strong correlation between the map's high and extremely high-risk zones and the actual damage observed during the flooding event, with 71.24% of damaged structures falling into these categories.

Future flood risk scenarios based on different SSPs revealed varying degrees of change in flood risk patterns. In SSP1, despite an overall reduction in flood risk across the eThekweni Metropolitan Municipality, the area of informal settlements intersecting with extremely high flood risk zones is projected to increase to 47 km<sup>2</sup> by 2050. SSP2 showed a more severe scenario, with the area of informal settlements intersecting with extremely high-risk zones expanding to 51.9 km<sup>2</sup>. SSP5 presented the most alarming projection, with informal settlements intersecting with extremely high-risk zones covering 69.9 km<sup>2</sup> by 2050.

The cross-scenario analysis identified 230 current informal settlements, covering 29.2 km<sup>2</sup>, that consistently show extremely high flood risk across all scenarios. An additional 59 settlements, spanning 5.5 km<sup>2</sup>, are at extremely high risk in three out of four scenarios. This analysis provides a robust framework for prioritising interventions and allocating resources. Looking at future expansion, the study identified 46.8 km<sup>2</sup> of projected informal settlement areas that would be at extremely high flood risk across all three future scenarios. An additional 5 km<sup>2</sup> would be at risk in two scenarios, and 18 km<sup>2</sup> in one scenario.

These findings highlight the urgent need for comprehensive flood risk management strategies in the eThekweni Metropolitan Municipality, particularly for informal settlements. The results underscore the importance of anticipatory planning and adaptive approaches that can respond to various potential future scenarios. By identifying consistently high-risk areas across multiple scenarios, this study provides decision makers with valuable insights for prioritising interventions and developing targeted strategies to protect vulnerable communities from the devastating impacts of flooding.

## **CHAPTER 5      CONCLUSIONS AND RECOMMENDATIONS**

### **5.1      Introduction**

This study has demonstrated the significant potential of integrating GIS with AG principles to enhance both current and future flood risk mapping in the eThekweni Metropolitan Municipality. By combining spatial analysis techniques with forward-thinking governance approaches, this research has provided insights into the complex dynamics of flood risk in urban areas, particularly in vulnerable informal settlements.

The following sections discuss the key findings of this study in relation to the research aim and its associated objectives. Each objective has contributed to a comprehensive understanding of flood risk in the eThekweni Metropolitan Municipality, from establishing historical context to developing future flood risk scenarios and practical recommendations. This discussion not only highlights the achievements of the study but also reflects on their implications for flood risk management and urban planning in the eThekweni Metropolitan Municipality and potentially other urban areas facing similar challenges.

Through this analysis, the study demonstrates how the integration of GIS and AG principles has allowed for a multi-temporal, and scenario-based approach to flood risk mapping. This approach provides decision makers with a tool for anticipating and preparing for future flood risks, ultimately contributing to more resilient and sustainable urban development in the eThekweni Metropolitan Municipality.

### **5.2      Discussion of the findings for each research objective formulated for the study**

The sections that follow discuss the findings relating to the individual research objectives set out in Chapter 1.

#### **5.2.1      Research Objective 1: To establish the background of urban flood risk trends on a regional and local scale**

The study established a theoretical background of urban flood risk trends on both regional and local scales. A compilation and analysis of flooding events in KwaZulu-Natal and the eThekweni Metropolitan Municipality from 1985 to 2023 revealed persistent flooding patterns, seasonal trends, and a large number of affected areas. This historical context, drawn from studies by Grab and Nash (2023), Botes (2014), Olanrewaju and Reddy (2022) and FloodList (2024), provided important insights into the recurring nature of flood events in the region.

The analysis highlighted an increase in the frequency of recorded flooding events over time, with the 2000s and 2010s showing more floods than the 1980s and early 1990s. This increase could be attributed to a combination of factors, including improved reporting, more flood occurrences due to climate change, or increased vulnerability from urbanisation and land-use changes. Clear seasonal patterns emerged, with most flooding events occurring during the wet season (October to March), although some floods were recorded in typically drier months, indicating potential changes in rainfall patterns.

Geographically, urban areas, particularly Durban and its surroundings (part of the eThekweni Metropolitan Municipality), were more frequently affected by flooding events. This suggests that urban areas may be more vulnerable due to impermeable surfaces and drainage issues, or it could reflect more thorough reporting in populated areas. Recent years have shown floods affecting inland areas as well, indicating a potential expansion of flood-prone regions in KwaZulu-Natal.

This historical analysis provides a crucial foundation for understanding the context of flood risk in the eThekweni Metropolitan Municipality, informing both current flood risk assessments and future projections.

#### **5.2.2 Research Objective 2: To discuss the theoretical tenants of anticipatory governance and its relevance for the management of urban flood risk in eThekweni Metropolitan Municipality**

The study explored the application of AG to urban flood risk mapping in the eThekweni Metropolitan Municipality using a two-pronged approach. Firstly, a comprehensive literature review examined five contexts in which AG has been applied: anticipatory climate governance, anticipatory innovation governance, anticipatory regulation, anticipatory disaster governance, and anticipatory risk management. This review provided a solid foundation for understanding AG applications across different fields of study, highlighting its versatility and potential in addressing complex challenges like urban flooding.

Secondly, the study incorporated AG principles directly into the methodology of flood risk mapping in the eThekweni Metropolitan Municipality, with a particular focus on Approach 3: pluralistic futures, societal mobilisation and co-creating alternatives, as proposed by Muiderman *et al.* (2020). This approach emphasised the importance of considering diverse multiple future scenarios in the process of anticipating and preparing for future flood risks.



By combining this approach with insights from anticipatory climate governance, which suggests likely changes in precipitation patterns, the study developed multiple future scenarios of flood risk. This multi-scenario approach allowed for a better understanding of potential future flood risks, accounting for uncertainties in climate change projections and urban development patterns.

Another key application of AG principles in this study was the anticipation of future horizontal growth of informal settlements by the year 2050 in the eThekweni Metropolitan Municipality. Using household growth projections, the research modelled potential horizontal expansion of informal settlements, providing a more comprehensive understanding of future flood risk that considers both changing climate conditions and evolving urban landscapes.

This practical application of AG to flood risk mapping in the eThekweni Metropolitan Municipality demonstrated how theoretical AG concepts could be translated into methodologies for addressing complex urban challenges. The study showed that AG principles can enhance the traditional GIS-based flood risk mapping approach by incorporating multiple future scenarios, leading to more robust and adaptable flood risk management strategies.

### **5.2.3 Research Objective 3: To discuss the use of and utility of GIS in mapping urban flood risk**

The utility of GIS in mapping urban flood risk was clearly demonstrated throughout the study. Various GIS techniques and applications were explored, highlighting the effectiveness of integrating and analysing multiple datasets related to flood risk factors. The study incorporated seven key datasets: elevation, slope, rainfall, drainage density, soil type, land use, and distance from rivers.

A MCDA approach was employed to combine these seven input layers, allowing for a weighted integration of the various flood risk factors. This comprehensive GIS analysis, enhanced by the MCDA methodology, provided a better understanding of the flood risk factors across the eThekweni Metropolitan Municipality. The GIS-based approach allowed for the creation of detailed flood risk maps that visually represent the spatial distribution of flood risk across the study area. These maps proved to be powerful tools for identifying areas of extremely high flood risk, particularly informal settlements, which are most vulnerable. Furthermore, the integration of GIS with AG principles enabled the development of future flood risk scenarios. By incorporating projected changes in rainfall patterns and informal settlement growth into the GIS analysis, the study was able to model potential future flood risk landscapes. This forward-looking approach demonstrates the flexibility and adaptability of GIS in handling complex, multi-temporal analyses.

The study also highlighted the potential of GIS in supporting decision-making processes. The visual nature of GIS outputs, such as flood risk maps, can effectively communicate complex spatial information to decision makers. This can facilitate more informed and inclusive decision making in flood risk management.

#### **5.2.4 Research Objective 4: To map the current and potential future areas of the eThekweni Metropolitan Municipality that are vulnerable to flooding events**

A significant achievement of this study was the mapping of the current and potential future areas of the eThekweni Metropolitan Municipality vulnerable to flooding events. The research identified specific informal settlements that are currently at risk of flooding, as well as those that may be at risk in the future in different scenarios.

For current flood risk, the study identified 289 informal settlements, an estimated 163 000 households and a total land surface of 34.7 km<sup>2</sup> in that eThekweni Metropolitan Municipality that carry extremely high flood risk. These settlements are scattered across various districts in the eThekweni Metropolitan Municipality, predominantly in low-lying coastal areas characterised by low elevations and gentle slopes.

Crucially, the study analysed the flood risk for current informal settlements, maintaining their current horizontal extent across four scenarios: the current flood risk scenario and three future scenarios based on different SSPs. This approach provided insights into how existing settlements might be affected by changing climate conditions, even without considering potential expansion.

The future scenarios, incorporating different SSPs with varying rainfall projections, were used to assess both current informal settlements and projected future informal settlement growth. In the best-case scenario (SSP1), the area of informal settlements at extremely high flood risk is projected to increase to 47 km<sup>2</sup> by 2050. The middle-of-the-road scenario (SSP2) showed a more severe projection, with 51.9 km<sup>2</sup> at extremely high risk. The worst-case scenario (SSP5) presented the most alarming projection, with 69.9 km<sup>2</sup> of informal settlements at extremely high flood risk by 2050.

A comprehensive cross-scenario analysis provided valuable insights into how flood risks may evolve over time and how different areas might be affected in various climate and urban development scenarios. This analysis identified 230 current informal settlements, covering 29.19 km<sup>2</sup>, that consistently show extremely high flood risk across all scenarios. An additional 59 settlements, spanning 5.47 km<sup>2</sup>, are at extremely high risk in three out of four scenarios.

This multi-scenario approach allowed for the identification of areas that consistently showed high flood risk across all scenarios, as well as areas where flood risk varied significantly depending on the scenario. Such information is invaluable for prioritising interventions and developing adaptive strategies that can be effective across a range of possible futures. By providing this multi-temporal and multi-scenario perspective, including the analysis of current informal settlements across all scenarios and the anticipation of informal settlement growth, the study can equip decision makers with a more comprehensive understanding of potential future flood risk challenges.

While this approach enhances understanding of current flood risks and allows for proactive planning in the face of climate change and urban growth, it also highlights areas for future research and methodological improvements. Notably, the integration of more advanced and detailed settlement growth modelling could significantly enhance the accuracy of identifying future priority areas for flood risk management. Such models could incorporate factors like socioeconomic drivers, land availability, and policy constraints to provide a more nuanced projection of informal settlement expansion.

Furthermore, the flooding scenarios developed in this study have the potential to serve as valuable inputs for suitability analysis in urban development planning. By overlaying these flood risk projections with other spatial data relevant to urban development, such as infrastructure networks, environmental constraints, and economic factors, planners could generate more comprehensive SDFs and scenarios. This integration would allow for a more holistic approach to urban planning that explicitly considers flood risk in long-term development strategies.

Although this study did not directly compare its findings with current IDPs or SDFs, there is significant potential for future research to bridge this gap. By aligning flood risk projections with existing policy frameworks, future studies could provide more targeted recommendations for policy adjustments and urban development strategies. This alignment would enhance the practical application of the research findings, directly informing policy decisions and contributing to more resilient urban planning in the eThekweni Metropolitan Municipality.

### **5.3 Recommendations**

The findings of this study, as discussed in relation to the first four research objectives, provide a solid foundation for addressing the fifth and final research aim: to make recommendations for future disaster risk reduction measures and AG principles to be implemented by the municipality using the maps produced. Drawing from the insights gained from this research, the next section presents a series of recommendations aimed at enhancing flood risk management in the eThekweni Metropolitan Municipality, with a particular focus on vulnerable informal settlements.

These recommendations are divided into two main categories: recommendations for future research and recommendations for practitioners/municipal officials. The research-oriented recommendations aim to advance the academic understanding and methodology of flood risk mapping using GIS and AG principles. The practice-based recommendations, on the other hand, provide actionable steps for municipal officials and disaster management professionals to improve flood risk management in the eThekweni Metropolitan Municipality, particularly focusing on vulnerable informal settlements.

By addressing both academic and practical aspects, these recommendations seek to bridge the gap between theoretical understanding and real-world application, ultimately contributing to more resilient and sustainable urban development in the eThekweni Metropolitan Municipality.

### **5.3.1 Recommendations for future research**

This research has shown that GIS can be a powerful tool when combined with AG principles in addressing complex urban challenges such as the flood risk mapping of informal settlements in the eThekweni Metropolitan Municipality. This integrated approach not only enhances the understanding of current flood risks but also enables proactive planning for multiple potential futures, which can contribute to more resilient and sustainable urban development in the eThekweni Metropolitan Municipality. The following recommendations can be identified:

- This study primarily used AG in the form of Approach 3: pluralistic futures, societal mobilisation and co-creating alternatives, based on the study of Muiderman *et al.* (2020). Future research could benefit from applying the other AG approaches from Muiderman *et al.* (2020) to flood risk mapping in the eThekweni Metropolitan Municipality. For instance, Approach 1: Probable futures, strategic planning, and risk reduction, could be used to develop more precise probabilistic models of flood risk in the eThekweni Metropolitan Municipality. Approach 2: Plausible futures, enhanced preparedness, and navigating uncertainty, might aid the development of adaptive capacities for a wider range of potential flood scenarios. Approach 4: Performative futures, critical interrogation, and political implications, could examine how different flood risk projections influence current decision making and policy development.
- Future studies could also expand the scope of analysis to include other factors that contribute to flood risk, such as infrastructure maintenance and infrastructure decline, existing adaptation measures, and socio-economic variables. This broader perspective

could provide a more comprehensive understanding of flood risk and flood vulnerability in the eThekweni Metropolitan Municipality.

- To enhance the accuracy and relevance of the flood risk mapping, future research should involve local communities and decision makers in the validation process of the flood risk maps. This participatory approach aligns with the principles of AG Approach 3 and could lead to more effective, context-specific solutions to flood-related challenges.
- Given the complex nature of flood risk mapping and management, future research could benefit from interdisciplinary collaborations that bring together experts in GIS, climate science, urban planning, and social sciences. This holistic approach could lead to more comprehensive and innovative solutions.
- Future studies could also focus on developing more dynamic models that capture the temporal aspects of flood risk, considering how factors such as climate change, urban development, and adaptation measures might interact over time.
- Future research studies can build on the foundation laid by this study and apply GIS and AG principles to flood risk mapping for other urban areas facing similar challenges.

### **5.3.2 Recommendations for practitioners/municipal officials**

Specific recommendations emerging from the study that can have a bearing on the work of disaster management practitioners and municipal officials in their efforts to reduce current and future flood risk include:

- Public officials and disaster risk managers could prioritise interventions in informal settlements consistently identified as high-risk across all scenarios. Immediate flood mitigation efforts could focus on the 230 settlements covering 29.2 km<sup>2</sup> that show extremely high flood risk in both current and future projections. Implementing EWSs and evacuation plans for these high-risk informal settlements, particularly those in low-lying coastal areas and near riverbanks, is crucial. These EWSs and evacuation plans could be tailored to the specific needs and constraints of informal settlements, considering factors such as limited infrastructure and high population density.
- The eThekweni Municipality could integrate the current flood risk maps as well as the future scenario flood risk maps into urban planning and development policies, using the

information from this study to guide decisions on land use, infrastructure development, and informal settlement upgrading programmes. The integration of flood risk maps will highlight the importance of anticipatory measures in addressing environmental challenges such as flooding and could help in developing more resilient urban spaces. A comprehensive flood management strategy for the eThekweni Metropolitan Municipality could be developed and implemented, considering both current risks and potential future scenarios. This flood management strategy could incorporate both structural measures, such as improved drainage systems and flood barriers, and non-structural measures, like community education, awareness programmes, and land-use regulations.

- To achieve this comprehensive flood management strategy, the municipality could establish an inter-departmental task force to address flood risks in informal settlements. This task force could use the study's findings to coordinate efforts across urban planning, disaster management, and community development departments. An inter-departmental approach could foster better communication and collaboration among different sectors, leading to more effective and holistic flood management strategies.
- Additionally, community-based flood resilience programmes could be initiated in high-risk informal settlements, focusing on raising awareness, building local capacity for flood preparedness, and implementing small-scale flood mitigation measures. These community-based programmes could incorporate local knowledge and participation in decision-making processes, ensuring that interventions are culturally appropriate and sustainable.
- The multi-scenario analysis conducted in this study could inform the development of flexible, adaptive management strategies that can respond to changing conditions over time, ensuring that flood management efforts remain effective in different future scenarios. This approach of using multi-scenario analysis recognises the inherent uncertainties in climate change projections and urban development patterns, allowing for adjustments as new information becomes available. The municipality could also consider developing a system for monitoring and evaluating the effectiveness of implemented flood management measures, enabling continuous improvement and learning.
- The GIS-based flood risk mapping approach used in this study could be integrated into regular municipal planning and review processes, with flood risk maps being regularly updated to ensure they remain a relevant decision-making tool. This integration of GIS-

based flood risk mapping could involve establishing protocols for data collection, analysis, and dissemination, ensuring that all relevant decision makers have access to the newest flood risk information.

- Furthermore, the eThekweni Metropolitan Municipality could consider developing partnerships with academic institutions, non-governmental organisations, and private sector entities to support ongoing research and innovation in flood risk management. Such collaborations on flood risk management could bring in additional expertise, resources, and perspectives, potentially leading to more innovative and effective solutions.
- The municipality could also explore the development of financial mechanisms to support flood risk reduction efforts in informal settlements. These financial mechanisms could include setting up dedicated funds for flood mitigation projects, exploring insurance schemes for informal settlement residents, or developing incentive programmes for property owners who implement flood-resilient measures.
- Lastly, the eThekweni Metropolitan Municipality could take a leadership role in sharing its experiences and learnings from this flood risk mapping study with other municipalities facing similar challenges. This knowledge sharing could involve participating in national and international forums on urban flood management, publishing case studies, and engaging in peer-to-peer learning activities. By sharing its experiences, the eThekweni Metropolitan Municipality could contribute to the broader body of knowledge on urban flood management and potentially influence policy and practice on a wider scale.

The recommendations presented above have directly addressed the fifth and final research objective: "To make recommendations on future disaster risk reduction measures and AG principles to be implemented by the municipality by using the maps made." These recommendations translate this study's findings into actionable steps for decision makers, enhancing flood risk management in the eThekweni Metropolitan Municipality and potentially serving as a model for other urban areas facing similar challenges. By incorporating principles of AG and using GIS as a tool for decision support, the eThekweni Metropolitan Municipality could enhance its resilience to flood risks and better protect its vulnerable communities in informal settlements in current and future flood risk scenarios. These recommendations, grounded in the flood risk maps produced by this study, provide a comprehensive framework for implementing disaster risk reduction measures and AG principles, therefore fulfilling the final objective of this research.

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