



An assessment of flood risk and vulnerability in coastal areas of KwaZulu-Natal

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PREFACE AND ACKNOWLEDGMENTS

This dissertation presents an assessment of flood risk and vulnerability in coastal KwaZulu-Natal, South Africa, with a focus on understanding the hydrological behaviour of key river systems and their associated impacts on surrounding communities. The study integrates hydrological and hydraulic modelling with spatial analysis to identify flood-prone areas, evaluate hazard levels, and assess vulnerability within the study area.

The research was conducted as part of the requirements for the completion of *Master of Environmental Management* in Ecological Water Requirements at the North-West University. The work presented is the original research of the author, except where explicitly acknowledged through referenced sources. All data sources, methodologies, and analytical approaches have been appropriately cited.

This study aims to contribute to the growing body of knowledge on flood risk management in South Africa, particularly in the context of increasing climate variability and urbanisation pressures. It is intended to support improved planning, decision-making, and resilience-building efforts in flood-prone coastal regions.

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ABSTRACT

Flooding is one of the most significant natural hazards affecting coastal regions worldwide, with increasing frequency and intensity driven by climate change, urbanisation, and environmental degradation. Coastal KwaZulu-Natal (KZN), South Africa, is particularly vulnerable due to its exposure to extreme rainfall events, storm surges, and densely populated river catchments. Despite recurring flood events, there remains limited spatially explicit information on flood-prone areas, vulnerability patterns, and associated risks. This study aimed to assess flood risk and vulnerability in the coastal regions of KwaZulu-Natal by integrating hydrological and hydraulic modelling with spatial and socio-economic analysis. The research focuses on key river systems, including the uMgeni, uMvoti, uMdloti, uMlazi, Mbokodweni, and uMkomazi catchments. Hydrological modelling was conducted using HEC-HMS to simulate rainfall–runoff processes, while hydraulic modelling using HEC-RAS was applied to determine flood depth, extent, and inundation patterns, consistent with integrated flood inundation modelling approaches described by Saksena *et al.* (2019). These outputs were integrated into a GIS environment (QGIS) to generate flood hazard maps. A vulnerability assessment was conducted using a Multi-Criteria Decision Analysis (MCDA) approach, incorporating socio-economic and environmental indicators such as population density, land use, settlement type, and proximity to rivers. The Analytic Hierarchy Process (AHP) was used to assign weights and develop a flood vulnerability index. The results indicate clear spatial variations in flood hazard and vulnerability across the study area. Larger river systems exhibited delayed but high-magnitude flood responses, while smaller, urbanised catchments showed rapid runoff and increased localised flood risk. Areas with high population density, informal settlements, and inadequate infrastructure were identified as the most vulnerable. The study highlights the importance of integrating hydrological modelling with socio-economic analysis to improve flood risk assessments. The findings provide valuable insights for disaster risk reduction, spatial planning, and climate adaptation strategies in KwaZulu-Natal. It is recommended that future efforts focus on improving data availability, strengthening early warning systems, and incorporating vulnerability assessments into policy and planning frameworks.

Key words: Flood risk, vulnerability, hydrological modelling, hydraulic modelling, socio-economic, flood inundation

ABBREVIATIONS AND ACRONYMS

AHP	Analytic Hierarchy Process
CCAM	Climate Change Adaptation and Mitigation
DEM	Digital Elevation Model
DWS	Department of Water and Sanitation
EM-DAT	Emergency Events Database
FVI	Flood Vulnerability Index
GIS	Geographic Information Systems
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modelling System
HEC-RAS	Hydrologic Engineering Center – River Analysis System
ICMA	Integrated Coastal Management Act
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
KZN	KwaZulu-Natal
MCDA	Multi-Criteria Decision Analysis
NDMC	National Disaster Management Centre
n	Manning’s Roughness Coefficient
NSE	Nash–Sutcliffe Efficiency
PCMP	Provincial Coastal Management Plan
QGIS	Quantum Geographic Information System
SAFFG	South African Flash Flood Guidance System

SCS	Soil Conservation Service
SRTM	Shuttle Radar Topography Mission
Stats SA	Statistics South Africa
UNDRR	United Nations Office for Disaster Risk Reduction
USACE	United States Army Corps of Engineers
UTM	Universal Transverse Mercator
WDNH	Weather- Driven Natural Hazards action
WMA	Water Management Area

KEY DEFINITIONS

Adaptive Capacity

The ability of systems, institutions, humans, and other organisms to adjust to potential damage, take advantage of opportunities, or respond to consequences **(IPCC, 2014)**.

Catchment

An area of land, defined by topographic boundaries, from which precipitation drains through surface runoff into a watercourse or system of watercourses, converging at a common outlet or point **(National Water Act 36 of 1998)**.

Disaster Risk

The potential loss of life, injury, or destroyed or damaged assets that could occur to a system, society, or community over a specified period, determined probabilistically as a function of hazard, exposure, and vulnerability **(UNDRR, 2017)**.

Exposure

The presence of people, infrastructure, housing, production capacities, and other tangible human assets in hazard-prone areas **(IPCC, 2014)**.

Flood

A natural hazard involving the overflow of water onto normally dry land, resulting in damage or risk to people, property, or the environment **(Disaster Management Act 57 of 2002; National Water Act 36 of 1998)**.

Floodplain

The area adjacent to a river or watercourse that is periodically inundated during flood events **(Brooker et al., 2023)**.

Flood Hazard

A potentially damaging physical event related to flooding, including its probability of occurrence, magnitude, depth, velocity, and duration **(IPCC, 2014)**.

Flood Inundation

The submergence of land areas by water as a result of a flood event **(National Water Act 36 of 1998)**

Flood Risk

The combination of the probability of a flood event and its potential adverse consequences for human health, the environment, cultural heritage, and economic activity (**IPCC, 2014**).

Flood vulnerability

Refers to the susceptibility of people, infrastructure, and the environment to flood impacts (**Nasiri, et al., 2016**).

Flood Vulnerability Index (FVI)

A composite indicator used to quantify the relative susceptibility of an area to flooding, based on multiple socio-economic and environmental variables (**Balica et al., 2012**).

Hydraulic Modelling

The simulation of water flow within river channels and floodplains to estimate water levels, velocities, and flood extents (**USACE HEC-RAS Hydraulic Reference Manual**).

Hydrological Modelling

The use of mathematical representations to simulate the movement, distribution, and quality of water within the hydrological cycle, particularly rainfall–runoff processes (**USACE HEC-HMS Technical Reference Manual**).

Resilience

The ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, and recover from the effects of a hazard in a timely and efficient manner (**UNDRR, 2017**).

Return Period

The average interval of time between events of a specified magnitude occurring in any given year, defined as the reciprocal of the annual probability of exceedance; over a long record, the average interval tends toward this figure (**KwaZulu-Natal COGTA, 2019**).

Vulnerability

The propensity or predisposition of a system, community, or population to be adversely affected by hazards, including sensitivity and lack of capacity to cope and adapt (**IPCC, 2014**).

Watercourse

A river or spring, a natural channel in which water flows regularly or intermittently, a wetland, lake, or dam into which or from which water flows (***National Water Act 36 of 1998***).

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CHAPTER 1 INTRODUCTION

1.1 Background

Flooding is widely recognised as the most frequent and destructive natural hazard globally, with significant impacts on human settlements, infrastructure, economies, and ecosystems (Jonkman, 2005; UNDRR, 2019). Flood events occur when rainfall and runoff exceed the capacity of river channels, drainage systems, or low-lying landscapes, resulting in the inundation of normally dry areas. In recent decades, flood risk has intensified due to a combination of climate variability, land use change, and rapid urbanisation, all of which have altered natural hydrological responses and increased human exposure (IPCC, 2022).

River flooding is the dominant form of flood hazard in many regions and is primarily driven by extreme rainfall events, catchment saturation, and runoff accumulation within drainage basins. The transformation of rainfall into runoff is strongly influenced by catchment characteristics such as slope, soil type, vegetation cover, and land use change (Smithers and Schulze, 2002; Hughes et al., 2014). Urbanisation significantly amplifies flood peaks by increasing impervious surfaces, reducing infiltration, and accelerating surface runoff into river systems (Du et al., 2012; McGrane, 2016). As a result, even relatively short-duration, high-intensity rainfall events can produce severe and rapid-onset flooding in urban and peri-urban catchments. Analysis of the Emergency Events Database (EM-DAT) records demonstrates that the frequency of recorded flood disasters has increased markedly since the 1970s. Although improvements in disaster reporting have contributed to this trend, increasing urbanisation, population growth, land-use change and climate variability have also increased human exposure and vulnerability to flooding. Consequently, floods continue to represent one of the most significant natural hazards in terms of both humanitarian impacts and economic losses worldwide.

In coastal catchments, river flooding remains the primary driver of inundation, although coastal processes can influence flood extent in low-lying areas near river mouths. Coastal geomorphology, including floodplains, estuaries, and dune systems, can modify the extent of flood propagation by either constraining or allowing river discharge to spread into surrounding areas (den Heijer et al., 2011). However, in the context of this study, riverine processes remain the dominant mechanism controlling flood generation and spatial distribution, particularly within inland and urban catchments of KwaZulu-Natal, South Africa.

Globally, increasing flood risk is strongly linked to climate change, which is expected to increase the frequency and intensity of extreme rainfall events (IPCC, 2021; Swain et al., 2020). These changes directly affect river systems by increasing peak discharge, reducing return periods of extreme floods, and overwhelming existing drainage infrastructure. In addition, land use transformation and urban expansion continue to increase exposure to flood hazards, particularly in developing regions where informal settlements often develop in high-risk floodplain environments (Salami et al., 2017).

In South Africa, flooding is a recurring and significant natural hazard, particularly in the eastern regions where rainfall is high and catchments are steep. The province of KwaZulu-Natal is especially vulnerable due to its highly variable rainfall, complex topography, and rapidly urbanising river catchments (Kruger and Nxumalo, 2017; Taylor et al., 2021b). River systems in this region respond quickly to rainfall events, producing flash floods that frequently impact urban infrastructure, transport networks, and residential areas. High population density, economic dependence on coastal zones, weak infrastructure, and inadequate disaster preparedness further increase vulnerability (Salami et al., 2017).

The coastal city of Durban and surrounding municipalities have experienced repeated flood disasters linked primarily to extreme rainfall and riverine flooding. The April 2022 floods represent one of the most severe recorded events in the region, causing extensive damage to infrastructure, housing, and livelihoods (Cogta, 2022; SAWS, 2022b; Fitchett, 2023). Historical analyses also indicate that flood events in KwaZulu-Natal have increased in frequency and severity over time, reflecting both climatic and socio-environmental change (Grab and Nash, 2023).

Although coastal influences may affect flood behaviour in low-lying estuarine areas, the most significant flood impacts in KwaZulu-Natal are driven by river catchment processes and intense rainfall events rather than marine-driven inundation. The interaction between steep catchments, urban expansion, and inadequate stormwater infrastructure further exacerbates flood risk. Poor land use planning, informal settlement growth in flood-prone areas, and insufficient maintenance of drainage systems all contribute to increasing vulnerability and exposure (Salami et al., 2017).

Despite the growing frequency of flood disasters, there remains limited spatially detailed information on where the highest flood risks occur, and which communities are most vulnerable within coastal KwaZulu-Natal catchments. Key hydrological and environmental factors such as floodplain extent, river channel capacity, soil infiltration characteristics, and land use change are often not fully integrated into local planning and risk assessment frameworks. This limits the effectiveness of flood mitigation and disaster preparedness strategies.

Flood risk is therefore best understood as the interaction between hazard, exposure, and vulnerability (Birkmann, 2007; Cardona et al., 2012). In river-dominated systems, hazard is primarily controlled by rainfall and catchment hydrology, exposure relates to the spatial distribution of settlements and infrastructure, and vulnerability reflects socio-economic conditions, preparedness, and adaptive capacity. Integrated flood risk assessment approaches that combine hydrological, spatial, and socio-economic data are therefore essential for improving resilience and supporting informed decision-making in flood-prone regions.

This dissertation, thus, aimed to assess flood risk and vulnerability in coastal KwaZulu-Natal, with a primary focus on riverine flooding processes and their interaction with human settlement patterns. The study sought to contribute to improved flood risk understanding and support more effective planning and disaster risk reduction strategies in vulnerable catchments.

1.2 Problem statement and rationale for the study

Floods are the most frequent disaster events globally and are associated with wide-ranging adverse impacts on systems, economies, and people. Global environmental and socio-economic change has contributed to increasing flood vulnerability and heightened exposure of populations to flood hazards (Kundzewicz and Menzel, 2003). These changes are driven by rapid population growth and its associated impacts on land use transformation, urban expansion, resource and food consumption, settlement development, and the modification of terrestrial ecosystems, all of which influence socio-economic and climatic systems and intensify flood risk. Due to global climate change and more frequent extreme precipitation coupled with rising sea levels, flooding events are predicted to increase in intensity, duration and frequency (Swain et al., 2020). Flood events in the coastal regions of KwaZulu-Natal are primarily associated with intense rainfall, storm surges, tropical cyclones, and other extreme or irregular precipitation events, with these hazards being further exacerbated by the impacts of climate change. Apart from natural events which pose risks of flooding, other factors that compound the effects of the flooding in South Africa have been anthropogenic, including inadequate urban planning, weak law enforcement, unregulated urban expansion, and insufficient implementation of relevant legislation (Salami et al., 2017). This contributes to poor service delivery and lack of maintenance and servicing of drainage networks, leading to these flooding events further deepening their effects and magnitude.

In many South African cities, urban planning has historically aimed to restrict development in flood-prone areas; however, this has inadvertently led to the occupation of adjacent open land by

informal settlements. These settlements are occupied due to fertile soils, and accessible water sources, and are often highly vulnerable to flooding due to their proximity to rivers, increasing exposure to flood hazards.

The floods of April 2022, similar to an event in Durban in 1856 (Grab and Nash, 2023), was the most devastating natural disaster on record within KwaZulu-Natal, and research suggests that flooding events have likely doubled over the last 100+ years with 210 flood events from 1900 to 2022 (Grab and Nash, 2023). Informal settlements in sensitive ecosystems, such as rivers and wetlands, and property on coastlines seem most affected by recent flooding events in Durban, KwaZulu-Natal. However, there is limited information on the spatial distribution of flood hazards, the areas most susceptible to flooding, the associated flood risks, the communities, infrastructure, and environmental resources that are most vulnerable. An understanding of catchment hydrology, flood hazard, inundation extent, and flood vulnerability is therefore essential for accurately assessing flood risk associated with extreme weather events.

1.3 Research aim and objectives

The study aimed to assess flood susceptibility, hazard, and vulnerability within selected coastal catchments of KwaZulu-Natal by integrating hydrological and hydraulic modelling with GIS-based spatial analysis in order to identify flood-prone areas, evaluate potential impacts on people, infrastructure, and environmental resources, and support effective flood risk management and mitigation. Furthermore, it looked at how the hydrology of the area plays a role in flood dynamics and the severity of the associated risks. Extreme rainfall and catchment hydrology determine flood susceptibility and inundation extent. The resulting flood characteristics, together with the exposure and vulnerability of communities, infrastructure, and environmental resources, influence the magnitude and spatial distribution of flood impacts.

To achieve the research aim, the following objectives were set out:

Objective 1

Analyse the hydrological characteristics of the selected coastal catchments and quantify rainfall-runoff processes associated with flood generation.

Objective 2

Simulate flood discharges, flood levels, and inundation extents using HEC-HMS and HEC-RAS.

Objective 3

Delineate flood hazard zones and flood inundation extent using GIS-based spatial analysis.

Objective 4

Assess the exposure and vulnerability of communities, infrastructure, land use, and environmental resources located within flood-prone areas.

Objective 5

Evaluate the potential social, environmental, and economic impacts associated with flooding.

Objective 6

Develop recommendations to improve flood risk management, mitigation, and planning within coastal KwaZulu-Natal.

The study adopts an integrated flood risk assessment framework in which hydrological and hydraulic processes are first modelled to determine flood hazard and inundation extent. These outputs are subsequently combined with spatial information on population, infrastructure, land use, and environmental resources to assess flood susceptibility and vulnerability. The resulting analysis provides a basis for evaluating potential flood impacts and informing flood risk management and mitigation strategies within the selected coastal catchments.

1.4 Scope of the research

The study focused on flood-prone coastal areas of KwaZulu-Natal, South Africa, as well as riverine zones within the selected study areas that are densely populated. This was undertaken to assess flood hazards and associated risks linked to flooding events.

1.5 Assumptions and limitations

The following assumptions have been identified within the research:

Data accuracy: The past and future data on flood events, hydrological phenomena, and socio-economic indicators are reliable.

Homogeneity of vulnerability: There is consistent vulnerability against flooding among different sub-groups of both socio-economic status and population demographics within the context of our study area.

Predictability of future climate events: Assume that future climate projections employed for assessing flood risks are a reliable and realistic representation of actual climate phenomena.

The following limitations have been identified for the research study:

Data availability and quality: Insufficient availability or low quality of data, especially in South Africa, can limit the accuracy and breadth of the analysis.

Modelling Uncertainties: uncertainties in the hydrological and hydraulic modelling approaches employed in the depiction of flood activity and their associated influences on coastal settlements.

Social and Economic Climate: Difficulty with assessing the interaction between environmental, social and economic components influencing flood risk (e.g., informal settlements, poverty and urbanisation).

Future Climate Uncertainty: Uncertainties concerning the impacts of future climate changes and the possibility of sea-level rise, the intensity of storm surges and precipitation shifts may also impact the validity of long-term flood risk projections.

1.6 Potential contribution of the research

Improved knowledge: It may enhance our comprehension of the intricate web of natural processes, such as hydrological dynamics involving extreme weather, and human processes such as urbanisation, land use changes and human actions, leading to impacts of flood risks in and around coastal regions.

Risk identification, prioritisation: The research can identify high-flood risk/vulnerability areas to aid policymakers and stakeholders in identifying and prioritising resources and interventions for the effective management of flood risk and adaptation planning.

Providing evidence in decision-making: The research can facilitate decision-making to be established at a much broader level, including planning for local government, national disaster management, and other relevant elements. It can contribute to community resilience to floods by educating the public and local stakeholders, promoting participatory approaches, and supporting community resilience.

Infrastructure planning and design: The findings of this study can inform the planning and implementation of critical infrastructure, including coastal protection structures, stormwater drainage systems, and land use zoning regulations. This can support more effective mitigation of flood risks and enhance the resilience of coastal and riverine environments.

Policy development and implementation: The research can contribute to evidence-based policies and regulations that seek to mitigate vulnerabilities to flooding and improve disaster response and recovery mechanisms, as well as sustainable development, with a focus on those areas in coastal regions.

Climate change adaptation: The research is critical for addressing the increasing occurrence and severity of extreme weather due to climate change and will contribute to the implementation of climate-adaptive infrastructure, which aids in mitigating the consequences of future floods associated with the coast of KwaZulu-Natal.

Building knowledge and skills: Sharing of knowledge and building capacity among researchers, practitioners, policymakers, and communities can contribute to the identification and implementation of innovative collaborative approaches for complex issues of flood risk in coastal communities.

1.7 Structure and outline of the dissertation

Chapter 1: Introduction

Chapter 1 provides the background and context for the study and introduces the research undertaken in this dissertation. It presents the problem statement and the rationale for the study, defines the research aim and objectives, outlines the scope of the research, discusses the underlying assumptions and limitations, and highlights the anticipated contribution of the study to flood risk assessment and management in coastal KwaZulu-Natal.

Chapter 2: Literature review

The literature review has information and knowledge gained from past studies on flood risks and vulnerabilities. It covers how previous studies on flood modelling were conducted and the outcomes. All key literature related to the study is summarised here, and key concepts addressed by critically evaluating existing literature. The literature review covers the history and future of flood events as described in existing literature, give further detail and information on flood risks

and vulnerabilities and how this data has previously been established. It also highlights successes and deficiencies in terms of previous literature.

Chapter 3: Methodology

The methodology section covers the approach taken in terms of methods used. The rivers chosen for the study are discussed, and data availability established. The sections thereafter comprise the data collection and the data analysis, inclusive of programs and software used. Methodological assumptions and limitations are also be discussed here.

Chapter 4: Results and discussion

The results of the study of the hydrological and hydraulic modelling are discussed, with its integration regarding land use planning and topography to establish risks and vulnerabilities. The different flood risk maps and flood hazard maps are presented here. An analysis of the different river systems and ranking in terms of risk and vulnerability categories are presented by means of maps, and/or tables, and/or figures. This section consists of the interpretation and discussion of the data.

Chapter 5: Conclusions and recommendations

This chapter is a summary of how the study identified areas most susceptible to flood impacts and assessed the risks and vulnerabilities of coastal KwaZulu-Natal. It ties up how the severity of risks and vulnerability analysed during the study is beneficial in providing information to relevant parties and how the research fits into the bigger information reserve regarding floods and disaster management. It highlights how this study fits in with the key literature that was addressed in the literature review chapter. This chapter consists of recommendations for further research.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Floods have consistently been identified as one of the most dominant natural hazards worldwide, both in terms of their frequency of occurrence and the number of people affected. Data compiled by the Emergency Events Database (EM-DAT) indicate that floods are among the most frequently recorded natural disasters globally and have affected more people than any other natural hazard over recent decades (EM-DAT, 2026). Although improvements in disaster reporting have contributed to the increasing number of recorded flood events, the growing impacts of flooding are also associated with population growth, rapid urbanisation, land-use change and climate variability, which collectively increase flood exposure and the vulnerability of communities. These trends emphasise that flooding is not solely a hydrological phenomenon but a complex interaction between natural processes and human systems, resulting in significant social, economic and environmental consequences.

Given the increasing global significance of flood disasters, a comprehensive understanding of the factors that influence flood risk and vulnerability is essential for developing effective flood risk management strategies. This chapter critically reviews the existing literature on flood risk and vulnerability from a global perspective before examining studies undertaken within Africa, Southern Africa and, more specifically, South Africa and KwaZulu-Natal. The review compares previous research approaches, modelling techniques and vulnerability assessment frameworks, highlighting their strengths, limitations and applicability to the present study. Emphasis is placed on understanding the hydrological and socio-economic processes that influence flood risk and how these have been investigated in previous studies, thereby establishing the knowledge gaps addressed by this research.

2.2 Global overview: Flood risk assessments and Vulnerability Analysis

Floods are among the most frequent and destructive natural hazards worldwide, posing significant threats to human life, infrastructure, economic development and environmental sustainability (Balica et al., 2013). Their increasing frequency and severity, driven by rapid urbanisation, land-use change and climate variability, have intensified the need for comprehensive flood risk assessments that consider not only the physical characteristics of flooding but also the vulnerability of exposed communities (UNDRR, 2022). As a result, flood risk assessment has

become a fundamental component of disaster risk reduction and sustainable development planning.

Flooding occurs through a range of hydrological processes and is generally classified according to the rate at which floodwaters develop. Rapid-onset floods, including flash floods, storm surges, tropical cyclone-induced flooding, river overtopping, dam failures and flooding resulting from intense rainfall, develop quickly, often within 48 hours, leaving limited time for warning and evacuation (Davis-Reddy & Vincent, 2017). In contrast, slow-onset floods develop gradually following prolonged periods of rainfall, resulting in the progressive inundation of floodplains and low-lying areas over several days or weeks (Davis-Reddy & Vincent, 2017). Coastal regions are particularly vulnerable because flood hazards may result from the combined effects of heavy rainfall, river flooding and storm surges associated with tropical cyclones, cut-off low-pressure systems and other severe weather events. The interaction of these hydrometeorological processes can substantially increase flood magnitude and the extent of inundation, particularly within coastal and riverine environments.

Although the terms hazard, exposure, vulnerability and risk are frequently used interchangeably within the flood literature, they represent distinct components of the flood risk framework (UNDRR, 2022). Flood hazard refers to the physical characteristics of a flood event, including its magnitude, depth, velocity and spatial extent. Exposure describes the people, infrastructure, ecosystems and economic assets located within areas that may be affected by flooding. Vulnerability refers to the susceptibility of these exposed elements to flood impacts and is influenced by a range of physical, social, economic and institutional factors, including settlement characteristics, infrastructure quality, poverty, governance and disaster preparedness (Nasiri et al., 2016). Flood risk is therefore determined by the interaction between flood hazard, exposure and vulnerability, reflecting the likelihood and severity of adverse consequences resulting from flood events (Koks et al., 2014). Understanding these relationships is essential because effective flood risk management requires not only reducing flood hazards but also minimising exposure and addressing the underlying drivers of vulnerability through appropriate planning, infrastructure development and disaster risk reduction strategies.

The consequences of flooding extend well beyond the immediate impacts of inundation. Flood events result in loss of life, displacement of communities, damage to infrastructure, disruption of economic activities, degradation of agricultural land and adverse environmental impacts (Balica et al., 2013). However, the severity of these impacts varies considerably between countries and regions because flood risk is strongly influenced by differences in levels of development,

governance capacity, infrastructure, land-use planning and disaster risk management practices. Developing countries are particularly vulnerable owing to rapid urbanisation, high population densities, informal settlement expansion, limited financial resources and inadequate infrastructure (Dewan, 2013). These factors often increase both exposure and vulnerability, resulting in disproportionately severe flood impacts compared with more developed regions.

Advances in remote sensing, Geographic Information Systems (GIS), hydrological and hydraulic modelling, and the increasing availability of high-resolution spatial datasets have significantly improved the ability to assess flood hazard, vulnerability and risk at regional and local scales. Nevertheless, the availability and quality of spatial data, technical capacity and institutional resources vary considerably between countries, influencing the methods adopted for flood risk assessment and the effectiveness of disaster risk management programmes. Consequently, flood risk assessments must be tailored to the specific physical, socio-economic and institutional characteristics of individual regions to support informed decision-making and effective flood risk reduction.

2.2.1 Flood risks and vulnerability in Europe and North/South America

Flood risk is widely recognised as a function of three interrelated components: flood hazard, exposure, and vulnerability, rather than the flood hazard alone (Barredo et al., 2007; Koks et al., 2014). Consequently, contemporary flood risk assessments have shifted from traditional hazard-based approaches towards integrated frameworks that combine hydrological processes with socio-economic and environmental characteristics to provide a more comprehensive understanding of flood risk. This transition recognises that communities exposed to the same flood event may experience substantially different impacts depending on their levels of vulnerability, the distribution of infrastructure and assets, land-use patterns, and the capacity of communities to prepare for and recover from flood events (Koks et al., 2014; Nasiri et al., 2016).

One of the earliest large-scale applications of this integrated approach was undertaken by Barredo *et al.* (2007) through the development of a pan-European flood risk assessment framework for the European Union. Unlike conventional flood hazard studies that focus primarily on hydrological characteristics such as discharge, flood depth or inundation extent, the framework incorporated flood hazard, exposure and vulnerability within a single GIS-based spatial database to produce harmonised flood risk maps across multiple countries. The study integrated datasets describing population density, land use, economic activity and flood hazard to calculate a

standardised flood risk index at both a 1 km grid resolution and the NUTS 3 administrative level. This represented a significant advancement over traditional flood mapping because it recognised that flood risk is influenced not only by the physical characteristics of flooding but also by the distribution of people, infrastructure and economic assets within flood-prone areas (Barredo et al., 2007).

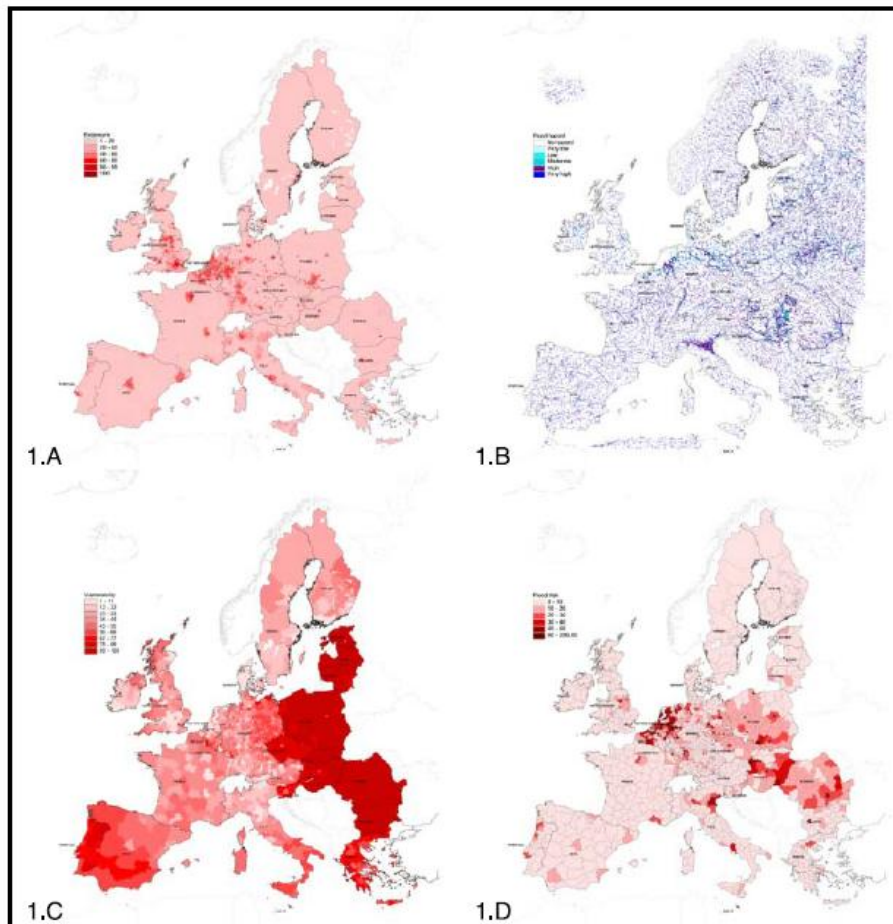


Figure 1-1 Flood risk assessment for the European Union, Bulgaria and Romania. 1.A) Flood exposure, 1.B) Flood hazard, 1.C) Flood vulnerability, and 1.D) Flood risk at NUTS 3 level (source: Barredo et al., 2007).

The principal strength of the approach proposed by Barredo *et al.* (2007) lies in its ability to integrate multiple spatial datasets within a consistent GIS framework, thereby allowing flood risk to be assessed over large geographical areas using standardised criteria. Such an approach facilitates regional planning, supports policy development and enables comparisons of flood risk across administrative boundaries. The development of a harmonised European flood risk database subsequently provided an important scientific foundation for the implementation of the

European Floods Directive, illustrating the growing importance of spatially explicit flood risk information for disaster risk reduction and land-use planning (Barredo et al., 2007).

Despite these advantages, the methodology adopted by Barredo et al. (2007) has several limitations. The study was conducted at continental and regional scales using relatively coarse spatial datasets, including a 1 km Digital Elevation Model (DEM), which limits its ability to represent local topographic variability and detailed flood behaviour within individual catchments. Consequently, the approach is better suited to strategic planning than detailed flood prediction at catchment or municipal scales. Furthermore, the flood hazard component was derived from existing flood hazard maps rather than physically based hydrological and hydraulic simulations. As a result, the framework did not explicitly represent rainfall-runoff processes, channel hydraulics, flood wave propagation or catchment-specific hydrological responses that influence flood inundation during individual flood events. The authors also acknowledged that the availability, consistency and spatial resolution of georeferenced datasets remained significant constraints and recommended that future assessments incorporate higher-resolution spatial data as these become available (Barredo et al., 2007).

Subsequent studies have expanded upon the conceptual framework proposed by Barredo *et al.* (2007) by integrating physically based hydrological and hydraulic models with GIS-based vulnerability assessments. For example, Saksena *et al.* (2019) demonstrated that coupling surface hydrology, subsurface hydrology and river hydraulics provides a more realistic representation of flood inundation dynamics than approaches relying solely on spatial overlay techniques. Similarly, Koks *et al.* (2014) argued that flood risk assessments should simultaneously evaluate hazard, exposure and social vulnerability because hazard information alone does not adequately explain the distribution of flood losses. Likewise, Nasiri *et al.* (2016) concluded that comprehensive flood vulnerability assessments require the integration of physical, social, economic and environmental indicators to accurately represent community vulnerability. Collectively, these studies demonstrate an evolution from broad-scale spatial risk mapping towards integrated modelling frameworks capable of representing both the physical processes that generate flooding and the socio-economic factors that influence flood impacts.

The increasing availability of Geographic Information Systems (GIS), remote sensing products and high-resolution spatial datasets has further transformed flood risk assessment by enabling the integration of hydrological modelling outputs with exposure and vulnerability indicators. Rather than simply identifying where flooding may occur, modern flood risk assessments seek to determine which populations, infrastructure, land uses and environmental resources are most

likely to be affected, thereby supporting risk-informed planning and disaster management (Koks et al., 2014; Nasiri et al., 2016). This shift reflects international recognition that effective flood risk management requires a multidisciplinary approach that combines engineering analyses with socio-economic and environmental considerations. The principal strength of GIS lies in its ability to visualise complex spatial relationships and communicate flood risk information to planners and decision-makers. Nevertheless, GIS analyses remain dependent upon the quality and spatial resolution of the underlying datasets. Consequently, uncertainty associated with DEM resolution, land-use classification and hydrological inputs propagates directly into flood hazard maps (Nasiri et al., 2016).

Although the framework developed by Barredo *et al.* (2007) provides a valuable conceptual basis for integrated flood risk assessment, relatively few studies have applied similar integrated methodologies within South African coastal catchments, particularly those characterised by rapidly expanding urban development and highly variable rainfall patterns. Existing South African studies have frequently focused either on hydrological modelling or on GIS-based flood susceptibility mapping, with fewer investigations combining hydrological modelling, hydraulic simulation and vulnerability assessment within a single analytical framework. This represents an important knowledge gap because the interaction between flood hazard, exposure and vulnerability varies considerably between catchments and requires locally calibrated assessments to support flood risk management.

The present study addresses this gap by integrating HEC-HMS hydrological modelling, HEC-RAS hydraulic simulations and GIS-based spatial analysis to evaluate flood susceptibility, flood hazard, inundation extent and flood vulnerability within selected coastal catchments of KwaZulu-Natal. Unlike the continental-scale assessment developed by Barredo *et al.* (2007), this research adopts a catchment-scale approach that incorporates locally calibrated rainfall and streamflow data to simulate flood behaviour before evaluating the exposure and vulnerability of communities, infrastructure, land use and environmental resources. Consequently, the study extends the principles of integrated flood risk assessment by providing a higher-resolution evaluation of flood risk that is directly applicable to local planning, disaster risk reduction and flood risk management within coastal KwaZulu-Natal.

2.2.2 Flood risks and vulnerability in Asia

Urbanisation is widely recognised as one of the primary anthropogenic factors influencing flood generation, particularly within rapidly developing catchments where natural land cover is progressively replaced by impervious surfaces. The expansion of urban areas alters natural hydrological processes by reducing infiltration, increasing surface runoff, shortening catchment response times, and increasing peak discharges during storm events (Du et al., 2012). Consequently, many recent flood studies have integrated hydrological modelling with land-use change analysis to improve understanding of how urban development influences flood susceptibility and flood behaviour.

A range of hydrological modelling approaches have been employed to investigate the relationship between urbanisation and flood dynamics. Physically based distributed models, including MIKE SHE, SWAT, HEC-HMS, DHSVM, L-THIA and CELTHYM, have been widely applied because they explicitly simulate rainfall-runoff processes and enable the evaluation of land-use change scenarios (Du et al., 2012). While these models share a common objective of representing catchment hydrological processes, they differ considerably in their complexity, data requirements, spatial resolution and computational demands. Highly distributed models such as MIKE SHE require extensive datasets describing groundwater, evapotranspiration and soil processes, whereas HEC-HMS provides a more practical alternative where data availability is limited, making it particularly suitable for catchment-scale flood studies in developing countries.

Hydrological modelling has become one of the most widely applied approaches for simulating rainfall-runoff processes and predicting flood generation at catchment scale. Models such as HEC-HMS, SWAT, MIKE SHE, TOPMODEL and DHSVM are commonly used to estimate runoff volumes, peak discharges and hydrograph characteristics that subsequently serve as inputs for hydraulic flood modelling (Ramírez, 2000; Du et al., 2012).

Among these models, the Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS) has been extensively applied because of its flexibility, relatively modest data requirements and ability to simulate catchments of varying size and complexity (USACE, 2022). The model incorporates several rainfall-loss methods, transform methods, routing algorithms and baseflow models, allowing users to select techniques appropriate to local hydrological conditions. Numerous studies have successfully applied HEC-HMS to flood forecasting, flood susceptibility assessment and design flood estimation (Du et al., 2012; Saksena et al., 2019).

Despite these advantages, HEC-HMS has several limitations. Model accuracy depends heavily on the quality of rainfall observations, streamflow records and parameter calibration. Parameters such as Curve Number, initial abstraction, lag time and routing coefficients introduce uncertainty because they are frequently estimated rather than directly measured (Ramírez, 2000). Furthermore, HEC-HMS simulates runoff generation but does not represent floodplain hydraulics or inundation processes, making hydraulic modelling necessary for comprehensive flood risk assessment.

These strengths and limitations are directly relevant to the present study, which employs HEC-HMS to simulate runoff generation within selected coastal catchments before transferring simulated hydrographs to HEC-RAS for hydraulic analysis.

The Hydrologic Engineering Center River Analysis System (HEC-RAS) has become one of the most widely used hydraulic models because it supports one-dimensional and two-dimensional flow simulations while integrating readily with Geographic Information Systems. Previous studies have demonstrated that coupling HEC-HMS with HEC-RAS provides significantly improved flood hazard representation because hydrological outputs can be translated directly into spatial flood inundation maps (Saksena et al., 2019).

However, hydraulic simulations remain sensitive to Digital Elevation Model resolution, channel geometry, Manning's roughness coefficients, bridge representations and boundary conditions. Errors in these datasets may substantially influence predicted flood depths and inundation extents (Saksena et al., 2019).

Du *et al.* (2012) demonstrated the advantages of integrating hydrological modelling with land-use change simulation by coupling HEC-HMS with a Cellular Automata-Markov (CA-Markov) model to investigate the hydrological impacts of urbanisation within the Qinhuai River Basin in China. Unlike conventional flood modelling studies that evaluate existing catchment conditions, their methodology incorporated historical satellite imagery to quantify land-use changes between 1988 and 2009 and subsequently simulated future urbanisation scenarios. This integrated approach enabled the direct assessment of how increasing impervious surfaces influence runoff generation, peak discharge and flood volume under different development scenarios.

The study utilised multiple spatial and hydrological datasets, including Landsat satellite imagery, Digital Elevation Models (DEMs), soil maps, rainfall records from seven-gauge stations, and streamflow observations from two gauging stations. Hydrological simulations were undertaken using HEC-HMS, with rainfall losses estimated using the Soil Conservation Service Curve

Number (SCS-CN) method, direct runoff simulated using the Clark Unit Hydrograph, channel routing represented using the Muskingum routing method, and baseflow estimated using a recession model (Du et al., 2012).

The principal strength of the study lies in its integration of hydrological modelling with dynamic land-use prediction. By combining HEC-HMS with the CA-Markov model, Du *et al.* (2012) were able to isolate the hydrological effects of urbanisation from other environmental changes, providing valuable insights into the relationship between impervious surface expansion and flood response. The incorporation of satellite-derived land-use information also strengthened the reliability of the modelling framework by allowing changes in urban development to be explicitly represented within the simulations. Such an approach demonstrates the importance of integrating remote sensing and GIS with hydrological models to evaluate future flood risk under changing land-use conditions.

The results demonstrated that urbanisation had a relatively limited influence on long-term annual runoff but substantially increased peak discharge and flood volume during individual flood events. Sensitivity analysis further revealed an approximately linear relationship between increasing impervious surface area and peak discharge, with smaller flood events exhibiting greater sensitivity to urbanisation than larger events (Du et al., 2012). These findings are consistent with previous hydrological studies, which have shown that urban development primarily influences the magnitude and timing of storm runoff rather than annual water yields (Ramírez, 2000). Similarly, Jewitt *et al.* (2015) reported that changes in land cover and catchment characteristics within KwaZulu-Natal significantly influence runoff generation and streamflow responses, particularly during high-intensity rainfall events.

Despite these strengths, several methodological limitations should be acknowledged. The study assumed that future urban growth would continue according to historical development trends represented by the CA-Markov model. Such assumptions may not adequately account for future planning policies, economic development, environmental regulations or climate change, all of which influence patterns of urban expansion. Furthermore, although HEC-HMS provides a robust representation of rainfall-runoff processes, it does not explicitly simulate two-dimensional floodplain hydraulics or spatial flood inundation. Consequently, while the model effectively estimates runoff generation and peak discharge, additional hydraulic modelling is required to predict flood depths, inundation extent and flood hazard distribution. This limitation has been highlighted by Saksena *et al.* (2019), who demonstrated that integrating hydrological simulations

with hydraulic modelling provides a more comprehensive representation of flood behaviour than hydrological modelling alone.

The findings of Du *et al.* (2012) are particularly relevant to rapidly urbanising regions where increasing impervious surfaces are expected to intensify flood hazards. However, the transferability of these findings to South African catchments should be considered with caution because differences in climate, rainfall characteristics, topography, land-use patterns and hydrological response influence flood generation. Within KwaZulu-Natal, for example, steep catchments, highly variable rainfall, and rapidly expanding urban settlements produce flood mechanisms that differ from those observed in eastern China (Jewitt *et al.* 2015; Mather, Garland & Stretch, 2019). Consequently, locally calibrated hydrological models remain essential for accurately representing flood behaviour within South African catchments.

Although numerous international studies have demonstrated the influence of urbanisation on flood hydrology, relatively few investigations have integrated hydrological modelling, hydraulic simulations and spatial flood vulnerability assessment within coastal catchments of KwaZulu-Natal. Existing studies have frequently focused on either land-use change, hydrological response or flood susceptibility independently, with limited integration of these components within a single modelling framework. The present study addresses this gap by integrating HEC-HMS hydrological modelling, HEC-RAS hydraulic simulations and GIS-based spatial analysis to evaluate how hydrological processes influence flood susceptibility, inundation extent and flood vulnerability across selected coastal catchments of KwaZulu-Natal. Unlike Du *et al.* (2012), which primarily examined the hydrological effects of urbanisation, this research extends the analysis by integrating flood hazard modelling with spatial assessments of exposure and vulnerability to support flood risk management and planning.

2.2.3 Flood risks and vulnerability in Africa

Flooding remains one of the most significant hydro-meteorological hazards affecting the African continent, where increasing urbanisation, population growth, climate variability and inadequate infrastructure have collectively increased both flood frequency and flood impacts (Salami *et al.*, 2017). Unlike many developed countries, where flood risk management is supported by extensive hydrological monitoring networks and long-term flood databases, many African countries continue to face significant limitations in hydrological data availability, flood monitoring infrastructure and institutional capacity. Consequently, flood risk assessments across Africa have increasingly

adopted integrated approaches that combine physical flood hazards with socio-economic vulnerability in order to better understand the factors contributing to flood disasters.

Although floods are primarily initiated by extreme rainfall and river overflow, numerous African studies demonstrate that the severity of flood impacts is largely determined by the interaction between natural processes and human activities. Rapid urbanisation, informal settlement expansion, inadequate stormwater infrastructure, poor solid waste management and unplanned development within floodplains have consistently been identified as major contributors to increasing flood risk across African cities (Akukwe, 2014; Salami et al., 2017). These findings reflect a growing consensus that flood disasters are rarely the result of hydrological processes alone but rather emerge from the combined influence of flood hazards, exposure and vulnerability.

Salami *et al.* (2017) argue that many existing flood risk assessments within Africa have traditionally focused on the physical characteristics of flooding while giving comparatively less attention to the socio-economic factors that influence vulnerability. Their review of flood vulnerability assessment frameworks highlighted that effective flood risk management requires a multidisciplinary approach integrating physical, social, economic, institutional and environmental dimensions of vulnerability. Drawing on established frameworks such as the Pressure and Release (PAR) model, the Bogardi-Birkmann-Cardona (BBC) framework and the Climate Change and Urban Vulnerability in Africa (CLUVA) framework, the authors proposed an integrated conceptual model specifically designed for flood risk assessment within African cities. Unlike earlier approaches that primarily quantified flood hazards, this framework recognised that vulnerability is dynamic and is strongly influenced by governance, institutional capacity, poverty, social inequalities, cultural factors and community resilience.

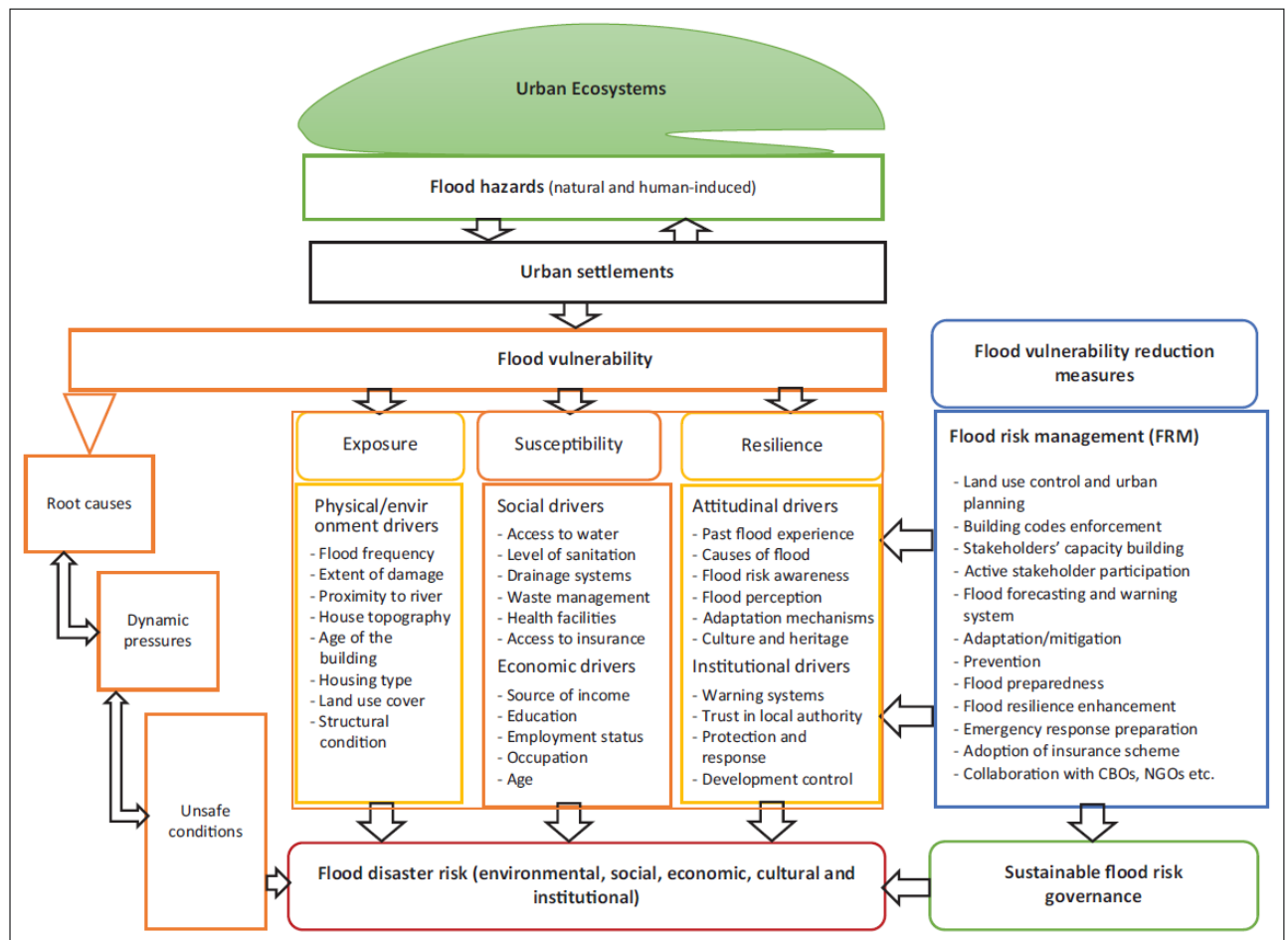


Figure 2-1: The flood vulnerability assessment: conceptual framework for African cities (Source Salami et al., 2017; adopted from Birkmann (2006a); Chambers (1989); Jean-Baptiste et al. (2013); Vojinović (2015) and Wisner et al. (2004).

A major strength of the framework proposed by Salami et al. (2017) is its recognition that flood vulnerability cannot be adequately represented using physical indicators alone. Instead, the study advocates participatory assessment methods that combine quantitative spatial information with qualitative information describing community perceptions, coping capacity and local knowledge. This represents a significant advancement over conventional flood hazard mapping because it acknowledges that communities experiencing similar flood hazards may experience substantially different impacts depending on their social and economic characteristics. Similar conclusions were reached by Nasiri, Yusof and Ali (2016), who emphasised that comprehensive flood vulnerability assessments require the integration of physical, social, economic and environmental indicators rather than relying exclusively on hydrological or hydraulic analyses.

Despite these contributions, the framework proposed by Salami *et al.* (2017) remains primarily conceptual. Although the study successfully synthesises existing vulnerability assessment methodologies, it does not incorporate physically based hydrological or hydraulic simulations capable of quantifying flood depths, velocities or inundation extents. Consequently, the framework provides valuable guidance for identifying vulnerable populations but offers limited capability for predicting the spatial distribution and magnitude of flood hazards. Similar limitations have been identified by Koks *et al.* (2015), who argued that hazard, exposure and vulnerability should be assessed simultaneously because evaluating vulnerability independently of flood hazard provides only a partial understanding of flood risk.

The challenges associated with urban flood risk are further illustrated by Akukwe (2014), who investigated the causes of recurrent flooding within Port Harcourt, Nigeria. Unlike Salami *et al.* (2017), whose work focused primarily on conceptual vulnerability assessment, Akukwe (2014) employed household questionnaires, interviews and field observations to investigate community perceptions of flood causation and identify the principal drivers of flooding. The study demonstrated that inadequate drainage infrastructure, blocked drainage systems, rapid urbanisation, increasing impervious surfaces and inappropriate land-use planning were considered more significant contributors to flooding than rainfall alone. More than 70% of respondents attributed flood occurrence primarily to anthropogenic factors, emphasising that poor governance and ineffective urban planning substantially increase flood risk within rapidly developing African cities.

Table 1-1: Respondents identified causes of flooding in Port Harcourt metropolis (Source: Akukwe, 2014)

Cause of flooding	No. of Responses	Percentage (%)	Rank
Absence of/ inadequate drainage facilities	102	15.74	1
Heavy rainfall	101	15.59	2
Blocked drainage systems	97	14.97	3
Impervious surfaces	93	14.35	4
Inappropriate town planning/ uncontrolled urbanisation	79	12.19	5
Poor drainage network	77	11.88	6
Flat terrain	46	7.10	7
Climate change	29	4.48	8
Unplanned development on flood plains	24	3.70	9
Total	648	100.00	

Although the participatory methodology adopted by Akukwe (2014) provides valuable insight into local perceptions of flood causation, it also illustrates the limitations of perception-based flood assessments. Household surveys provide important socio-economic information but cannot independently quantify flood hazard characteristics such as flood extent, water depth or flow velocity. Consequently, while the study successfully identifies the perceived causes of flooding and supports improved urban planning recommendations, it cannot accurately simulate flood behaviour or evaluate how future hydrological conditions may influence flood risk. This limitation highlights the importance of integrating community-based assessments with physically based hydrological and hydraulic modelling approaches.

Collectively, the studies by Salami *et al.* (2017) and Akukwe (2014) demonstrate an important evolution in African flood risk research. Earlier investigations often concentrated on identifying the physical causes of flooding or documenting historical flood impacts, whereas more recent studies increasingly recognise that effective flood risk assessment requires simultaneous consideration of flood hazards, exposure, vulnerability and institutional capacity. Nevertheless, significant methodological challenges remain. Many African flood studies continue to rely on conceptual frameworks, household surveys or GIS-based vulnerability mapping without incorporating hydrological modelling capable of representing rainfall-runoff processes or hydraulic simulations capable of predicting flood inundation. Furthermore, limited hydrological datasets, sparse monitoring networks and inconsistent spatial information continue to constrain the accuracy of flood risk assessments across much of the continent (Salami *et al.*, 2017).

The increasing availability of Geographic Information Systems (GIS), remote sensing technologies and physically based hydrological models provides new opportunities to overcome these limitations. Studies integrating hydrological modelling with GIS-based spatial analysis have demonstrated improved capability for predicting flood hazard and evaluating the exposure of communities, infrastructure and environmental resources (Du *et al.*, 2012; Saksena *et al.*, 2019). However, relatively few African investigations have successfully integrated hydrological modelling, hydraulic simulation and vulnerability assessment within a single analytical framework, particularly within coastal catchments characterised by complex hydrological responses and rapid urbanisation.

These limitations are particularly relevant within South Africa, where flood hazards are influenced by highly variable rainfall, steep catchments, rapidly expanding urban development and increasing climate variability. Although several South African studies have investigated flood susceptibility, hydrological modelling or flood vulnerability independently, comparatively few have

combined HEC-HMS hydrological modelling, HEC-RAS hydraulic simulations and GIS-based vulnerability assessment to evaluate flood risk within multiple coastal catchments. The present study addresses this gap by integrating these complementary approaches to assess flood susceptibility, inundation extent, exposure and vulnerability across selected coastal catchments of KwaZulu-Natal. In doing so, the study extends existing African flood risk research beyond conceptual vulnerability assessment by providing a physically based and spatially explicit evaluation of flood risk that directly supports disaster risk reduction, spatial planning and flood risk management.

2.2.4 Flood risks and vulnerability in South Africa

Southern Africa is among the regions most vulnerable to hydroclimatic extremes, with flood events occurring with increasing frequency and intensity, resulting in substantial socio-economic, environmental and infrastructural impacts. The region experiences a wide range of flood-generating mechanisms, including tropical cyclones, cut-off low-pressure systems, intense convective thunderstorms and prolonged rainfall associated with frontal systems (Davis-Reddy & Vincent, 2017). Although these meteorological drivers initiate flooding, numerous studies have demonstrated that the magnitude of flood impacts is strongly influenced by catchment characteristics, land-use change, exposure, and the vulnerability of communities and infrastructure. Consequently, contemporary flood risk assessments increasingly recognise that flood disasters result from the combined influence of hydrological hazards and socio-economic vulnerability rather than extreme rainfall alone (Koks et al., 2015; Nasiri et al., 2016).

The increasing frequency of severe flood events across Southern Africa has highlighted the need for integrated flood risk assessment frameworks that combine hydrological modelling with spatial vulnerability analysis. Davis-Reddy and Vincent (2017) argue that while tropical cyclones and intense rainfall events remain the principal drivers of flooding in Southern Africa, the severity of flood impacts is substantially exacerbated by inadequate stormwater infrastructure, poor land-use planning, settlement expansion within floodplains, environmental degradation and limited disaster preparedness. Similar conclusions have been reported internationally, where vulnerability and exposure have been shown to influence flood impacts as much as the magnitude of the flood hazard itself (Koks et al., 2015). These findings emphasise that effective flood risk management requires multidisciplinary approaches that simultaneously evaluate flood hazard, exposure and vulnerability.

Historically, Southern Africa has experienced several catastrophic flood events that have shaped flood risk management policy within the region. The 1987 floods in KwaZulu-Natal resulted in widespread destruction of transport infrastructure, extensive displacement of communities and the loss of approximately 388 lives (Grobler, 2003). More recently, Cyclone Eline in 2000 caused severe flooding across Mozambique, Zimbabwe, Botswana and South Africa, resulting in substantial economic losses and demonstrating the transboundary nature of flood hazards within Southern Africa (Davis-Reddy & Vincent, 2017). These events highlighted the limitations of reactive disaster management approaches and reinforced the importance of proactive flood risk assessment, improved early warning systems and integrated catchment management.

Recent climate projections suggest that flood risk within Southern Africa is likely to increase due to changing rainfall patterns, increasing rainfall intensity, rapid urbanisation and continued expansion of infrastructure into flood-prone areas (Davis-Reddy & Vincent, 2017). Climate-sensitive sectors, including agriculture, water resources, transport infrastructure and coastal settlements, are expected to experience increasing exposure to flood hazards. However, Davis-Reddy and Vincent (2017) emphasise that climate change should not be viewed as the sole driver of increasing flood risk. Rather, flood impacts arise from the combined influence of climatic hazards, exposure, vulnerability and the adaptive capacity of affected communities, highlighting the importance of incorporating socio-economic factors into flood risk assessments.

While regional assessments provide valuable insight into the drivers of flood risk, they often rely on broad-scale climate analyses and historical flood records that provide limited information regarding flood behaviour at individual catchment scales. Consequently, recent South African research has increasingly incorporated Geographic Information Systems (GIS), remote sensing and hydrological modelling to improve the spatial representation of flood hazards and support local flood risk management.

For example, Nhlamo *et al.* (2025) developed drought and flood risk maps for the Olifants River Basin using a GIS-based Multi-Criteria Decision Analysis (MCDA) framework combined with the Analytic Hierarchy Process (AHP). Their study integrated rainfall, topography, slope, land use, soil texture, proximity to rivers and flow accumulation to identify flood-prone areas and demonstrated the value of GIS for regional-scale flood susceptibility mapping. However, because the methodology relied primarily on weighted spatial overlays rather than physically based hydrological and hydraulic simulations, the resulting flood maps represent relative flood susceptibility rather than dynamic flood inundation. Similar limitations have been identified by Nasiri *et al.* (2016), who noted that GIS-based vulnerability assessments provide valuable spatial

information but cannot independently simulate flood behaviour or predict flood depths, velocities and flood extents.

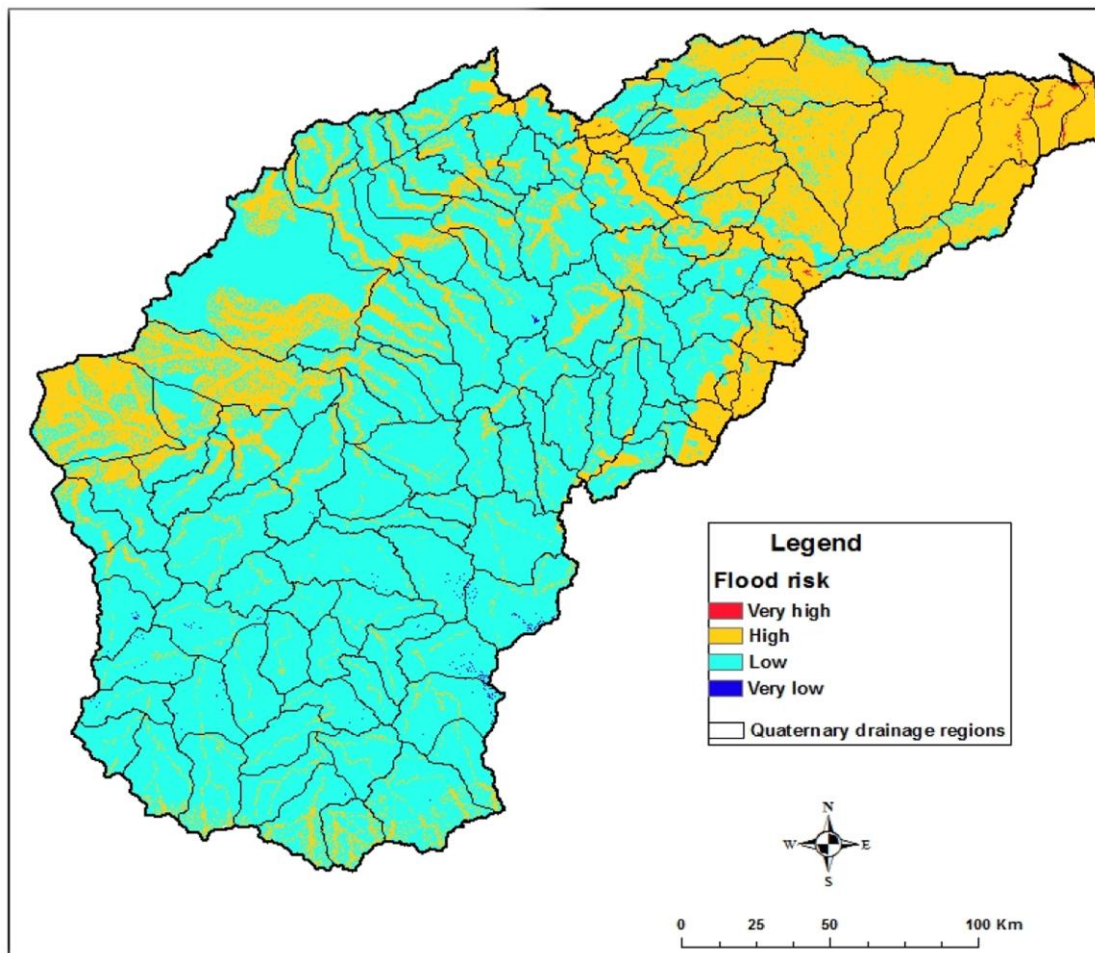


Figure 3-1: Flood risk areas in the Olifants River Basin. (source: Nhamo et al., 2025).

Recent flood vulnerability assessments increasingly employ Multi-Criteria Decision Analysis (MCDA) combined with the Analytic Hierarchy Process (AHP) to integrate multiple physical and socio-economic indicators within a single vulnerability index (Nasiri et al., 2016). These methods are particularly valuable where vulnerability depends upon numerous interacting variables that cannot easily be measured using hydrological models alone. The principal advantage of AHP is that it provides a transparent and systematic method for assigning relative importance to different vulnerability indicators through pairwise comparisons while evaluating the consistency of expert judgement. Consequently, AHP has become one of the most frequently applied weighting techniques in GIS-based flood vulnerability studies (Nasiri et al., 2016). However, AHP also has limitations. Indicator weights remain dependent upon expert judgement and may therefore

introduce subjectivity into vulnerability assessments. Furthermore, MCDA techniques identify relative vulnerability rather than directly simulating flood processes, meaning that they should ideally be integrated with hydrological and hydraulic modelling to provide comprehensive flood risk assessments. The present study adopts this integrated approach by combining physically based flood hazard modelling with AHP-based vulnerability assessment.

In contrast, Smithers and Schulze (2002) focused on improving flood estimation procedures within South Africa through the refinement of hydrological design methods. Their comprehensive review highlighted significant limitations in South African design flood estimation, including uncertainties associated with rainfall estimation, Areal Reduction Factors (ARF), catchment lag estimation and regional flood frequency analysis. The authors advocated continuous simulation techniques, improved regionalisation methods and enhanced hydrological datasets to improve the reliability of design flood estimation. Although their work was primarily intended for engineering design, it provides the hydrological foundation upon which physically based flood modelling studies have subsequently been developed.

Within KwaZulu-Natal, hydrological investigations have similarly demonstrated the importance of understanding catchment-specific responses to extreme rainfall. Jewitt *et al.* (2015) showed that the province's highly variable rainfall patterns, steep catchment gradients and rapidly changing land use create complex hydrological responses that cannot be adequately represented using generalised regional parameters. Their work emphasised that locally calibrated hydrological models are essential for accurately simulating runoff generation, peak discharge and flood response, particularly in rapidly urbanising coastal catchments.

More recently, the devastating April 2022 floods have become the focus of several studies that collectively demonstrate the importance of integrating meteorological analyses, hydrological modelling and vulnerability assessments. Thoithi *et al.* (2023) investigated the atmospheric processes responsible for the event and demonstrated that the unprecedented rainfall resulted from the interaction of a cut-off low-pressure system, a mesoscale convective system and a coastal meso-low. Their findings highlight the complexity of the meteorological processes responsible for extreme rainfall events and emphasise the need for hydrological models capable of accurately representing rainfall-runoff responses under extreme conditions. However, while the study provided valuable insight into the meteorological drivers of the disaster, it did not extend its analysis to catchment hydrology, flood inundation modelling or spatial vulnerability assessment.

Complementing this work, Grab and Nash (2023) reconstructed the historical chronology of flooding in KwaZulu-Natal from 1836 to 2022 and demonstrated that the province has experienced

a marked increase in the frequency and impacts of major flood events over the past century. Their analysis identified more than 250 documented floods and concluded that the April 2022 event represented the most severe flood disaster recorded in KwaZulu-Natal in terms of fatalities, infrastructure damage and socio-economic losses. Unlike meteorological studies that focus on the physical drivers of flooding, Grab and Nash (2023) placed the April 2022 disaster within its historical context, illustrating that increasing exposure, urbanisation and development within flood-prone areas have substantially amplified flood impacts over time. Nevertheless, the study remained primarily historical and descriptive, highlighting long-term flood trends rather than quantitatively modelling flood behaviour or assessing flood susceptibility within individual catchments.

Similarly, Govender (2023) demonstrated that the exceptional impacts of the April 2022 floods reflected not only the unprecedented rainfall but also rapid urbanisation, ageing stormwater infrastructure, informal settlement expansion and increasing exposure of communities and critical infrastructure within the eThekweni Metropolitan Municipality. Collectively, the findings of Thoithi *et al.* (2023), Grab and Nash (2023) and Govender (2023) illustrate that recent flood disasters in KwaZulu-Natal cannot be explained by meteorological extremes alone but instead result from the combined influence of extreme rainfall, catchment characteristics, infrastructure limitations and increasing socio-economic vulnerability.

Coastal regions of KwaZulu-Natal are particularly vulnerable because they experience the combined influence of fluvial flooding, intense convective rainfall, stormwater flooding and coastal processes. Mather *et al.* (2019) demonstrated that South Africa's eastern coastline is exposed to multiple coastal flood hazards, including storm surges, elevated sea levels and extreme wave conditions associated with tropical cyclones and severe storm events. Although their study focused primarily on coastal processes, it highlighted the importance of considering compound flooding, whereby river flooding coincides with elevated coastal water levels, increasing the severity of flood impacts within coastal catchments. This is particularly relevant to KwaZulu-Natal, where many river systems discharge directly into the Indian Ocean and are simultaneously influenced by both inland hydrological processes and coastal dynamics.

Collectively, studies undertaken in Southern Africa demonstrate a clear progression from descriptive accounts of historical flood events towards integrated flood risk assessments that combine hydrological modelling, GIS, remote sensing and socio-economic vulnerability analysis. Nevertheless, important methodological gaps remain. Many South African studies have focused independently on meteorological analyses (Thoithi *et al.*, 2023), historical flood chronologies

(Grab & Nash, 2023), flood susceptibility mapping (Nhlamo et al., 2025), or hydrological design methods (Smithers & Schulze, 2002). Comparatively few studies have integrated hydrological modelling (HEC-HMS), hydraulic modelling (HEC-RAS) and GIS-based flood vulnerability assessment within multiple coastal catchments of KwaZulu-Natal. Furthermore, despite the extensive research generated following the April 2022 floods, relatively few studies have used these events to develop locally calibrated, process-based flood risk models that combine flood generation, inundation modelling and vulnerability assessment.

The present study addresses these limitations by integrating HEC-HMS hydrological modelling, HEC-RAS hydraulic simulations and GIS-based spatial analysis to assess flood susceptibility, flood inundation, exposure and vulnerability across selected coastal catchments of KwaZulu-Natal. Unlike previous South African studies that have generally focused on individual components of flood risk, this research combines physically based hydrological and hydraulic modelling with spatial vulnerability assessment to provide a comprehensive understanding of flood risk that supports disaster risk reduction, spatial planning and climate adaptation within coastal KwaZulu-Natal.

2.3 Geographic context and climate

Southern Africa generally has a warm climate, with most areas experiencing an average annual temperature above 17 °C. During summer, temperatures can exceed 40 °C in the desert regions of Namibia and Botswana. In contrast, winter temperatures decrease from north to south, being coldest in the high-altitude areas of South Africa, Lesotho, and Zimbabwe (Davis-Reddy and Vincent, 2017). The region experiences summer from December to February, autumn from March to May, winter from June to August, and spring from September to November.

Rainfall in southern Africa varies significantly due to the influence of ocean currents and prevailing atmospheric circulation systems (Tyson and Preston-Whyte, 2000; Reason and Jagadheesha, 2005). The highest precipitation occurs near the equator and eastern Madagascar, with annual rainfall reaching up to approximately 3,100 mm (Nicholson, 2000). The region is characterised by a distinct seasonal cycle, with a wet summer period from November to March and a dry winter from April to October, except in equatorial regions and eastern Madagascar, where rainfall occurs throughout the year (Nicholson, 2000; Christensen et al., 2007). In contrast, the Cape region of South Africa experiences winter rainfall associated with mid-latitude cyclones, while areas such

as Tanzania exhibit a bimodal rainfall pattern with two distinct rainy seasons (Reason and Jagadheesha, 2005).

Key climatic controls include the region's position within the southern hemisphere circulation systems, particularly the seasonal migration of the Intertropical Convergence Zone (ITCZ), as well as the influence of complex topography and contrasting oceanic conditions (Tyson and Preston-Whyte, 2000). The warm Indian Ocean enhances moisture availability and promotes higher rainfall along the eastern coastal regions, whereas the cold Benguela Current along the Atlantic Ocean contributes to arid conditions in western areas (Reason and Jagadheesha, 2005). These interacting factors result in diverse climate zones across southern Africa, ranging from arid deserts to humid subtropical regions. Furthermore, natural climate variability, including the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), plays a significant role in modulating rainfall patterns and interannual variability (Nicholson, 2000; Christensen et al., 2007).

The El Niño–Southern Oscillation (ENSO) is a recurring climate phenomenon that significantly impacts global weather patterns, leading to extreme events like floods and droughts. It occurs every two to seven years and is characterised by variations in sea-surface temperature, rainfall, air pressure, and atmospheric circulation across the equatorial Pacific (Davis-Reddy and Vincent, 2017).

The ENSO cycle has two phases: El Niño, the warm phase with above-average sea-surface temperatures in the east-central Pacific and below-average temperatures in the western Pacific; and La Niña, the cold phase with the opposite temperature pattern. Each phase typically lasts one to two years (Davis-Reddy and Vincent, 2017).

In southern Africa, El Niño is usually associated with below-average rainfall during the summer, while La Niña tends to bring above-average rainfall. However, the impact of ENSO on rainfall varies, and factors such as land temperatures and regional conditions can influence the severity and distribution of droughts (Davis-Reddy and Vincent, 2017). ENSO also affects the winter rainfall region of South Africa, with El Niño years generally bringing higher rainfall in May to July and La Niña years bringing lower rainfall (Davis-Reddy and Vincent, 2017).

2.3.1 Climate change impacts, evolving climatic patterns, and conditions contributing to flood vulnerability along the KwaZulu-Natal coast.

Due to climate change, southern Africa has been warming significantly over the last century, and the regional distribution of temperature increases is not uniform, with some regions experiencing greater change than others. Studies have indicated that in the dry season decreases in rainfall and the number of rainfall days over parts of the country, and other studies show that inter-annual rainfall variability over southern Africa has increased since the late 1960s and that droughts have become more intense and widespread in the region due to rising temperatures and decreasing rainfall in certain areas. (Davis-Reddy and Vincent, 2017).

Sea-surface temperatures (SST) are rising at all latitudes along the African coastline, with the most significant increases seen in the northern Atlantic and the north-west and south-west Pacific. SSTs are also rising in the Indian Ocean. However, lower or negative SST trends are noted in the eastern Pacific along the Americas' coastlines, with some variation between data sets. These patterns align with other studies and are anticipated to persist due to climate change. Changes in SSTs can significantly impact the upwelling strength in the Benguela Current and the Agulhas Current, which are crucial for southern Africa's climate (Davis-Reddy and Vincent, 2017).

Global sea-level rise (SLR) over the past decade has averaged about 3.3 ± 0.4 mm per year. According to the IPCC AR5, both global warming and SLR are expected to persist for centuries, even if greenhouse gas levels are stabilised or reduced, due to the long timescales involved in climate processes and feedback (Davis-Reddy and Vincent, 2017).

Detecting changes in rainfall is challenging due to its high spatial and year-to-year variability, and trends in rainfall across Africa are uncertain because much of the continent lacks sufficient observational data for robust conclusions over the past century (Davis-Reddy and Vincent, 2017).

Analysis of the CRU TS 3.23 dataset, which spans from 1900 to 2014, shows that southern Africa's rainfall has significant inter-annual and inter-decadal variability. This includes periods of both above-average and below-average rainfall, such as from 1973 –1976 (wet) and in 1993 (dry). The data indicates alternating wet and dry cycles, leading to extreme weather events like floods and droughts. However, there is little evidence of a significant overall trend toward either increased or decreased rainfall, and different datasets show inconsistent results. Any changes detected are weak and not statistically significant (Davis-Reddy and Vincent, 2017).

Further analysis of multi-decadal rainfall patterns in southern Africa reveals that the 1960s were generally drier, except in certain countries like Angola and Tanzania. The 1970s saw a shift to wetter conditions in some areas, while the 1990s were notably drier, especially due to the 1991/1992 drought. The 2000s experienced generally wetter conditions, except along the southwestern coast of Africa and the eastern coast of Tanzania (Davis-Reddy and Vincent, 2017).

Trends in extreme weather events cannot be detected with high confidence due to data constraints. Some trends, such as an increase in hot days and a decrease in cold days, are more apparent and align with global warming. Cold temperatures, including frost days, have decreased and are expected to become less frequent in the future (Davis-Reddy and Vincent, 2017).

Even though changes in extreme rainfall events are harder to detect due to high spatial and temporal variability, evidence suggests an increase in dry spells and a subsequent increase in daily rainfall intensity (Davis-Reddy and Vincent, 2017). Climate change is expected to impact the magnitude, timing, and distribution of storms that cause floods, and projections based on CCAM downscaling indicate an increase in the frequency of extreme rainfall events (defined as 20 mm of rain in 24 hours) in the eastern parts of southern Africa (Davis-Reddy and Vincent, 2017). This includes Mozambique, Tanzania, parts of Zambia and Zimbabwe, the northeastern corner of South Africa, and the west coast of Madagascar. These changes are driven by modelled shifts in the landfall of tropical cyclones from the Indian Ocean.

While projecting changes in thunderstorms, including hail and lightning, is challenging due to their small-scale nature, some studies suggest that more intense thunderstorms could become more frequent in tropical and subtropical Africa under a warmer climate (summarised in Davis-Reddy and Vincent, 2017). This aligns with a global trend towards heavier rainfall events, as a warmer atmosphere holds more water vapor.

Future changes in tropical cyclones, including their intensity, frequency, and duration, remain highly uncertain. Simulating tropical cyclones accurately is difficult, and there are large uncertainties in projections. However, increased temperatures and water vapor levels suggest that heavy precipitation associated with tropical storms and cyclones might rise (Davis-Reddy and Vincent, 2017).

Coastal storm surges are expected to increase globally due to sea-level rise and potentially more frequent and intense sea storms, along with higher wave heights. Even without changes in storm intensity, higher sea levels could amplify the impact of smaller storms on coastlines. However,

region-specific projections for these surges are currently made with low confidence (Davis-Reddy and Vincent, 2017).

Shoreline stability, including erosion and structural under-scouring, is influenced by both natural processes and human activities. Identifying areas at high risk or vulnerability is crucial for effective coastal zone management. This involves predicting future risks under climate change scenarios and studying coastal hazards like waves and flooding. Such information supports strategic planning for new developments and infrastructure, as well as helps in identifying suitable climate adaptation measures for existing at-risk areas. The issue with sea-level rise (SLR) extends beyond just the increase in sea level; it also involves its interaction with more intense storms and shifting wind patterns, which could overwhelm existing coastal infrastructure. This is a significant concern, particularly for the exposed South African coastline, though it has not been extensively studied (Theron, 2007).

Currently, predicting changes in storm patterns, wind speeds, and wave energy is challenging. However, increased storm activity and severity are expected to be the most noticeable impacts. Higher sea levels will cause even smaller storms to surpass current protection measures.

Wave conditions, influenced by ocean winds, exhibit seasonal variations. During winter, wave heights rise as frontal systems move north, while summer sees a decrease in wave heights due to high-pressure systems pushing low-pressure systems south (Mather et al., 2019).

There is limited data on potential changes in oceanic wind patterns off southern Africa. Climate change projections indicate that increases in wind intensity may contribute to larger wave heights and greater wave energy, thereby influencing coastal erosion, sediment transport, estuarine mouth dynamics, and the severity of coastal flooding along the South African coastline (Mather et al., 2019). Key hazards to coastal infrastructure from sea storms and climate change include:

- Increased seawater levels are causing flooding and inundation of low-lying areas.
- Alterations in wave conditions and metocean climate lead to direct impacts on coastal structures.
- Coastal erosion and damage to foundations and structures.
- Extreme events, such as high tides combined with SLR, are expected to overwhelm existing infrastructure more frequently over time.

The primary drivers of these hazards are changes in waves and seawater levels, with winds and currents playing a lesser role.

2.4 Determinants and Indicators of flood risks and vulnerability

Determinants of Flood Risk:

a. Geographic and Environmental Factors:

- **Topography:** Low-lying areas and floodplains are more susceptible to flooding.
- **Soil Type:** Soil permeability affects how quickly water is absorbed; clayey soils have lower permeability, increasing flood risk.
- **Land Use:** Urbanisation, deforestation, and agriculture can alter natural drainage patterns, increasing flood risk (Nhamo et al., 2025).

b. Hydrological Factors:

- **Rainfall Intensity and Duration:** Heavy and prolonged rainfall can overwhelm drainage systems and lead to flooding.
- **River Flow:** High river discharge, especially during heavy rains or snowmelt, can cause riverine flooding.

c. Climate Change:

- **Sea Level Rise:** Increased sea levels can exacerbate coastal flooding.
- **Extreme Weather Events:** More frequent and intense storms can lead to higher flood risks.

d. Infrastructure and Management:

- **Drainage Systems:** Inadequate or poorly maintained drainage systems can increase flood risk.
- **Flood Defences:** The presence and condition of levees, dams, and sea walls affect vulnerability.

e. **Socio-economic Factors:**

- **Population Density:** Higher population density in flood-prone areas increases potential damage and loss of life.
- **Economic Development:** Wealthier communities may have better infrastructure and emergency services, reducing vulnerability.

Indicators of Flood Risk and Vulnerability:

a. **Exposure Indicators:**

- **Floodplain Maps:** Maps showing areas prone to flooding based on historical data and topography.
- **Population in Flood-prone Areas:** The number of people living in high-risk flood zones.

b. **Sensitivity Indicators:**

- **Infrastructure Quality:** Condition and capacity of drainage systems and flood defences.
- **Land Use Patterns:** Types of land use and how they impact flood risk (e.g., urbanisation, deforestation).

c. **Adaptive Capacity Indicators:**

- **Emergency Response Plans:** Existence and quality of flood emergency preparedness and response plans.
- **Public Awareness:** Level of awareness and education about flood risks and preparedness among the population.

d. **Historical Data:**

- **Past Flood Events:** Frequency, severity, and impact of past flooding events in the area.
- **Economic Losses:** Historical data on economic losses due to flooding.

e. **Vulnerability Indicators:**

- **Housing Quality:** The resilience of housing structures to flood damage.
- **Access to Resources:** Availability of resources for flood prevention and recovery, such as insurance and financial assistance.

These determinants and indicators provide a comprehensive understanding of flood risks and vulnerabilities, guiding effective flood management and mitigation strategies.

2.5 Social vulnerability assessment and socio-economic impacts of floods

Common Approaches to Vulnerability Assessments

Vulnerability assessments are essential tools used to identify, measure, and prioritise key climate change risks (Davis-Reddy and Vincent, 2017). They are often necessary for developing effective adaptation strategies and policies, as they shed light on the factors that create risks and how to enhance a system's resilience to these risks. Despite the challenges in defining criteria for quantifying vulnerability, several approaches have been developed and utilised. These include:

- **Proxy or Indicator-Based Approaches:** Using specific indicators or proxies to estimate vulnerability.
- **Model and GIS-Based Methodologies:** Employing models and geographic information systems (GIS) for analysis.
- **Participatory and Multi-Stressor Approaches:** Engaging stakeholders and considering multiple stressors in the assessment.

There are three main approaches used, each with its own strengths and weaknesses as indicated in Table 2-1 below, and often, elements from these different approaches are combined to provide a comprehensive and stronger evaluation.

Table 2-1: Strengths and weaknesses of common vulnerability methodologies (source: Davis-Reddy and Vincent, 2017)

Type	Description	Strengths	Weaknesses
Indicator based	Indicator-based methodologies use a specific set or combination of proxy indicators in order to produce measurable outputs across various spatial scales. Examples of indicators include the Livelihood Vulnerability Index (LVI) (Hahn et al. 2009), Household Adaptive Capacity Index (HACI), Well-being Index (HWI), Index of Social Vulnerability to Climate Change for Africa (SVA).	• Produce measurable outputs across various spatial scales that can be easily used by policymakers • Valuable for monitoring trends and exploring the implementation of adaptation responses	• Limited by lack of reliable data, particularly socio-economic sources, at the scale required for assessment • Challenges associated with testing and validating the metrics used, such as good governance.
Model and GIS-based	Model- and GIS-based methods incorporate biophysical and socio-economic modelling, and display vulnerability spatially through mapping. These methods commonly focus on a specific driver of change or sector and apply statistical measures and mapping techniques to display vulnerability as well as measures of adaptive capacity and resilience.	• Mapping of climate change vulnerability provides an insight into the vulnerability of a place, and may have some value in identifying vulnerable places and people	• Typically, a snapshot of vulnerability, failing to encapsulate spatial and temporal drivers of structural inequalities
Participatory approaches	Participatory approaches focus on including stakeholders in the assessment process, and this can be done in a variety of ways and to various extents. A range of tools for participatory vulnerability assessments exist, including cognitive mapping, interviews, surveys, vulnerability matrices, stakeholder engagement workshops and expert-based inputs.	• Recognise the local or context-specific knowledge that exists within a system, and the fact that many aspects are best known by those individuals operating within that system	• The perception and understanding shared by participants should ideally be complemented with supporting socio-economic and biophysical data • Challenges associated with identification of the appropriate target group, and ensuring that all voices are heard and equally included in the process

When conducting a vulnerability assessment, the choice of approach should align with the assessment's purpose, the spatial scale (from national to local levels), and available resources like data and budget (Davis-Reddy and Vincent, 2017). There is no universal method for

vulnerability assessments, and often a mix of bottom-up and top-down methods is used for specific case studies. Best practice guidelines should be followed.

Typically, vulnerability to climate change is assessed through three main components:

- a. **Exposure:** Evaluates how current and future climate conditions might impact the system, using climate projections (Davis-Reddy and Vincent, 2017).
- b. **Sensitivity:** Assesses how susceptible the system is to climate impacts, considering factors such as infrastructure condition and ecosystem health. This is usually based on current data.
- c. **Adaptive Capacity:** Measures the system's ability to respond to changes, influenced by social factors, financial resources, institutional support, and regulatory frameworks. Assessing adaptive capacity often requires detailed primary research or extensive social data.

The outcome of a vulnerability assessment according to Davis-Reddy and Vincent (2017) can be:

- a. **Quantitative:** Provides an overall vulnerability score derived from calculations of various indicators.
- b. **Scoring/Rating:** Uses participatory processes to rate vulnerability as high, medium, or low.
- c. **Qualitative:** Offers descriptive insights based on group discussions or literature review.

Each approach has its validity, and while a combination of methods is ideal, practical constraints often limit this option.

2.6 Mitigation and Adaptation strategies

2.6.1. Early Warning Systems:

South Africa has invested in early warning systems to provide timely information on potential flooding events. These systems use meteorological data, river gauges, and weather forecasts to predict floods and issue warnings to affected areas. Some of these systems are as follows:

South African Weather Service (SAWS)

SAWS is the official provider of severe weather warnings, including for floods. It uses meteorological data, satellite imagery, and radar to:

- Issue Impact-Based Severe Weather Warnings.
- Provide Flash Flood Guidance via a dedicated system (SAFFG – see below).
- Disseminate alerts through SMS, website, media, and mobile apps.

South African Flash Flood Guidance System (SAFFG)

This system, developed with the World Meteorological Organisation (WMO) and the Hydrologic Research Centre (HRC), provides real-time flash flood guidance using satellite rainfall estimates, ground-based rainfall observations and Runoff models to determine flood potential. It supports municipalities and disaster managers in rapid decision-making for localised flash flood threats.

Department of Water and Sanitation (DWS) Flood Forecasting and Hydrological Monitoring

DWS operates a Hydrological Monitoring System with real-time data from river gauges and rain stations, and Flood Forecasting and Early Warning Systems in major river basins (e.g., Vaal, Limpopo, Orange). These systems are linked to provincial disaster management centres.

Municipal Disaster Management Centres

According to the Department of Co-operative Governance (2023), local governments use:

- Community-based alert systems (sirens, loudhailers),
- WhatsApp groups, local radio stations, and
- Partnerships with SAWS to relay warnings.

These centres play a key role in communicating last-mile alerts to vulnerable communities.

Mobile Alert Apps and Communication Platforms

- WeatherSMART App by SAWS,
- MySAWS App, which sends localised weather alerts,

- Integration with Cell Broadcast Systems and social media platforms to extend outreach.

2.6.2. Floodplain Management:

Floodplain management is a critical component of flood risk reduction. This includes land use planning, zoning regulations, and building codes designed to minimise the impact of floods on communities and infrastructure.

2.6.3. Infrastructure Improvements:

Investments in infrastructure such as dams, levees, and flood barriers help control and manage floodwaters. Maintenance and upgrading of existing infrastructure are also essential to ensure its effectiveness during extreme weather events.

2.6.4. Community-Based Approaches:

Community involvement is crucial in flood risk management. Local communities are engaged in flood preparedness and response activities, including emergency drills, evacuation plans, and public awareness campaigns.

2.7 Flood risk management and Coastal Disaster Management programmes in South Africa

Flood Risk Management and Coastal Disaster Management Programs in South Africa

The 2023 review of South Africa's National Disaster Management Framework modernises the country's disaster risk management approach in alignment with global standards such as the Sendai Framework for Disaster Risk Reduction (SFDRR). This framework responds to escalating risks from climate change, urbanisation, infrastructure decay, and socio-economic challenges.

South Africa faces multiple and increasing disaster risks—ranging from floods, droughts, pandemics, and fires to technological and social threats. Despite the enactment of the Disaster Management Act (2002) and the publication of the original 2005 framework, implementation has been fragmented. The revised framework provides a coherent, integrated, and inclusive policy that promotes resilience and sustainable development.

The framework is built on four Key Performance Areas (KPA) supported by three Enablers:

- **KPA 1: Integrated Institutional Capacity**

Establishes governance structures like the Intergovernmental Committee on Disaster Management (ICDM).

Promotes cooperation among national, provincial, and municipal centres.

Encourages regional and international collaboration.

- **KPA 2: Disaster Risk Assessment and Monitoring**

Details a standardised methodology for hazard and vulnerability assessment.

Promotes real-time risk analysis and community-based risk profiling.

Guides risk prioritisation and early warning systems.

- **KPA 3: Disaster Risk Reduction (DRR)**

Mainstream DRR into development planning and infrastructure investment.

Emphasises prevention and mitigation.

Ensures measurable reductions in disaster losses through targeted programs.

- **KPA 4: Preparedness, Response and Recovery**

Clarifies roles and responsibilities in disaster response.

Enhances contingency planning and inter-agency coordination.

Stresses post-disaster recovery, rehabilitation, and resilience-building.

Enablers

- **Enabler 1: Information Management and Communication**

Establishes an integrated system for data sharing, GIS mapping, early warning, and communication.

- **Enabler 2: Education, Training, Public Awareness, and Research**

Promotes capacity building through accredited disaster management education.

Advocates for inclusion of DRR content in school curricula.

Supports public awareness campaigns and research partnerships.

- **Enabler 3: Funding Arrangements**

Introduces mechanisms for sustainable funding across all government levels.

Encourages disaster risk financing, budgeting integration, and emergency reserves.

Implementation Approach:

Emphasises the District Development Model (DDM) for coordinated localised implementation. KPAs and Enablers are tracked via Key Performance Indicators (KPIs) and guidelines to ensure accountability.

This revised framework marks a strategic shift from reactive disaster response to proactive risk reduction and resilience building. It aims to create a safer, more prepared South Africa by fostering intergovernmental collaboration, empowering communities, and aligning with global best practices.

Coastal Disaster Management

KwaZulu-Natal Coastal Management Programme:

The Integrated Coastal Management Act (ICMA) of South Africa and its implementation through provincial frameworks like the KwaZulu-Natal Coastal Management Programme (PCMP) 2024–2029 focus on building climate change resilience and adapting to coastal vulnerabilities, including flooding. These programmes address issues such as coastal erosion, sea-level rise, and the impacts of extreme weather events on coastal communities.

The ICMA promotes integrated coastal management (ICM), which includes identifying vulnerable areas and implementing strategic responses to coastal threats such as sea-level rise, storm surges, and flooding.

Provincial and Municipal Coastal Management Programmes (CMPs) are key tools enabled by the ICMA to align local development with national adaptation goals. For example, the KZN PCMP prioritises coastal vulnerability, adaptation, and resilience as one of its eight core areas, aiming to minimise the risk of flood-related disasters through planning and enforcement.

Protection of Natural Buffers: ICMA underscores the conservation of estuaries, wetlands, and dune systems that provide natural flood defences. The KZN PCMP supports this by managing coastal vegetation and sandy shores that help reduce inland flood impacts.

Land use Regulation: Through the designation of Coastal Management Lines (CMLs), the Act helps prevent inappropriate development in flood-prone coastal zones, thereby mitigating potential flood damage.

Public Participation and Awareness: The Act calls for community involvement and awareness-building, which are critical for effective flood preparedness and response at the local level. South Africa has implemented an Integrated Coastal Management (ICM) policy to address coastal risks. This policy emphasises the need for a holistic approach to managing coastal zones, incorporating aspects such as erosion control, habitat protection, and sustainable development.

Coastal Protection Infrastructure:

Coastal protection infrastructure, such as seawalls, groynes, and revetments, is constructed to protect coastal areas from erosion and storm surges. These structures are designed based on scientific assessments of coastal processes and projected sea-level rise.

Research and Monitoring:

Ongoing research and monitoring of coastal processes are essential for understanding and predicting coastal hazards. South Africa supports research initiatives to improve knowledge of coastal dynamics, sea-level rise, and the impacts of climate change on coastal areas.

Disaster Response and Recovery:

Coastal disaster management includes response and recovery plans for extreme events such as hurricanes and storm surges. These plans involve coordination between national and local agencies, as well as international support when necessary.

Challenges and Future Directions

- **Data Gaps:** There are ongoing challenges related to the availability and accuracy of data for flood risk and coastal hazard assessments. Improved data collection and analysis are needed for better risk management.
- **Climate Change:** The impacts of climate change, including increased frequency and intensity of extreme weather events, pose significant risks. Adaptation strategies must be integrated into flood and coastal disaster management programs to address these challenges.
- **Resource Constraints:** Limited resources and funding can hinder the implementation and maintenance of flood risk and coastal disaster management measures. Increased investment and prioritisation of these programs are necessary for effective risk reduction.

Overall, South Africa's flood risk and coastal disaster management programs aim to reduce vulnerability, enhance resilience, and protect communities from the adverse effects of floods and coastal hazards. Continued efforts in planning, infrastructure development, and community engagement are essential for managing these risks effectively.

2.8 Chapter summary

This chapter presents a concise overview of flood risk and vulnerability, linking global experiences with the South African context. It distinguishes between rapid- and slow-onset floods, triggered by storms, climate variability, and human-induced landscape changes. Flood risk is defined as the potential for damage, while vulnerability refers to the susceptibility of communities and infrastructure, shaped by environmental, socio-economic, and institutional factors.

Globally, floods are the most frequent and destructive natural disasters, disproportionately impacting developing nations due to inadequate infrastructure and urban sprawl. In Europe and the Americas, advanced assessments use GIS and socio-economic data within policy frameworks like the EU Floods Directive. In Asia, urbanisation, such as in China's Qinhuai River basin, has increased flood risk through land use changes.

In Africa, flood vulnerability is intensified by informal urban development, poverty, weak infrastructure, and limited data. Human activities, such as blocked drainage in cities like Port Harcourt, exacerbate flooding. Researchers advocate for participatory, context-specific assessments using frameworks like PAR, BBC, and CLUVA.

South Africa faces significant flood and drought risks, worsened by climate change, outdated hydrological models, and socio-economic disparities. GIS-based studies, such as in the Olifants River Basin, show the benefits of integrated risk mapping. However, key challenges remain in early warning systems, land use planning, and resilient infrastructure, particularly in coastal areas like KwaZulu-Natal.

Flood risk drivers in southern Africa include:

- Environmental/geographic factors (e.g., low-lying terrain, deforestation),
- Hydrological factors (e.g., heavy rainfall),
- Climate change (e.g., sea-level rise),
- Infrastructure limitations (e.g., poor drainage),
- Socio-economic challenges (e.g., informal settlements, low adaptive capacity).

South Africa addresses flood risk through early warning systems (e.g., SAWS, SAFFG), zoning laws, infrastructure investments, and community education. The updated National Disaster Management Framework (2023), aligned with the Sendai Framework, emphasises institutional

capacity, risk assessment, disaster risk reduction, and preparedness. Coastal strategies under the Integrated Coastal Management Act (ICMA) focus on erosion control and land use regulation.

Despite these efforts, data gaps, limited resources, and climate pressures persist. The effectiveness of these systems may not be as adequate as required, and some systems have either fallen away or not being updated and used. The chapter highlights the need for integrated, participatory, and locally tailored strategies to enhance resilience across South Africa and the wider African region.

CHAPTER 3 METHODOLOGY

3.1 Introduction

Flood modelling within developing countries is frequently constrained by limited hydrological monitoring networks, incomplete historical records, and the scarcity of high-resolution topographic datasets (Di Baldassarre et al., 2018; Van Niekerk et al., 2017). Consequently, this study adopted an integrated modelling framework that utilised freely available geospatial datasets together with observed rainfall and river flow records obtained from South African agencies to reconstruct the April 2022 flood event across selected coastal catchments of KwaZulu-Natal. The development of this event-based modelling framework also establishes a basis for future predictive applications, whereby rainfall forecasts, design rainfall events or climate scenario data could be incorporated to assess potential flood behaviour and inundation under different future conditions.

Terrain information was obtained from the NASA Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (30 m spatial resolution), accessed through OpenTopography (NASA SRTM, 2013), while land-cover information was obtained from the ESRI Sentinel-2 Land Cover Explorer. Rainfall observations were sourced from eThekweni Municipality rainfall datafeed stations and observed river flow records were obtained from Department of Water and Sanitation (DWS) gauging stations. Historical flood information used to contextualise the modelling results was obtained from the Emergency Events Database (EM-DAT), Disaster Management Institute of Southern Africa (DMISA), and official disaster reports relating to the April 2022 KwaZulu-Natal floods.

HEC-HMS Version 4.9 was used for terrain preprocessing, watershed delineation and stream network generation. These outputs were subsequently transferred to HEC-RAS Version 6.6, where the hydraulic simulations were performed using the Rain-on-Grid (RoG) approach. Within this framework, observed rainfall was applied directly to the terrain surface, while measured river flows from DWS gauging stations were incorporated as hydraulic boundary conditions representing observed discharges during the April 2022 flood event.

The overall methodology consisted of five sequential stages:

- acquisition and preprocessing of terrain, rainfall, river flow, soil and land-cover datasets;
- watershed delineation and hydraulic geometry preparation using HEC-HMS;
- hydraulic simulation of the April 2022 flood event using the HEC-RAS Rain-on-Grid methodology;

- GIS-based flood hazard, exposure and vulnerability assessment using Multi-Criteria Decision Analysis (MCDA) and the Analytic Hierarchy Process (AHP); and
- interpretation of flood hazard and vulnerability patterns through spatial analysis.

This integrated workflow enabled the physical simulation of flood inundation together with spatial evaluation of flood vulnerability, providing a comprehensive assessment of flood risk across multiple coastal catchments in KwaZulu-Natal.

3.2 Research approach and design

This study adopted a quantitative, spatially explicit research design based on the integration of hydrological modelling, hydraulic modelling and Geographic Information Systems (GIS) to evaluate flood susceptibility, flood hazard, flood inundation and flood vulnerability across selected coastal catchments within KwaZulu-Natal. A quantitative research approach was considered appropriate because the objectives of the study required numerical simulation of rainfall-runoff processes, estimation of river discharges, prediction of flood inundation and spatial assessment of flood exposure and vulnerability. Unlike qualitative research approaches, which primarily investigate perceptions or experiences of flooding, quantitative flood modelling enables objective measurement of hydrological processes and allows flood characteristics to be represented spatially using repeatable analytical methods.

The research design integrates deterministic hydrological and hydraulic modelling with GIS-based vulnerability assessment. Deterministic models are widely used in flood studies because they explicitly simulate the physical processes governing runoff generation, channel routing and floodplain inundation based on mathematical representations of catchment hydrology and river hydraulics (Balica *et al.*, 2013). This approach differs from empirical or statistical flood susceptibility mapping, which estimates flood-prone areas primarily through historical observations or weighted spatial overlays without explicitly representing the underlying hydrological processes.

The methodological framework adopted in this study was informed by previous international and South African flood studies. Balica *et al.* (2013) distinguished between deterministic modelling approaches, which utilise physically based hydrological and hydraulic simulations to estimate flood hazard, and parametric approaches, which employ vulnerability indicators derived from readily available socio-economic and environmental datasets. Recognising the strengths and limitations of both approaches, the present study combines physically based flood modelling with GIS-based vulnerability assessment to provide a more comprehensive evaluation of flood risk.

Similarly, Dewan (2013) demonstrated the value of integrating Geographic Information Systems (GIS) and remote sensing for natural hazard assessment, emphasising that flood hazards are inherently spatial phenomena requiring spatially explicit analytical techniques. Dambe (2020) further demonstrated that combining remote sensing, GIS, hydrological modelling and hydraulic simulation provides an effective framework for flood hazard mapping and flood risk assessment. The present study builds upon these approaches by integrating HEC-HMS, HEC-RAS and GIS within a unified modelling framework.

Primary modelling datasets were compiled from publicly available national and provincial databases. Digital Elevation Models and topographic datasets were obtained through OpenTopography, and land use information from ESRI Sentinel-2 Land Cover Explorer. Rainfall observations were obtained from eThekweni Municipality rainfall stations taken from the eThekweni datafeeds website. Streamflow data was obtained from Department of Water and Sanitation (DWS) gauging stations, while historical flood information was obtained from the EM-DAT international disaster database, the Disaster Management Institute of Southern Africa (DMISA), and official disaster reports published following the April 2022 floods.

Data analysis comprised three integrated components. Hydrological analysis was undertaken within HEC-HMS to simulate rainfall-runoff processes and generate flood hydrographs. Hydraulic modelling within HEC-RAS was subsequently used to estimate flood depths, flow velocities and flood inundation extents. Finally, model outputs were incorporated within a GIS environment to produce flood inundation maps, depicting flood risk, and flood vulnerability maps. Vulnerability was assessed through Multi-Criteria Decision Analysis (MCDA) using weighted environmental and socio-economic indicators identified through literature review and expert judgement. The resulting maps were complemented by hydrographs, statistical summaries and graphical analyses to facilitate interpretation of flood behaviour across the selected catchments.

3.3 Case study selection

The study was undertaken within the coastal region of KwaZulu-Natal, South Africa, with particular emphasis on six major river catchments situated within the Pongola–Mtamvuna Water Management Area (WMA). The selected catchments comprise the uMngeni, uMvoti, uMdloti, uMlazi, Mbokodweni and uMkomazi River systems.

These catchments were selected using purposive sampling based on four criteria: (i) documented history of severe flooding, (ii) hydrological significance, (iii) degree of urban development and

exposure, and (iv) availability of hydrological and meteorological datasets required for the flood modelling.

The selected catchments have experienced repeated flood events over recent decades, culminating in the catastrophic April 2022 floods, which caused extensive loss of life, widespread infrastructure damage and significant socio-economic disruption throughout KwaZulu-Natal (COGTA, 2022; EM-DAT, 2022). Collectively, the catchments represent a range of hydrological environments, from highly urbanised and canalised systems such as the uMlazi River to larger, more natural floodplain systems including the uMkomazi and uMvoti Rivers. This variability provides an opportunity to compare flood behaviour across catchments with differing geomorphological characteristics, land use patterns and degrees of urbanisation.

Particular emphasis was placed on catchments located within the eThekweni Metropolitan Municipality because this region contains the highest population density within KwaZulu-Natal and experiences substantial flood exposure associated with rapid urbanisation, extensive impervious surface development and widespread informal settlement expansion adjacent to river corridors (Taylor et al., 2021a; COGTA, 2022). Major transport infrastructure, industrial developments, residential areas and critical water supply infrastructure are concentrated within these catchments, increasing both flood exposure and socio-economic vulnerability.

Although the Thukela River represents the largest river basin within KwaZulu-Natal, it was excluded from the present study because much of the basin is characterised by comparatively lower population densities and reduced urban development relative to the selected coastal catchments. Furthermore, the principal objective of this research was to evaluate flood susceptibility and vulnerability where flood impacts on communities, infrastructure and economic activities are greatest. The selected catchments therefore provide a more representative assessment of flood risk within rapidly urbanising coastal KwaZulu-Natal.

The April 2022 flood event, which occurred between 8 and 18 April 2022 (as stated in EM-DAT records), was selected as it represents one of the most destructive flood disasters recorded in South Africa's recent history. The hydraulic simulations were undertaken using the observed rainfall associated with the April 2022 KwaZulu-Natal flood event, recorded between 8 and 18 April 2022.

Modelling an observed historical event enabled comparison of simulated inundation patterns with documented flood impacts and provided a realistic basis for evaluating flood hazard and vulnerability.

The event resulted in widespread flooding, extensive infrastructure failure, numerous fatalities and significant economic losses throughout KwaZulu-Natal (EM-DAT, 2022; COGTA, 2022). The exceptional magnitude of the event, combined with the availability of rainfall observations, streamflow records and documented flood impacts, provided an appropriate basis for evaluating the performance of the integrated HEC-HMS, HEC-RAS and GIS modelling framework developed in this study.

3.4 Sampling process

The flood risk and vulnerability assessment focused on the main river channels and catchments within and surrounding the eThekweni Metropolitan Municipality in coastal KwaZulu-Natal, South Africa. The study adopted a stratified purposive sampling approach commonly used in flood risk and vulnerability assessments to ensure that areas with high flood exposure and varying socio-economic conditions were adequately represented (Tehrany et al., 2017; Phiri and Mazvimavi, 2020).

Firstly, the study area was delineated to include major river catchments and streams that significantly influence flood dynamics within the coastal region of KwaZulu-Natal. Historical flood records, disaster reports, and spatial flood hazard information associated with previous flood events, particularly the April 2022 floods, were used to identify flood-susceptible zones within the study area (COGTA, 2022; NDMC, 2022). The uMgeni and uMlazi River systems were considered particularly significant because they drain highly urbanised and densely populated areas within the eThekweni Metropolitan Municipality and have historically experienced severe flooding events, including those associated with the April 2022 disaster (Taylor et al., 2021a; COGTA, 2022).

The uMdloti and Mbokodweni catchments were also included because of their proximity to urban and industrial developments and their susceptibility to stormwater exceedance and localised flooding. In addition, the uMvoti and uMkomazi River systems, although located outside the eThekweni Metropolitan Municipality, were incorporated into the study because they are major river systems within the Pongola–Mtamvuna Water Management Area (WMA) and contain settlements, agricultural activities, and urban land uses situated close to river channels and floodplains. Their inclusion allowed for comparative assessment across catchments with differing hydrological, geomorphological, and socio-economic characteristics.

The study area was then stratified according to key physical and socio-economic variables known to influence flood risk, including proximity to rivers and streams, land use and land-cover characteristics, population density, and settlement type (presence of informal settlements) (Tehrany et al., 2017; van Niekerk et al., 2020b).

Four principal stratification variables were used:

- **Hydrological setting**, based on river catchment boundaries and drainage characteristics;
- **Land use and degree of urbanisation**, distinguishing highly urbanised, peri-urban and predominantly rural catchments;
- **Population density and settlement characteristics**, with particular emphasis on densely populated areas and informal settlements located within flood-prone zones; and
- **Historical flood occurrence**, based on documented flood records, disaster reports and observed impacts associated with previous flood events, particularly the April 2022 KwaZulu-Natal floods (COGTA, 2022; NDMC, 2022).

These variables were selected because previous research has demonstrated that flood risk is governed not only by the physical characteristics of flooding but also by differences in land use, settlement patterns, infrastructure development and population exposure (Tehrany et al., 2017; Van Niekerk et al., 2020b).

Once the strata had been established, purposive sampling was used to ensure that each stratum was represented within the study. Selection focused on catchments that exhibited:

- documented histories of recurrent flooding;
- significant population exposure;
- varying degrees of urbanisation;
- differing geomorphological characteristics; and
- sufficient hydrological and meteorological data to support physically based modelling.

Priority was given to densely populated urban and peri-urban areas, informal settlements located within floodplains, and regions with documented histories of severe flood impacts.

This process resulted in the selection of six river catchments: the **uMgeni, uMlazi, uMdloti, Mbokodweni, uMvoti and uMkomazi** rivers.

The uMgeni and uMlazi catchments represent highly urbanised systems characterised by extensive infrastructure development, dense populations and numerous informal settlements. The uMdloti and Mbokodweni catchments represent smaller coastal systems affected by rapid urban expansion and industrial development. The uMvoti and uMkomazi catchments were selected to represent larger coastal river systems with contrasting geomorphological characteristics, lower levels of urbanisation and different flood response mechanisms. Collectively, these catchments provide a representative range of flood environments encountered along the KwaZulu-Natal coastline.

This approach is consistent with integrated flood risk assessment frameworks, which recognise that flood risk arises from the combined influence of flood hazard, exposure and vulnerability rather than from flood hazard alone (Cardona et al., 2012).

3.4.1 Sample size

The study area encompasses the major river systems within the eThekweni Metropolitan Municipality and adjacent hydrological systems, with particular emphasis on the coastal catchments that drain into the Indian Ocean. These river systems form critical components of the regional drainage network and are highly susceptible to hydrological variability and extreme weather events. In recent years, the region has experienced an increase in the frequency and intensity of extreme rainfall events, resulting in elevated flood risk and associated impacts on surrounding communities, infrastructure, and ecosystems (Taylor et al., 2021b; COGTA, 2022).

For the purpose of this research, the sample size consisted of the principal river catchments and their associated tributaries within the municipal boundary and nearby coastal drainage systems. The selection of these river systems was guided by their hydrological significance, historical flood occurrence, and proximity to densely populated and rapidly developing areas (DWS, 2014; COGTA, 2022). Major rivers were prioritised because they serve as primary conduits for stormwater discharge during intense rainfall events and therefore represent key locations where flood hazards and vulnerability are most pronounced.

A purposive sampling approach was adopted to ensure that the river systems included in the study adequately represented the diversity of hydrological and socio-economic conditions present within the Pongola–Mtamvuna Water Management Area (WMA). This approach allowed for the

inclusion of river systems known to experience recurrent flooding, significant urban encroachment, and varying land use characteristics (Phiri and Mazvimavi, 2020; van Niekerk et al., 2020a). Tributaries and secondary streams connected to the major rivers were also incorporated into the sample to capture upstream–downstream interactions and to better understand how catchment-scale processes influence flood risk within coastal zones (Tehrany et al., 2017).

The selected sample, therefore, provides a representative cross-section of river systems within the water management area, enabling a comprehensive assessment of flood risk and vulnerability across different environmental and settlement contexts. The approach further aligns with integrated flood risk assessment frameworks that recognise flood risk as a function of both physical hazard and social vulnerability (Cardona et al., 2012).

3.5 Data collection

Rainfall data for this study were obtained from the eThekweni Metropolitan Municipality data feeds for stations located within the Pongola-Mtamvuna WMA. The spatial distribution of rainfall monitoring stations across the study area was uneven, resulting in limited coverage along the full longitudinal extent of some river systems. To address this limitation, rainfall stations located closest to the coastal sections of the selected rivers were prioritised for analysis, as these areas are most relevant to the study’s focus on coastal catchments and downstream flood impacts.

The Mvoti River falls outside the jurisdiction of the eThekweni Metropolitan Municipality, and consequently, no municipal rainfall stations were available within this catchment. To compensate for this data gap, rainfall records from the Ballito rainfall station, located approximately 20 km from the river system, were used as a proxy. Although rainfall data for the uMvoti River catchment are available from the uMgeni-uThukela Water website, these records are limited to daily measurements and only extend back approximately five years. The available data was therefore used primarily to validate the rainfall patterns observed at the Ballito station and to confirm that the proxy data were representative of rainfall conditions within the uMvoti catchment.

Hourly rainfall data was retrieved for the selected stations to capture the temporal dynamics of the extreme rainfall event analysed in this study. The analysis focused on the April 2022 flood event that affected large parts of KwaZulu-Natal. Rainfall data was extracted for the period between 8 April 2022 and 18 April 2022, corresponding to the timeline of the event recorded in

the Emergency Events Database (EM-DAT). A summary of flood events for KwaZulu-Natal obtained from the EM-DAT database is provided in Annexure A.

In addition to rainfall data, river flow station data was obtained from the Department of Water and Sanitation gauging stations located within the selected catchments. The spatial locations of these monitoring stations are presented in Annexure B. Both rainfall and river flow monitoring stations selected for the analysis were located downstream of major dams along the chosen river systems. This approach was adopted to ensure that the hydrological data used in the study more accurately reflects downstream discharge patterns and potential flood inundation conditions within the lower reaches of the catchments. The rainfall and stations used for data collection for the study are presented in Table 3-1.

Table 3-1: Rainfall and flow stations used for data collection in this study.

River	Rainfall data: Stations used	Flow data: Stations used
Mvoti River	eThekwini datafeeds: Ballito WWTW rain station	DWS: U4H006
Mdloti River	eThekwini datafeeds: Mdloti WWTW station	eThekwini datafeeds: Mdloti River Lev
uMgeni River	eThekwini datafeeds: uMgeni Kennedy road station	eThekwini datafeeds: uMgeni 2 Athone Lev
uMlazi River	eThekwini datafeeds: uMlazi Peace road station	DWS: U6H00371
Mbokodweni River	eThekwini datafeeds: Athlone Park Res rain station	eThekwini datafeeds: Mbokodweni 1 Lev
UMkomazi River	Umkomazi SAPS rain station	eThekwini datafeeds: Umkomaas 2 River Lev

To ensure temporal consistency, river flow observations corresponding to the April 2022 flood event (8–18 April 2022) were extracted to coincide with the rainfall records obtained from the eThekwini datafeeds rainfall monitoring network. Using datasets from the same flood event ensured that both rainfall and river flow represented identical hydrometeorological conditions.

Rainfall observations and river flow records were checked for completeness, converted to a consistent date and time format, and aligned to the simulation period used in HEC-RAS.

Digital Elevation Model (DEM) data used in this study were retrieved from OpenTopography, an open-access geospatial data platform that provides high-resolution topographic datasets. Terrain information was obtained from the NASA Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a spatial resolution of 30 m. The SRTM DEM provides near-global elevation coverage and has a reported absolute vertical accuracy of approximately ± 16 m (90% confidence) and a horizontal positional accuracy of approximately ± 20 m (Farr et al., 2007). Although the accuracy of SRTM data may vary according to terrain complexity, vegetation cover and land surface characteristics, it has been widely applied in regional and catchment-scale flood hazard assessments where higher-resolution topographic datasets, such as LiDAR, are unavailable (Farr et al., 2007; NASA JPL, 2013; Sanders, 2007). The SRTM DEM was selected because it provides reliable elevation information suitable for watershed delineation, terrain analysis, drainage extraction, and hydraulic flood modelling within data-scarce environments (Rodríguez et al., 2006).

The DEM data was used extensively throughout the study to support hydrological and hydraulic modelling processes. Elevation information was applied to delineate catchment boundaries, extract river networks, determine flow direction and flow accumulation, generate longitudinal river profiles, and identify low-lying flood-prone areas within the coastal catchments of KwaZulu-Natal. In addition, the DEM formed a critical input into the HEC-RAS hydraulic modelling process, where terrain elevation data were used to simulate flood extents, flood depths, and inundation patterns during extreme rainfall events.

The use of SRTM-derived DEMs is consistent with previous flood modelling and GIS-based hydrological studies conducted in developing regions where higher-resolution topographic datasets such as LiDAR are often unavailable or financially inaccessible (Tehrany et al., 2017; Mutua et al., 2020). Although the 30 m spatial resolution of the DEM introduces some vertical uncertainty in fine-scale urban floodplain delineation, the dataset was considered suitable for regional-scale flood hazard assessment and catchment analysis within the study area (Rodríguez et al., 2006).

To ensure spatial consistency during GIS analysis, all raster datasets were resampled to a common spatial resolution of 30 m, corresponding to the resolution of the Digital Elevation Model used in the hydrological and hydraulic modelling. Vector datasets, including river centrelines and

catchment boundaries, were projected to the common coordinate reference system (WGS 84 / UTM Zone 36S; EPSG:32736) before rasterisation and overlay analysis.

Spatial Resolution and Scale Limitations

The spatial resolution of the input datasets influences the level of detail that can be represented within the flood modelling process. The 30 m SRTM DEM adequately represents major river channels, valley morphology and catchment topography but cannot accurately represent small drainage channels, road embankments, stormwater infrastructure, culverts or local topographic depressions. Consequently, the resulting flood hazard maps are appropriate for catchment-scale and regional flood assessment but should not be interpreted as property-scale flood delineation.

In addition, SRTM is a Digital Surface Model (DSM) rather than a bare-earth Digital Terrain Model (DTM). Radar elevations therefore include the influence of vegetation, buildings and other surface objects, particularly within densely vegetated riparian zones and urban environments. This can introduce vertical elevation errors that influence derived channel geometry and subsequently affect simulated flood depths and flood extents (Gesch et al., 2014; Schumann & Bates, 2018).

The use of DEM-derived cross-sections therefore introduces uncertainty into hydraulic modelling results. Channel capacity may be underestimated where river channels are inadequately represented, while floodplain elevations may be locally overestimated or underestimated depending on vegetation cover and terrain characteristics. These uncertainties are particularly evident within narrow river reaches where channel widths are smaller than the DEM cell size.

Despite these limitations, numerous studies have demonstrated that SRTM-derived terrain data remain appropriate for catchment-scale and regional flood hazard assessments where high-resolution LiDAR data are unavailable (Cook & Merwade, 2009; Sanders, 2007). The primary objective of this study was to identify regional flood susceptibility, inundation patterns and vulnerable areas across multiple coastal catchments rather than to undertake detailed engineering design of individual flood protection structures. Consequently, the SRTM dataset was considered appropriate for the scale and objectives of the present study.

Similarly, land use and soil datasets available at regional scales may not fully capture small-scale variations in surface characteristics that influence infiltration and runoff generation. The results therefore provide a robust representation of regional flood susceptibility while recognising that finer-scale datasets such as airborne LiDAR and detailed stormwater infrastructure would improve local flood prediction.

Land Use and Land Cover Data

Land use and land cover (LULC) data were incorporated into the study to characterise surface conditions influencing runoff generation, infiltration, surface roughness and flood vulnerability. While the Digital Elevation Model (DEM) defines the topographic controls governing the direction and accumulation of surface flow, land cover data provide information on the physical characteristics of the land surface that influence hydrological response and the exposure of people and infrastructure to flooding.

The land cover dataset was obtained from the Esri Sentinel-2 Land Cover Explorer, which is derived from multispectral Sentinel-2 satellite imagery using a deep learning classification algorithm developed by Impact Observatory in partnership with Esri, Microsoft and the National Geographic Society (Esri, 2024). The original dataset has a spatial resolution of 10 m, making it one of the highest-resolution freely available global land cover products suitable for regional flood modelling and spatial vulnerability assessments.

The dataset classifies land cover into nine primary classes, namely water, trees, flooded vegetation, crops, built areas, bare ground, rangeland, snow/ice and clouds. Within the coastal KwaZulu-Natal study area, the dominant classes included **Developed areas (High; medium and low intensity)**, **cultivated crops**, **natural vegetation (grassland)**, **forests**, **water bodies**, **wetlands (flooded vegetation)** and **barren land rock/sand/clay**. These land cover classes were considered representative of the principal surface characteristics influencing hydrological processes within the selected catchments.

Land cover information was used to interpret spatial variations in runoff generation and flood behaviour across the study area. Built-up areas were recognised as having extensive impervious surfaces that reduce infiltration and increase the volume and rate of surface runoff, thereby contributing to higher flood peaks and shorter catchment response times. Conversely, forested areas, natural vegetation and grasslands promote rainfall interception, infiltration and temporary surface storage, reducing runoff volumes and delaying peak discharge. Flooded vegetation and wetlands contribute to natural water storage and attenuation of floodwaters, while agricultural land exhibits intermediate hydrological behaviour depending on cultivation practices, vegetation cover and soil condition (Dewan, 2013; Tehrany et al., 2017).

The land cover dataset also formed an important input into the GIS-based flood vulnerability assessment. Within the Multi-Criteria Decision Analysis (MCDA) and Analytic Hierarchy Process (AHP) framework, land cover was used as one of the spatial criteria for identifying areas with

differing levels of vulnerability. Urban and built-up areas, particularly densely populated settlements and informal residential developments located adjacent to river channels, were assigned higher vulnerability because of the greater concentration of exposed populations, infrastructure and economic assets. In contrast, natural vegetation, forests and undeveloped land generally exhibited lower vulnerability owing to reduced human exposure.

Although the Esri Sentinel-2 Land Cover dataset provides substantially higher spatial resolution (10 m) than many global land cover products, several limitations remain. The classification represents land cover conditions for a specific period and may not fully capture recent urban expansion, land use changes or temporary land cover disturbances occurring after image acquisition. Classification inaccuracies may also occur where spectrally similar land cover types are present or where seasonal vegetation changes influence image interpretation. Nevertheless, the dataset has demonstrated high thematic accuracy and provides an appropriate level of spatial detail for regional flood hazard and vulnerability assessments (Karra et al., 2021).

3.5.1 Data Processing

Following data collection, all datasets were processed and standardised to ensure compatibility for spatial analysis, hydrological modelling, and flood risk mapping. Data processing involved data cleaning, spatial preparation, derivation of flood-related variables, and preparation of inputs for hydrological and hydraulic modelling. Geographic Information System (GIS) tools within QGIS 3.44.3 were used for spatial data processing, while hydrological and hydraulic simulations were conducted using HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) 4.9 (USACE, 2022) and HEC-RAS (Hydrologic Engineering Center – River Analysis System) 6.6 (USACE, 2024).

Data processing and model computation followed the following steps: Data acquisition → Terrain preprocessing (HEC-HMS) → Catchment delineation and stream network generation → Export of hydraulic geometry to HEC-RAS → Rainfall and boundary condition preparation → Rain-on-Grid hydraulic simulation (HEC-RAS) → Flood depth, velocity and inundation mapping → GIS-based flood hazard mapping → AHP/MCDA flood vulnerability assessment → Integrated flood risk assessment and spatial analysis. All collected datasets were examined for completeness, accuracy, and consistency before analysis. Rainfall records obtained from available monitoring stations were reviewed to remove anomalies and incomplete entries. Where gaps occurred, data

from the nearest available stations were used to ensure continuity in the hydrological modelling process.

Spatial Data Preparation

The coordinate reference system adopted for the study was WGS 84 / UTM Zone 36S, which is widely used for geospatial analysis and mapping applications within KwaZulu-Natal and South Africa because of its suitability for regional-scale spatial analysis and reduced spatial distortion (ESRI, 2020; QGIS Development Team, 2023). Standardising all datasets into a single projection system ensured that spatial layers could be accurately integrated, compared, and analysed within the GIS environment. Spatial datasets including river networks, catchment boundaries, settlement layers, land use data, and infrastructure information were clipped to the defined study area to limit the analysis to relevant spatial extents and improve processing efficiency (Longley et al., 2015).

Raster datasets such as the Digital Elevation Model (DEM) were resampled to a common spatial resolution to ensure compatibility between datasets and consistency during hydrological and hydraulic modelling processes. Grid alignment procedures were further applied so that all raster datasets shared the same spatial extent, coordinate system, and cell size, thereby minimising spatial discrepancies and improving the accuracy of overlay analyses and raster-based modelling outputs (Burrough et al., 2015).

Derivation of Hydrological and Terrain Variables

Additional variables required for flood modelling were derived from the processed datasets. The SRTM 30m DEM (USGS, 2015) was used in HEC-RAS to create a new RAS terrain, which is used for streamline creation. River networks and catchment boundaries were delineated from the DEM to support hydrological modelling.

Land use and land cover datasets obtained from ESRI Sentinel-2 Land Cover Explorer were prepared to represent surface characteristics influencing runoff generation. These datasets were used to assign hydrological parameters, which are required inputs for hydrological modelling.

Preparation of Hydrological Model Inputs

Hydrological modelling focused on the rainfall–runoff process within a catchment. It estimates how rainfall is transformed into streamflow (Ramírez, 2000).

Terrain data derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) were imported into HEC-HMS and used to delineate watershed boundaries, sub-basins, stream networks and flow paths for each study catchment. Terrain preprocessing was first undertaken to remove artificial depressions (sink filling), thereby producing a hydraulically connected terrain surface suitable for drainage analysis. Following sink correction, drainage preprocessing was performed to derive flow direction and flow accumulation grids, which were subsequently used to automatically delineate drainage networks, stream reaches, watershed boundaries and junctions. The resulting basin model provided the spatial framework for the study and comprised sub-basins, reaches, junctions and catchment outlets. These processed terrain layers were then exported from HEC-HMS for use in HEC-RAS, where they formed the basis of the hydraulic model geometry. The hydrological outputs generated by HEC-HMS therefore consisted of:

- watershed (catchment) boundaries;
- river reaches;
- junction locations;
- sub-basin polygons;
- flow paths; and
- watershed connectivity.

These layers were derived from the SRTM Digital Elevation Model following sink filling, flow direction analysis and flow accumulation processing. The completed basin model was then exported to HEC-RAS, where it provided the spatial framework required for hydraulic modelling.

Hydraulic Boundary Conditions

The hydraulic model was developed within HEC-RAS Version 6.6 using a two-dimensional (2D) computational domain encompassing the selected river catchments. Boundary conditions were defined to ensure realistic representation of surface water movement through the model domain.

The principal model inputs comprised:

Upstream condition - Rainfall was applied directly to the terrain surface using the Rain-on-Grid approach rather than prescribing inflow hydrographs at upstream boundaries. Consequently,

runoff was generated internally within each computational cell according to rainfall intensity, infiltration characteristics, surface roughness and local topography.

Downstream boundary- A Normal Depth boundary condition was assigned at the downstream outlet of each catchment. The normal depth was calculated using the average channel bed slope derived from the SRTM Digital Elevation Model, allowing water to leave the computational domain under gradually varied flow conditions. This approach is recommended where observed downstream stage data are unavailable (Brunner, 2024).

Internal boundaries- River centrelines, breaklines and channel banks exported from HEC-HMS were incorporated into the HEC-RAS geometry to guide flow routing through the computational mesh. Manning's roughness coefficients were assigned according to land-cover classifications derived from the ESRI Sentinel-2 Land Cover dataset.

Hydraulic Model Data Preparation

Hydraulic modelling was undertaken using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) Version 6.6, developed by the United States Army Corps of Engineers (USACE, 2024). HEC-RAS is a physically based hydraulic modelling software that simulates the movement of water through river channels and adjacent floodplains by solving the two-dimensional shallow water equations over a computational mesh. The model was used to simulate flood depths, flow velocities, water surface elevations and flood extents associated with the April 2022 flood event within the selected coastal catchments (USACE, 2024).

The Rain-on-Grid (RoG) functionality available in HEC-RAS Version 6.6 was adopted to simulate rainfall-driven flooding within the hydraulic model. While HEC-HMS was used to characterise the hydrological response of the study catchments, the Rain-on-Grid approach enabled observed rainfall to be applied directly to the HEC-RAS computational mesh, allowing rainfall, infiltration, excess runoff, overland flow, channel routing and floodplain inundation to be simulated simultaneously within a single modelling environment (USACE, 2024). This approach provides a spatially distributed representation of both pluvial and fluvial flooding without requiring externally generated inflow hydrographs for the hydraulic simulations.

The hydraulic model domain was developed using the processed Digital Elevation Model and river network described in the preceding sections. Computational mesh generation, terrain processing and boundary condition assignment were completed within HEC-RAS prior to

simulation. Model parameters, including infiltration and computational settings, were configured in accordance with the Rain-on-Grid workflow described in the HEC-RAS Version 6.6 User's Manual (USACE, 2024).

The hydraulic simulations produced spatial outputs including flood depth, water surface elevation, flow velocity and flood extent for each catchment. These outputs were exported to QGIS for subsequent flood hazard mapping and integration with the GIS-based flood vulnerability assessment.

Although the Rain-on-Grid approach enables the representation of spatially variable rainfall directly within the hydraulic model, the accuracy of the simulations remains dependent on the quality and spatial distribution of the input datasets, including rainfall observations, terrain data and model parameterisation. These factors were considered during model development and should be recognised when interpreting the hydraulic model outputs (USACE, 2024).

Data Reclassification and Standardisation

To support flood vulnerability analysis, spatial variables such as settlement class (informal), land use, population density, and proximity to rivers were reclassified into standardised vulnerability classes. Continuous variables were categorised into five classes ranging from very low to very high vulnerability based on hydrological relevance and literature guidance.

Integration of Spatial Database

All processed datasets, including terrain variables, land use layers, hydrological outputs, and hydraulic flood extents, were integrated into a spatial database within QGIS. This integrated database formed the foundation for subsequent flood hazard, vulnerability, and risk assessments conducted within the study.

3.6 Data analysis

Risks and vulnerabilities was assessed using geospatial software and comprise land use maps, population density maps and flood inundation maps. Information on vulnerabilities in terms of social groups and settlements impacted by floods will be obtained from databases such as Stats SA (<https://www.statssa.gov.za/>) , World Pop (<https://www.worldpop.org/>) and EM-DAT

(<https://www.emdat.be/>), documented information from previous studies, and experiences from similar past events.

3.6.1 Hydrological Modelling

3.6.1.1 HEC-HMS Model Overview

The Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) Version 4.9 was used to support the hydrological preparation and representation of the selected KwaZulu-Natal coastal catchments (USACE, 2022). Terrain information derived from the DEM was processed to identify drainage patterns and define the hydrological structure of the study area. This included the delineation of basin and sub-basin boundaries, identification of river reaches and junctions, and preprocessing of terrain depressions and sinks to establish hydrologically connected drainage pathways.

The resulting catchment and drainage information provided the spatial framework required for subsequent hydraulic model development. Relevant processed spatial data were exported and incorporated into the HEC-RAS modelling environment, where the two-dimensional Rain-on-Grid simulations were undertaken. Observed rainfall was applied directly within HEC-RAS rather than being used to generate rainfall–runoff hydrographs in HEC-HMS. Consequently, HEC-HMS primarily supported **catchment delineation and hydrological data preparation**, while HEC-RAS was used to simulate rainfall-driven surface runoff, flow routing and floodplain inundation.

3.6.2 Hydraulic Modelling

3.6.2.1 HEC-RAS Model Description

Hydraulic modelling was undertaken using HEC-RAS Version 6.6 within a two-dimensional (2D) computational domain. The Rain-on-Grid (RoG) approach was used to apply observed rainfall directly to the computational mesh, while the Diffusion Wave equation set was selected to simulate the movement of water across the terrain and floodplains (USACE, 2024). The Diffusion Wave formulation simplifies the two-dimensional shallow-water equations by neglecting inertial terms while retaining the effects of gravity, water-surface gradients and frictional resistance, making it suitable for rainfall-driven overland flow and flood inundation modelling (USACE, 2024). Conservation of mass within the two-dimensional computational domain is represented by:

$$\frac{\partial H}{\partial t} + \nabla \cdot (hV) = q$$

where H is the water-surface elevation (m), h is water depth (m), V is the depth-averaged velocity vector (m s^{-1}), t is time (s), and q represents source and sink terms, including rainfall and infiltration (USACE, 2024).

3.6.2.2 Geometry and Boundary Conditions

The HEC-RAS hydraulic model was developed as a two-dimensional (2D) computational domain using the processed terrain and drainage information prepared during catchment delineation. A computational mesh was generated across the model domain to represent the movement of water over the terrain, river channels and adjacent floodplains. **Manning's roughness coefficients (n)** were assigned according to land-cover type to represent spatial variations in resistance to flow. The values applied included for open water and for woody wetlands, with the remaining land-cover classes assigned their corresponding roughness values used in the model (USACE, 2024). Observed rainfall was applied directly to the computational domain using the **Rain-on-Grid (RoG)** approach and was spatially distributed across the 2D computational mesh, allowing rainfall-generated surface runoff to be routed across the terrain. At the downstream limits of the model domain, normal-depth boundary conditions based on the local slope were specified to allow flow to exit the model domain (USACE, 2024).

An unsteady-flow simulation was configured for the April 2022 rainfall event, with the Diffusion Wave equation set used to route flow across the computational domain. The resulting flood depth, velocity and inundation extent outputs were subsequently exported for flood hazard mapping and further spatial analysis in QGIS.

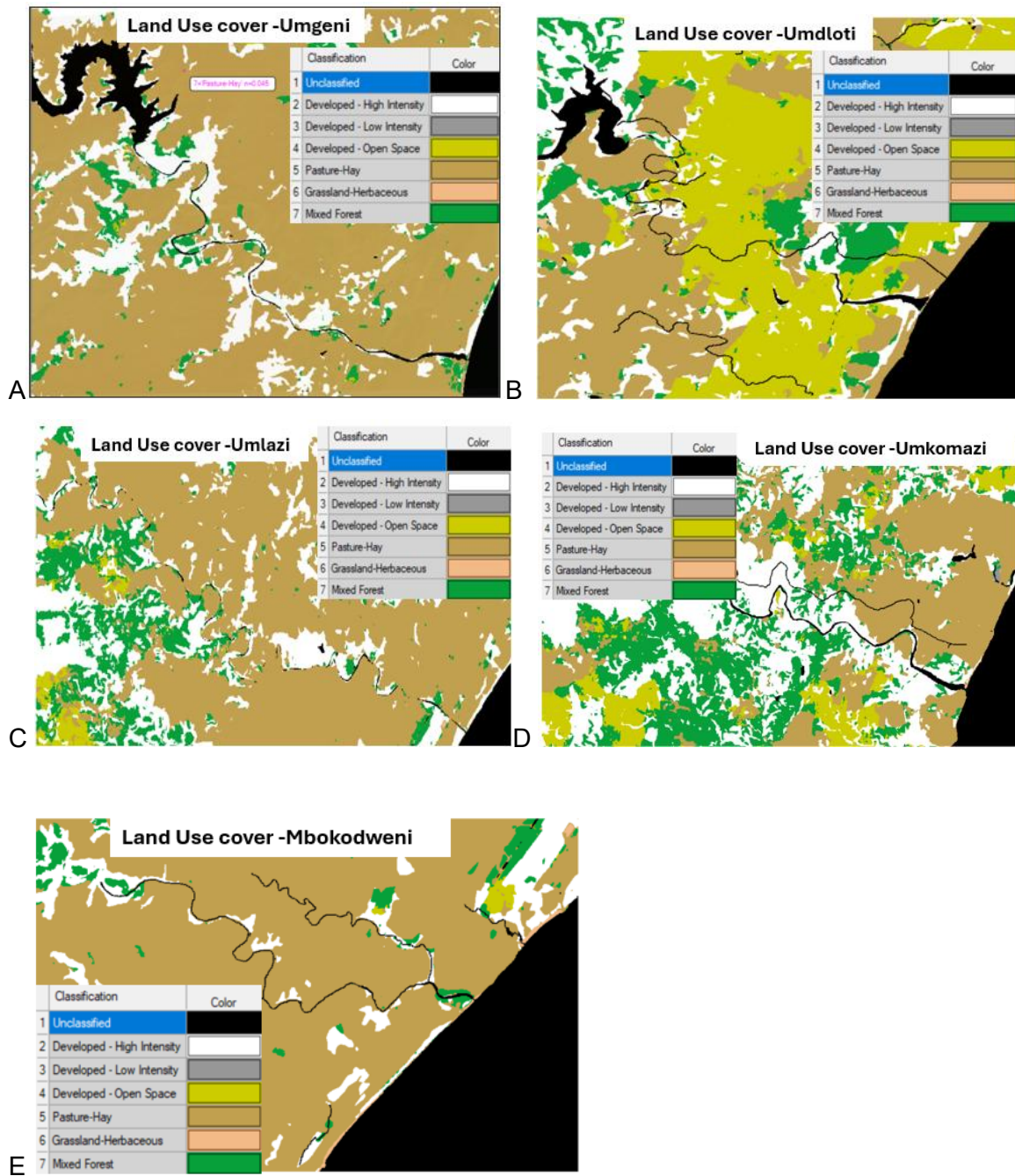


Figure 3-2: Land cover maps using Manning roughness coefficients that were used to develop flood inundation maps in HECRAS. A) uMgeni River; B) uMdloti River; C) uMlazi River; D) uMkomazi River; E) Mbokodweni River.

3.6.2.3 Model Evaluation

Model evaluation was based on assessing whether the simulated flood inundation patterns were consistent with the documented impacts of the April 2022 flood event. The simulated flood extents, flood depths and spatial distribution of inundation were compared qualitatively with historical flood reports, documented areas of flooding, and official post-disaster assessments published by the KwaZulu-Natal Provincial Government, the Cooperative Governance and Traditional Affairs (COGTA), the National Disaster Management Centre (NDMC), and the Emergency Events Database (EM-DAT). Attention was given to the model's ability to reproduce flooding within the major river corridors, urban floodplains and low-lying coastal areas known to have been affected during the April 2022 disaster.

The reliability of the modelling results was further assessed by considering the quality of the input datasets and the assumptions associated with the hydraulic modelling approach. Sources of uncertainty include the use of the 30 m SRTM Digital Elevation Model, which may not adequately represent fine-scale floodplain topography, river bathymetry, bridges, culverts and other hydraulic structures, together with assumptions regarding land surface roughness, infiltration parameters and the spatial distribution of rainfall between monitoring stations. These limitations are acknowledged when interpreting the flood hazard and vulnerability maps and are discussed further in Chapter 4.

Despite these limitations, the integrated modelling framework provides a robust representation of the spatial characteristics of the April 2022 flood event and offers a suitable basis for evaluating flood hazard, exposure and vulnerability across the selected coastal catchments of KwaZulu-Natal.

3.6.2.4 Flood Inundation Mapping

Simulated water surface elevations were exported to QGIS, representing flood depth and extent. These were laid onto a basemap to identify flood hazard areas. Flood inundation maps were produced for the major flood event in 2022 across the major KZN river basins identified for the study.

3.6.3 Vulnerability Assessment

A Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) incorporating the Analytic Hierarchy Process (AHP) was employed to develop a spatial Flood Vulnerability Index (FVI) for the eThekweni Metropolitan Municipality. The AHP, originally developed by Saaty (1980), is one of the most widely applied decision-support techniques in flood vulnerability and environmental suitability assessments because it enables the systematic weighting of multiple criteria according to their relative importance (Saaty, 1980; Tehrany et al., 2017). Within flood vulnerability studies, MCDA-AHP provides a transparent and reproducible framework for integrating environmental and socio-economic indicators into a single composite index (Nasiri et al., 2016; Salami et al., 2017).

Unlike the flood hazard assessment, which was based on hydrological and hydraulic modelling using HEC-HMS and HEC-RAS, the vulnerability assessment focused on the susceptibility of communities and land uses to flood impacts. Vulnerability was therefore represented by four indicators describing both physical exposure and socio-economic conditions, namely **river proximity, informal settlements, population density, and land use**. These indicators were selected following an extensive review of international and South African flood vulnerability studies, which consistently identify population distribution, settlement characteristics, land use and proximity to rivers as major determinants of flood vulnerability (Balica et al., 2013; Koks et al., 2014; Nasiri et al., 2016; Salami et al., 2017). Collectively, these variables represent the exposure and susceptibility components of vulnerability rather than the flood hazard itself.

Prior to the MCDA, all spatial datasets were pre-processed within QGIS to ensure spatial consistency. Vector datasets representing rivers, land use and informal settlements were projected to a common coordinate reference system (EPSG:32736; WGS 84 / UTM Zone 36S) and converted to raster format using a common spatial resolution and extent. The population density raster was similarly reprojected to the same coordinate reference system. All raster layers were aligned to ensure that each cell represented the same geographic location before overlay analysis. This standardisation was essential to prevent spatial misalignment and ensure that the weighted overlay produced a continuous and geographically consistent vulnerability surface. Each indicator was subsequently standardised to a common ordinal scale ranging from **1 (Very Low Vulnerability) to 5 (Very High Vulnerability)** using the *Reclassify by Table* tool in QGIS.

River proximity was derived by generating a Euclidean distance raster from the river network using the GDAL Proximity algorithm. The resulting distance raster was reclassified into five vulnerability classes, with areas closest to river channels assigned the highest vulnerability score

(5) and areas furthest from rivers assigned the lowest score (1). This approach reflects the greater likelihood of riverine inundation occurring in areas immediately adjacent to river channels (Barredo et al., 2007).

Population density was obtained from a gridded population dataset and reclassified into five classes based on population density values. Higher population densities were assigned progressively higher vulnerability scores because densely populated areas generally contain larger concentrations of exposed people, increasing evacuation complexity, potential loss of life and pressure on emergency response systems during flood events (Koks et al., 2014; Nasiri et al., 2016).

Land-use classes were similarly reclassified according to their relative susceptibility to flood impacts. Built-up residential, commercial and industrial land uses were assigned higher vulnerability scores owing to their greater potential for infrastructure damage and economic losses, whereas natural vegetation and undeveloped land received lower vulnerability scores (McGrane, 2016; Nasiri et al., 2016).

Informal settlements were represented as a binary raster in which informal settlement areas were assigned the maximum vulnerability score of **5**, while all remaining areas were assigned a background value of **1**. This classification reflects the recognised vulnerability of informal settlements, which are frequently characterised by substandard housing, inadequate drainage infrastructure, limited access to basic services and reduced adaptive capacity. These characteristics increase their susceptibility to flood impacts despite being exposed to the same flood hazard as formally developed areas (Salami et al., 2017; Davis-Reddy & Vincent, 2017). Table 3-2 below summarises the four indicators incorporated within the vulnerability assessment and the rationale for their inclusion.

Table 3-2: Indicators used in the flood vulnerability assessment and assigned weights

Indicator	Rationale for inclusion	Weight (%)
River proximity	Communities located closer to river channels are more likely to experience inundation during river flooding and therefore exhibit greater physical exposure.	40
Informal settlements	Informal settlements generally comprise low-quality housing with inadequate infrastructure and reduced adaptive capacity, making these communities particularly susceptible to flood impacts.	30
Population density	Areas with higher population densities contain larger concentrations of exposed people, increasing the potential consequences of flood events.	20
Land use	Different land-use classes exhibit varying levels of susceptibility to flood damage, with built-up areas generally experiencing greater economic losses than natural land cover.	10

Terrain slope was intentionally excluded from the vulnerability assessment. Although slope is frequently incorporated into flood susceptibility mapping because it influences runoff generation and overland flow, it was already explicitly represented within the hydrological and hydraulic modelling through the Digital Elevation Model used in HEC-HMS and HEC-RAS. Including slope within both the hazard and vulnerability assessments would therefore duplicate terrain information and introduce bias through double counting. Consistent with the conceptual distinction between hazard and vulnerability, only variables describing the exposure and susceptibility of communities and land uses were incorporated within the MCDA (Koks et al., 2014; Nasiri et al., 2016).

The relative importance of each vulnerability indicator was determined using the Analytic Hierarchy Process. Pairwise comparisons were undertaken using Saaty's (1980) nine-point preference scale, in which a value of 1 represents equal importance and 9 represents extreme importance of one criterion over another. Intermediate values (2, 4, 6 and 8) represent compromise judgements between the principal scale values. The resulting pairwise comparison

matrix was normalised to derive criterion weights representing the relative contribution of each indicator to overall flood vulnerability.

The weighting scheme assigned the greatest importance to river proximity (40%), followed by informal settlements (30%), population density (20%) and land use (10%). These weightings reflect the dominant influence of river exposure on riverine flood impacts while recognising the significant contribution of socio-economic vulnerability associated with informal settlements and densely populated urban environments (Tehrany et al., 2017; Phiri & Mazvimavi, 2020).

The consistency of the pairwise comparison matrix was evaluated using the Consistency Ratio (CR), which yielded a value of 0.0074. As this value is substantially lower than the maximum acceptable threshold of 0.10 proposed by Saaty (1980), the pairwise comparisons were considered internally consistent and the derived weights suitable for subsequent spatial analysis.

The standardised raster layers were combined using the **Raster Calculator** in QGIS through a weighted linear overlay to produce the Flood Vulnerability Index:

$$FVI = (0.40 \times RP) + (0.30 \times IS) + (0.20 \times PD) + (0.10 \times LU)$$

where **RP** represents river proximity, **IS** informal settlements, **PD** population density and **LU** land use.

The resulting Flood Vulnerability Index represents a continuous raster surface describing the relative spatial distribution of flood vulnerability across the eThekweni Metropolitan Municipality. The continuous index was subsequently classified into five vulnerability classes (Very Low, Low, Moderate, High and Very High) to facilitate interpretation and integration with the flood hazard outputs generated from HEC-RAS. This raster-based MCDA approach provides a transparent, reproducible and spatially continuous assessment of flood vulnerability and overcomes the limitations associated with point-based or buffer-based vulnerability mapping approaches previously identified by the examiners.

3.7 Ethical considerations

This study primarily utilised secondary data obtained from publicly available national, provincial, and institutional databases, including hydrological, meteorological, topographic, and socio-

economic datasets. No direct human participation, interviews, or collection of personal information were involved in the research process. All spatial and environmental data were used strictly for academic and research purposes, with appropriate acknowledgement of the relevant data sources and institutions.

Ethical consideration was also given to the responsible communication and application of the study findings. The flood hazard, vulnerability, and risk maps generated through this research have the potential to support disaster risk reduction and community safety initiatives within KwaZulu-Natal. These findings and spatial outputs are to be shared with relevant municipalities, disaster management authorities, and planning departments to assist in informing communities located within potentially high-risk flood environments. The dissemination of this information may contribute toward improved awareness, flood preparedness, spatial planning, and risk reduction strategies, particularly within vulnerable and informal settlement areas. The ethics number for this study is NWU-01215-24-A9.

3.8 Methodological assumptions and limitations

This study is based on several assumptions necessary to support the hydrological and hydraulic modelling processes, as well as the vulnerability assessment:

Data reliability: It is assumed that the rainfall, topographic (DEM), and socio-economic datasets used are accurate, representative, and sufficiently reliable for modelling and spatial analysis.

Hydrological model representation: The terrain-processing and catchment delineation procedures are assumed to adequately represent the principal drainage patterns, sub-catchment boundaries, river networks and flow pathways within the selected catchments based on the spatial resolution and accuracy of the available terrain data.

Hydraulic model performance: The HEC-RAS 2D model is assumed to provide a reasonable representation of rainfall-driven surface flow and floodplain inundation using the available terrain, rainfall, land-cover and infiltration data. The Rain-on-Grid approach and Diffusion Wave formulation are assumed to adequately represent the dominant flow processes at the spatial scale of this study, while recognising uncertainties associated with input-data resolution, rainfall-gauge coverage and model parameterisation.

Spatial representation of model parameters: Model parameters, including Manning's roughness coefficients and infiltration characteristics, were assumed to adequately represent the

corresponding land-cover and surface conditions within the model domain, while recognising that local-scale spatial variability may not be fully captured by the available datasets.

Static land use conditions: Land use and land cover are assumed to remain constant during the modelling period, without accounting for short-term changes such as urban expansion or land degradation.

Homogeneity of vulnerability indicators: Socio-economic indicators used in the vulnerability assessment are assumed to adequately represent spatial patterns of vulnerability across the study area.

Climate stationarity: The analysis assumes that historical rainfall data used for modelling is representative of current conditions, without explicitly incorporating future climate change projections.

Despite the methodological approach adopted, several limitations may influence the accuracy and interpretation of the results:

Data availability and quality: The availability, spatial coverage and temporal resolution of rainfall, streamflow and socio-economic data varied across the study area, introducing uncertainty into the modelling and vulnerability assessment.

Spatial resolution: The 30 m terrain and spatial datasets may not fully represent fine-scale features such as small drainage channels, culverts, road embankments and detailed channel geometry, which may influence local flood behaviour.

Rainfall representation: Rainfall was interpolated between available gauges for the Rain-on-Grid simulations; therefore, localised rainfall variability may not have been fully captured, particularly in areas with sparse gauge coverage.

Hydraulic model simplification: The HEC-RAS 2D Diffusion Wave approach provides a simplified representation of complex hydraulic processes, and the model did not explicitly represent all urban drainage infrastructure, sediment transport, debris blockage or infrastructure failure.

Model parameter uncertainty: Manning's roughness coefficients and infiltration parameters were assumed to be representative of the corresponding surface and land-cover conditions, although local spatial and temporal variations may occur.

Model validation: Limited observed inundation and consistent streamflow data restricted comprehensive quantitative calibration and independent validation of the April 2022 flood simulations. The model outputs should therefore be interpreted as catchment-scale representations rather than precise predictions of local flood conditions.

Vulnerability assessment: The vulnerability assessment incorporated river proximity, informal settlements, population density and land use. While these represent important dimensions of vulnerability, other socio-economic factors could not be included because of limitations in consistently available spatial data.

Future conditions: The study reconstructed the April 2022 flood event and did not explicitly model future climate, land-use or urban-development scenarios. The results should therefore not be interpreted as predictions of future flood conditions.

Data availability: Limitations in the availability and spatial coverage of socio-economic and hydrological data constrained aspects of the analysis. Vulnerability maps could not be developed for the uMvoti and uMkomazi catchments because consistent population-density data and, particularly, spatial datasets identifying informal settlements were unavailable. Although observed rainfall from the April 2022 event was incorporated directly into the HEC-RAS Rain-on-Grid simulations, comprehensive calibration and independent validation using multiple historical flood events could not be undertaken because consistent high-temporal-resolution rainfall and discharge records were not available across all study catchments. The hydraulic modelling should therefore be regarded as a reconstruction of the April 2022 flood event rather than a fully calibrated predictive model. Where suitable observations were available, model outputs were compared with recorded streamflow and documented flood impacts to provide a qualitative assessment of the simulated flood behaviour.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses the results of the hydraulic modelling, flood hazard mapping and vulnerability assessment undertaken for the selected coastal catchments of KwaZulu-Natal (KZN). The analysis integrates outputs from the HEC-RAS 2D Rain-on-Grid simulations with GIS-based spatial analysis in QGIS to examine the spatial characteristics of flooding during the April 2022 event. Particular attention is given to simulated flood depths and inundation extents, their spatial distribution across the study catchments, and the relationship between flood hazard and areas of increased socio-economic vulnerability.

The analysis focuses on the uMngeni, Mdloti, uMvoti, uMlazi, Mbokodweni and uMkomazi catchments, which represent important river systems along the KwaZulu-Natal coastal region (DWS, 2018). Hydraulic modelling results are presented for the selected catchments, while the vulnerability assessment is limited to catchments for which sufficiently consistent socio-economic and spatial data were available. The vulnerability analysis integrates population density, informal settlements, land use and proximity to rivers to identify spatial variations in vulnerability. The chapter is structured around three principal components: (i) hydraulic modelling and flood inundation characteristics, (ii) flood hazard classification and spatial patterns, and (iii) vulnerability assessment and its relationship with the modelled flood hazard. The findings are interpreted in relation to the physical and socio-economic characteristics of the study area and the documented impacts of the April 2022 KwaZulu-Natal flood event.

4.2 Hydrological Modelling Results

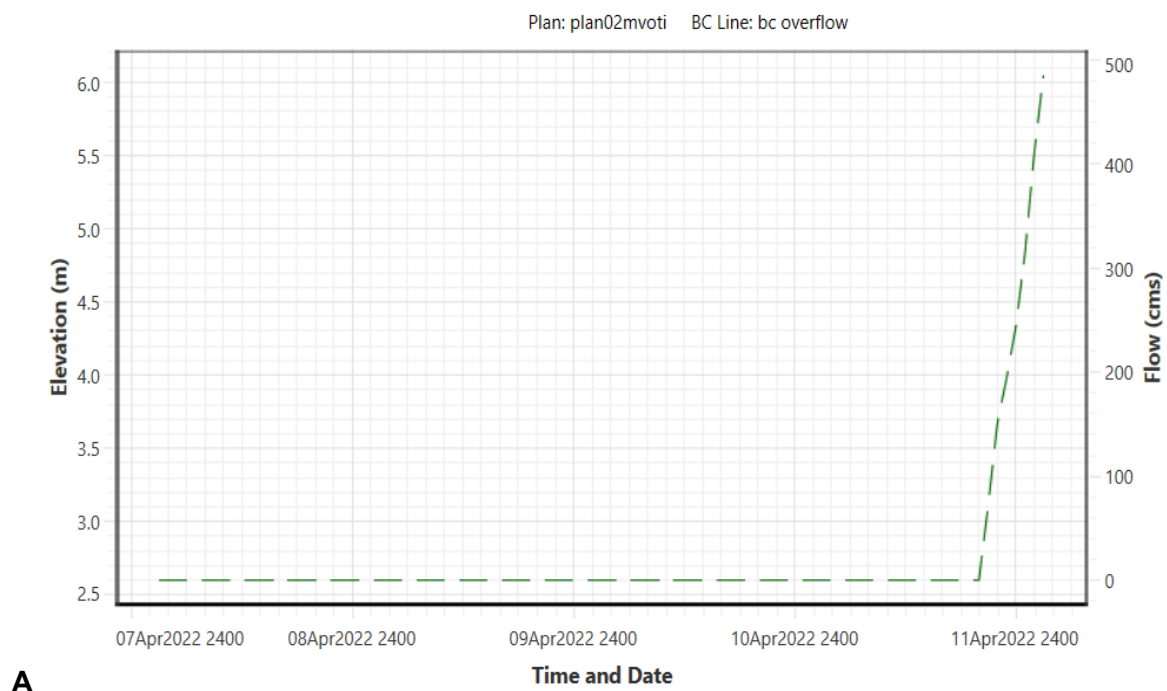
4.2.1 Hydrological and Hydraulic Model Performance

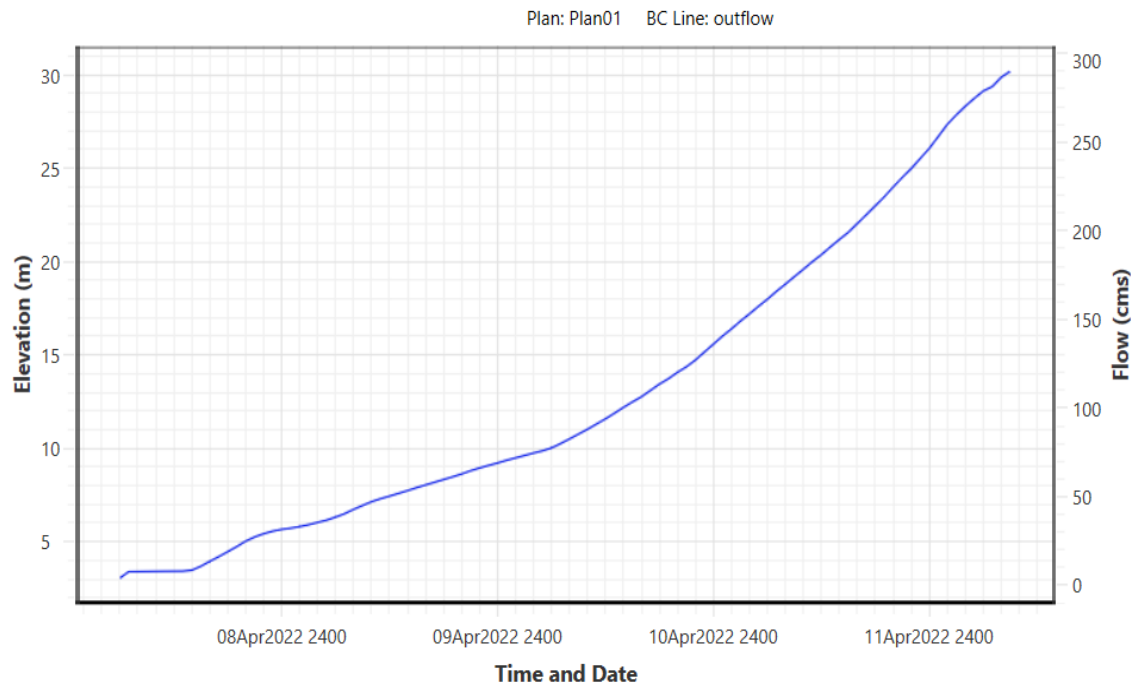
The hydrological and hydraulic modelling framework was developed to reproduce the observed flood behaviour associated with the April 2022 KwaZulu-Natal flood event. The simulation utilised observed rainfall recorded between 8 and 18 April 2022, together with terrain, land cover and river network data to simulate flood generation, routing and inundation across the selected catchments.

Observed streamflow data obtained from Department of Water and Sanitation (DWS) gauging stations were used to compare simulated flow responses with measured river discharges where data were available. Rainfall inputs were obtained from the eThekweni Metropolitan Municipality rainfall datafeed stations, which provided high-temporal-resolution rainfall observations across the study area.

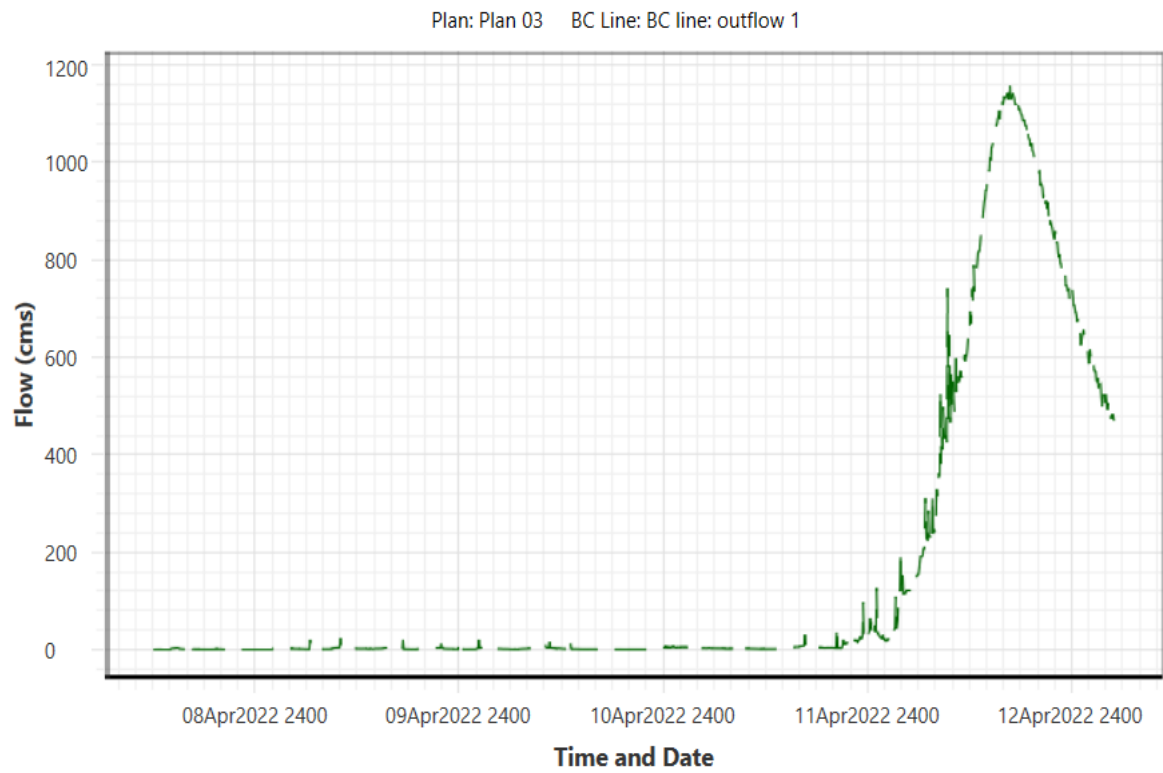
The simulated hydrographs indicated that river discharges increased rapidly following the onset of extreme rainfall, with peak flows generally occurring between 11 and 13 April 2022, consistent with observed rainfall patterns and reported flood impacts across coastal KwaZulu-Natal.

The uMgeni and Mvoti Rivers exhibited the strongest model performance, reflecting relatively well-defined hydrological behaviour and more reliable input datasets. The uMkomazi River also demonstrated good model agreement, particularly in representing peak flows associated with the April 2022 event. In contrast, the smaller catchments—namely the Mdloti, uMlazi, and Mbokodweni Rivers—showed slightly lower performance metrics. This can be attributed to their highly urbanised nature, rapid runoff response, and the influence of stormwater infrastructure, which introduces complexity into rainfall–runoff processes and reduces model predictability (Fletcher et al., 2013).



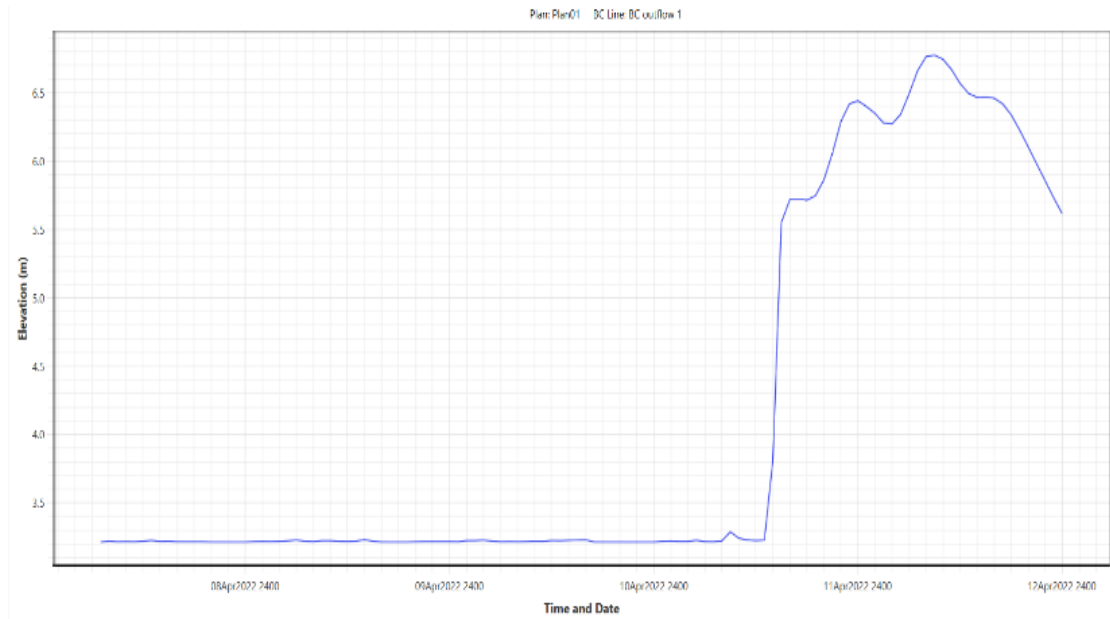


B



C

D



E

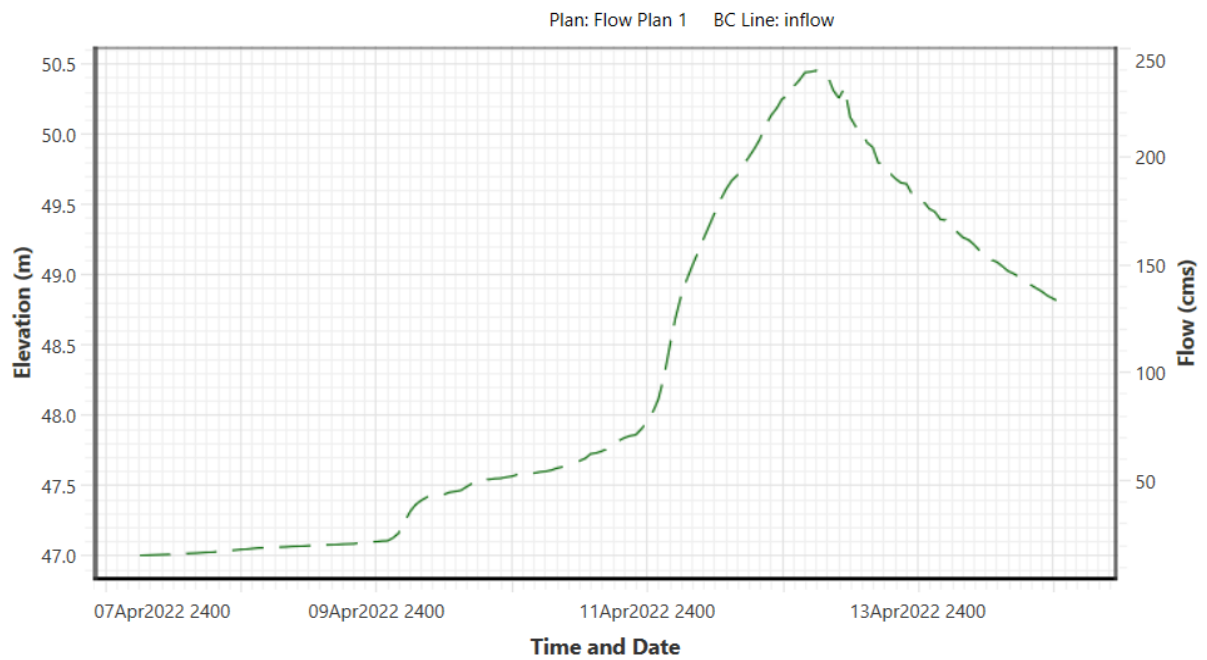


Figure 4-1: Flood hydrographs simulating the April 2022 flood event, for the rivers in this study using HEC-RAS computation. A) uMvoti River; B) uMdloti River; C) uMgeni River; D) uMlazi River; E) uMkomazi River.

Overall, comparison of the modelled flow behaviour with the available observed discharge records shown in Figure 4-1 indicates general agreement in the timing and pattern of elevated flows during

the April 2022 event. The rapid increase in discharge and distinct peak-flow periods indicate the strong response of the river systems to the intense rainfall experienced during the event. The correspondence in the timing and overall pattern of elevated flows across the catchments further illustrates the widespread nature of the flood event along the KwaZulu-Natal coastal region. Differences in peak discharge between catchments also highlight the influence of catchment size, drainage characteristics, land cover and degree of urbanisation on the magnitude and timing of the flood response.

4.2.2 Rainfall–Runoff Response

The hydrographs indicate that the intense rainfall experienced during the April 2022 event produced pronounced increases in river flow across the six study catchments. Peak flows occurred between 11 and 13 April 2022, coinciding with the period of extreme rainfall across the eThekweni region and surrounding coastal areas (SAWS, 2022). The observed rainfall records from this event were used as inputs to the HEC-RAS Rain-on-Grid hydraulic simulations.

The hydrographs reveal clear contrasts in hydrological response between the larger river systems (uMngeni, uMvoti and uMkomazi) and the smaller, more urbanised catchments (Mdloti, uMlazi and Mbokodweni). The uMngeni River is characterised by a high-magnitude but relatively delayed response, reflecting its larger catchment area and greater potential for catchment storage. This response is associated with substantial flood volumes and extensive inundation, particularly within downstream urban areas.

A similar pattern is evident in the uMkomazi River, which exhibited a comparatively slower response but generated extensive flooding within low-lying areas. The uMvoti River displayed an intermediate response, characterised by comparatively high flows and a more rapid rise than the larger uMngeni and uMkomazi systems.

In contrast, the hydrographs presented in Figure 4-1 show that the Mdloti, uMlazi and Mbokodweni catchments exhibited steep rising limbs and relatively short response times, indicating the rapid development of flood flows. Their smaller catchment areas, steeper gradients and greater extent of urban development promote rapid surface runoff by reducing infiltration and increasing the proportion of impervious surfaces. Consequently, these catchments are more susceptible to rapid-onset flooding, with water levels capable of rising over relatively short periods. This behaviour is particularly important within the densely developed uMlazi and Mbokodweni

catchments, where the concentration of people, infrastructure and development increases the potential consequences of flooding.

Overall, the results demonstrate considerable spatial variation in flood response across the coastal KwaZulu-Natal catchments. Smaller and more urbanised catchments exhibited more rapid responses, whereas the larger river systems generally displayed slower responses associated with more extensive and sustained flooding. These differences highlight the importance of catchment size, topography, land cover, urban development and catchment storage in controlling flood behaviour (Jewitt et al., 2015; Fletcher et al., 2013; Taylor et al., 2021b). The contrasting responses have important implications for flood risk management: smaller urban catchments may require rapid early-warning and stormwater-management interventions, while larger river systems require planning that accounts for the broader spatial extent and duration of inundation.

4.3 Hydraulic Modelling Results (HEC-RAS)

Flood inundation maps presented in Figures 4-2 to 4-11 were generated using HEC-RAS Version 6.6. Observed rainfall from the April 2022 flood event was applied directly to the two-dimensional computational domain, while catchment boundaries and stream networks prepared during the hydrological processing stage were used to support the hydraulic model setup. HEC-RAS simulated rainfall-driven surface flow and floodplain inundation, producing spatial outputs of flood depth, velocity and inundation extent.

The hydraulic modelling results indicate that inundation was predominantly concentrated along the main river corridors, adjacent floodplains and low-lying areas. These locations generally provide greater opportunity for floodwaters to spread laterally across the surrounding terrain. In the uMngeni catchment, extensive inundation is evident within downstream developed areas, while similar concentrations of flooding occur along the Mdloti and Mbokodweni river corridors.

4.3.1 Depth and Velocity distribution

Flood depth and velocity are important indicators of flood hazard intensity, as increasing depths and flow velocities generally increase the potential consequences for people, infrastructure and property (Chow et al., 1988; Jonkman, 2005). The simulations indicate substantial spatial

variation in both parameters, with deeper flooding generally concentrated within river channels and adjoining low-lying floodplain areas.

Within the uMkomazi catchment, the inundation pattern broadens considerably towards the coast, as illustrated in Figure 4-11. Lower-lying terrain and downstream hydraulic conditions may contribute to the lateral spreading and retention of floodwater in these areas. This is consistent with findings by Hughes *et al.* (2014), who highlight the role of wetlands in attenuating flow but prolonging inundation duration. Although flow velocities may decrease as water spreads across broader floodplain areas, prolonged or deeper inundation can still result in substantial impacts on infrastructure, property and surrounding environments.

4.3.2 Flood Inundation Maps

The maximum simulated water-depth outputs were exported from HEC-RAS into the GIS environment for spatial visualisation and analysis. Figures 4-2 to 4-11 present the spatial distribution of simulated flood depths across the study catchments during the April 2022 event.

Unlike the classified flood hazard maps presented subsequently, these outputs display continuous flood-depth values, allowing spatial variations in inundation depth to be examined across the modelled areas. Flood depth is an important indicator of hazard severity because increasing water depth is generally associated with greater potential consequences for people, buildings and infrastructure. The continuous depth surfaces therefore provide the basis for the subsequent classification of flood hazard levels.

Across the study catchments, greater simulated flood depths were generally concentrated within the main river channels, adjoining floodplains and low-lying areas, with shallower inundation occurring towards the margins of the flooded areas. These spatial patterns are broadly consistent with documented accounts of the April 2022 KwaZulu-Natal floods, which reported severe impacts within river corridors, low-lying areas and densely developed settlements (NDMC, 2022; Govender, 2023).

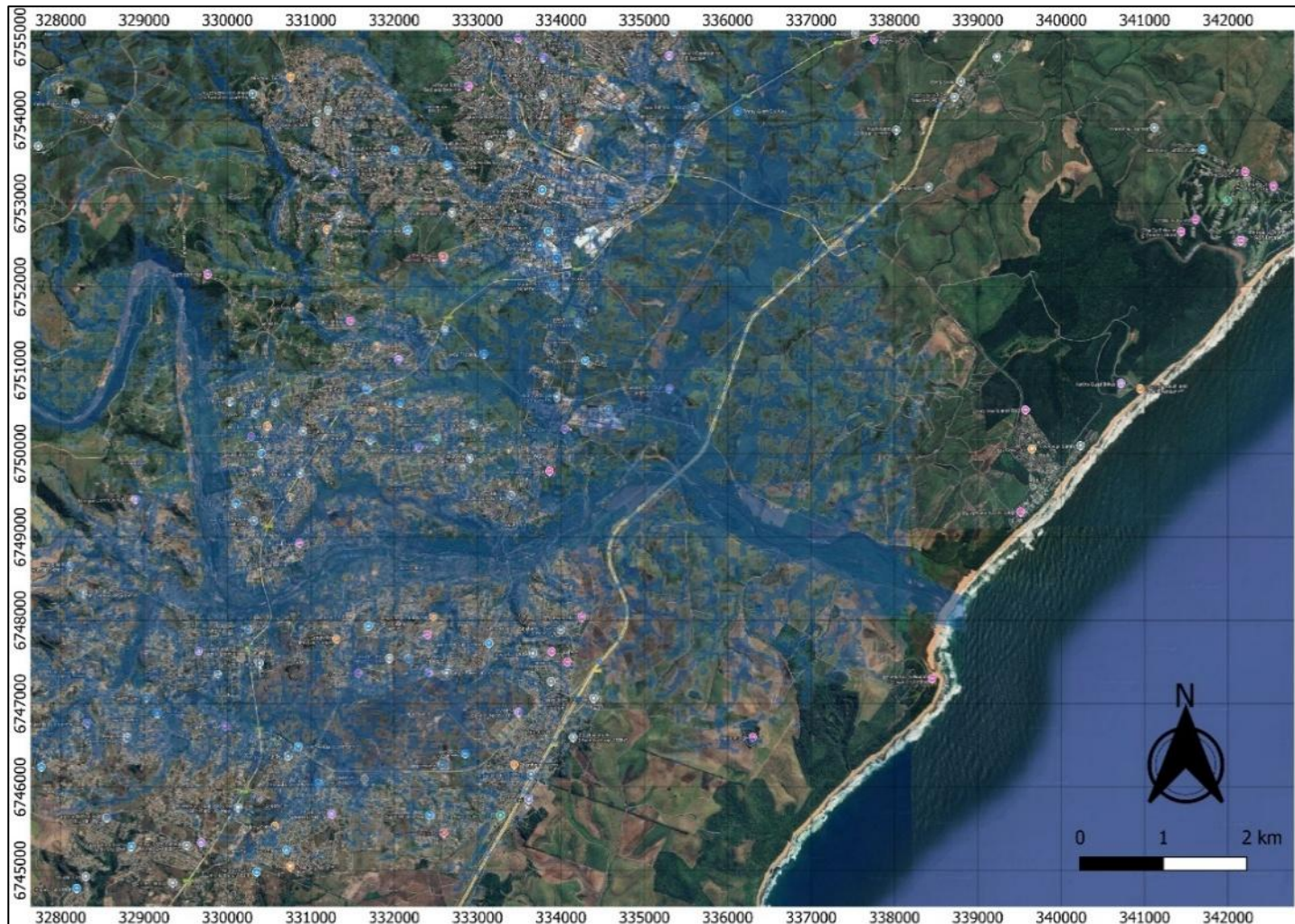


Figure 4–2: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along Mvoti River during the simulated flood event.

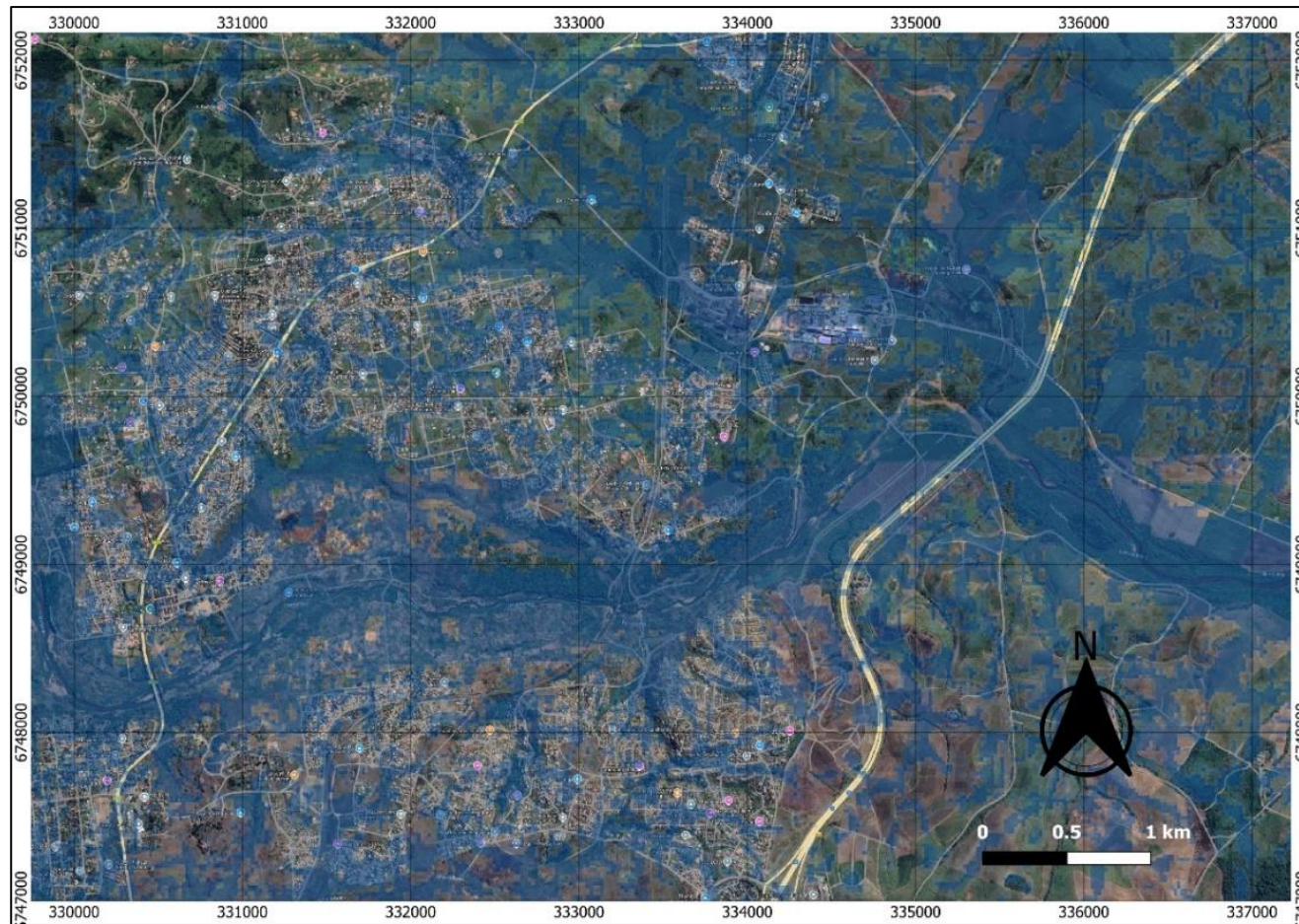


Figure 4–3: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along Mvoti River focused on KwaDukuza Municipality during the simulated flood event

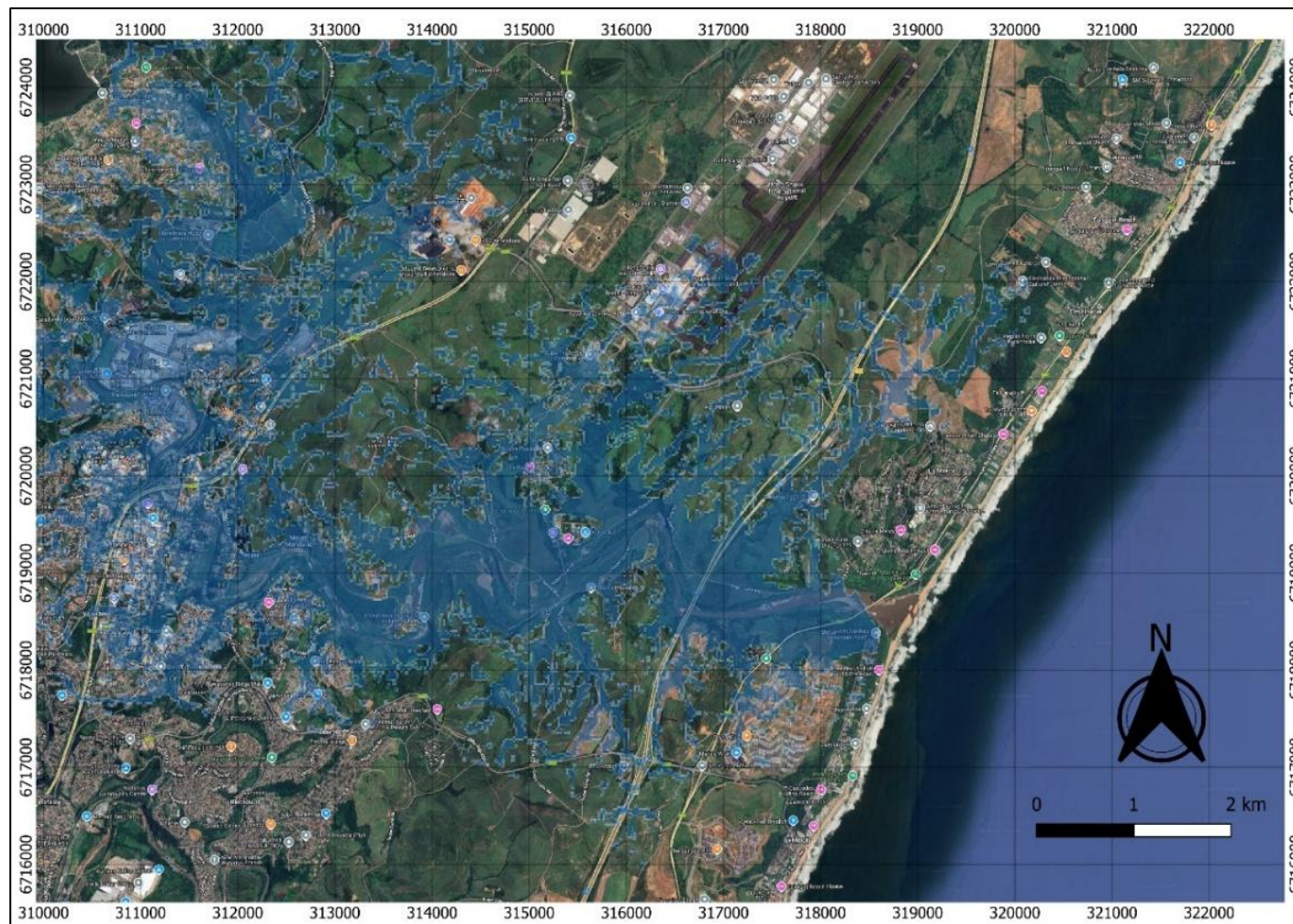


Figure 4–4: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along Mdloti River during the simulated flood event.

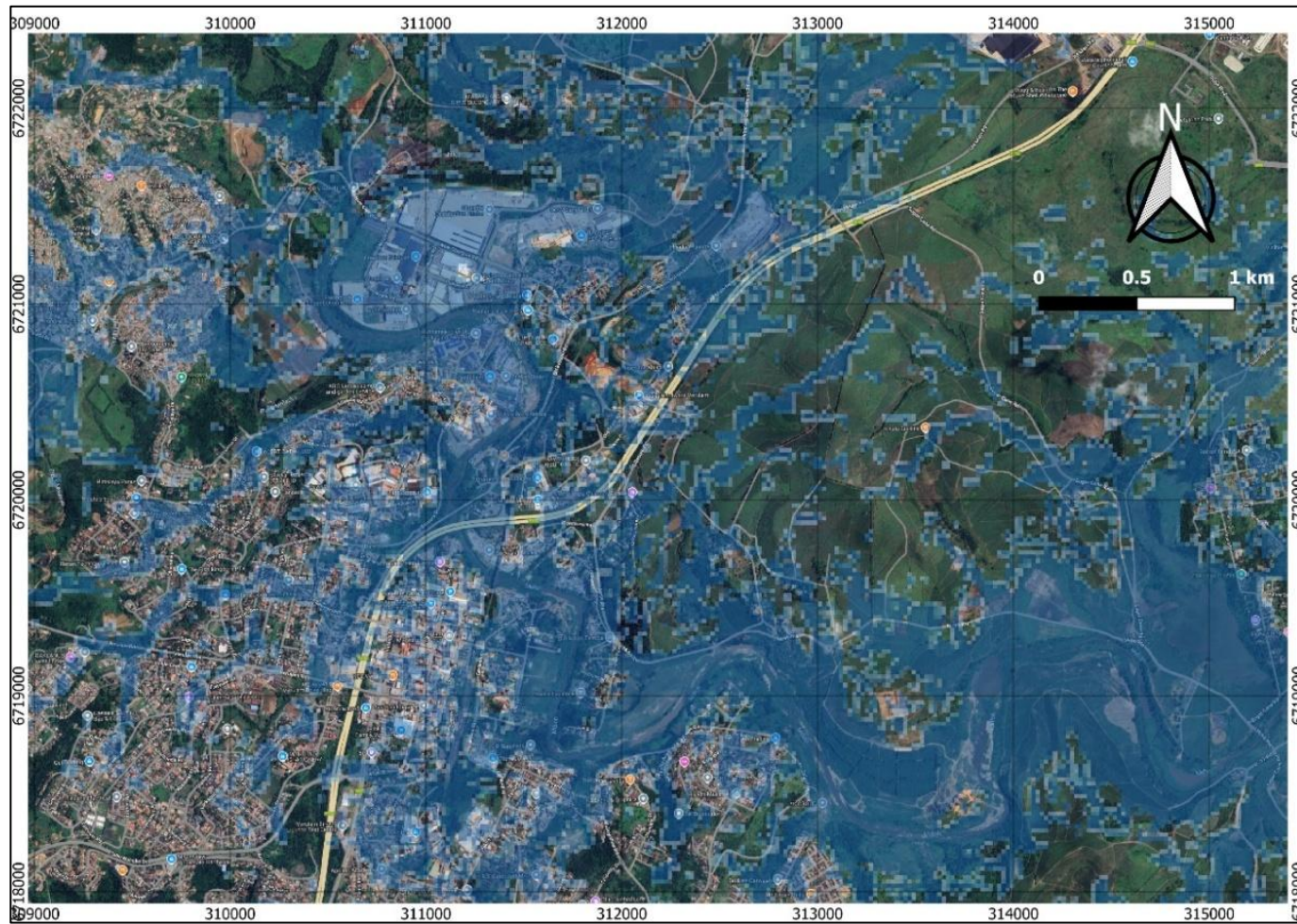


Figure 4–5: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along Mdloti River during the simulated flood event (zoomed in to the Canelands and Verulam area)

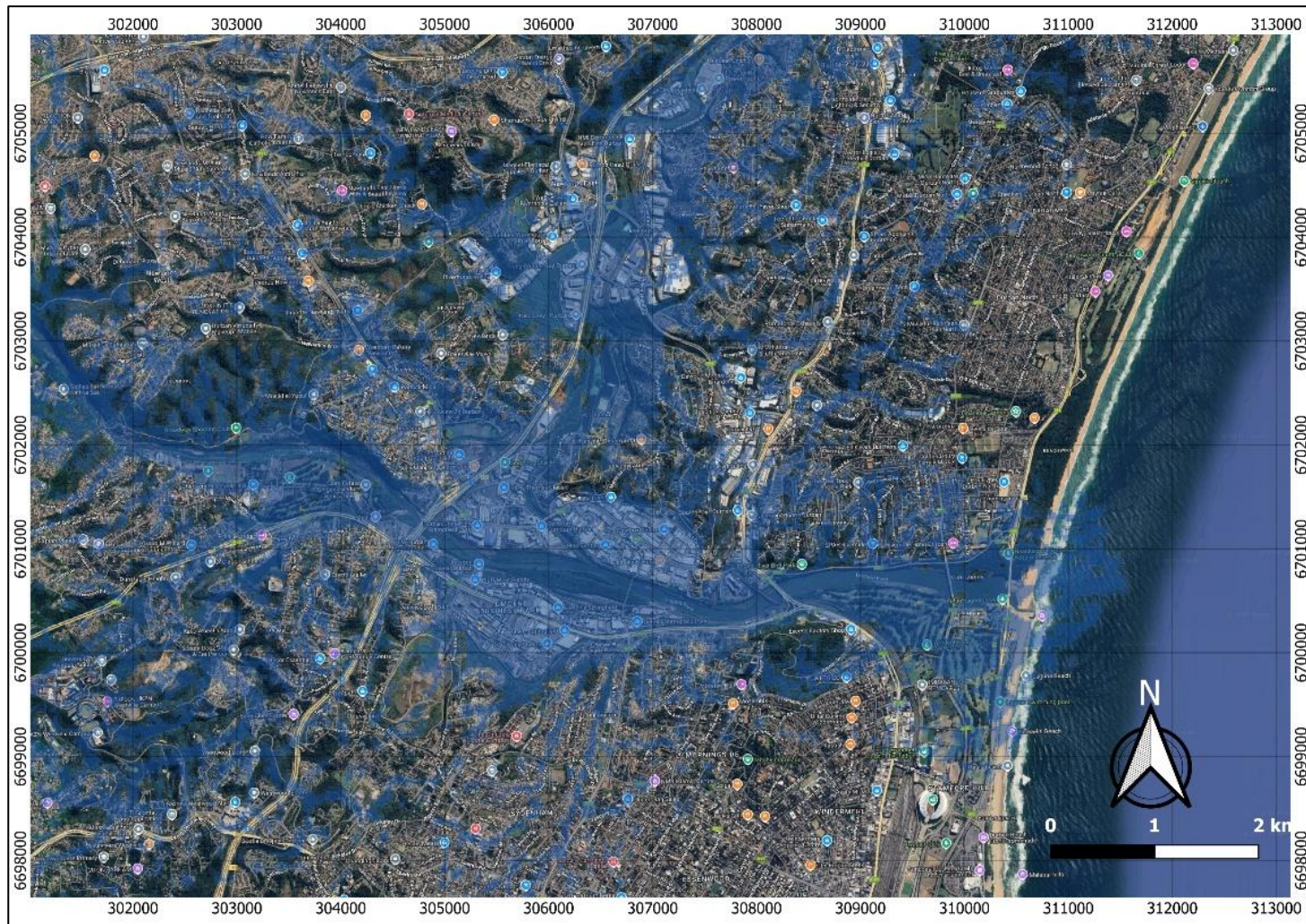


Figure 4–6: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along uMgeni River during the simulated flood event. (Durban–Inanda section).

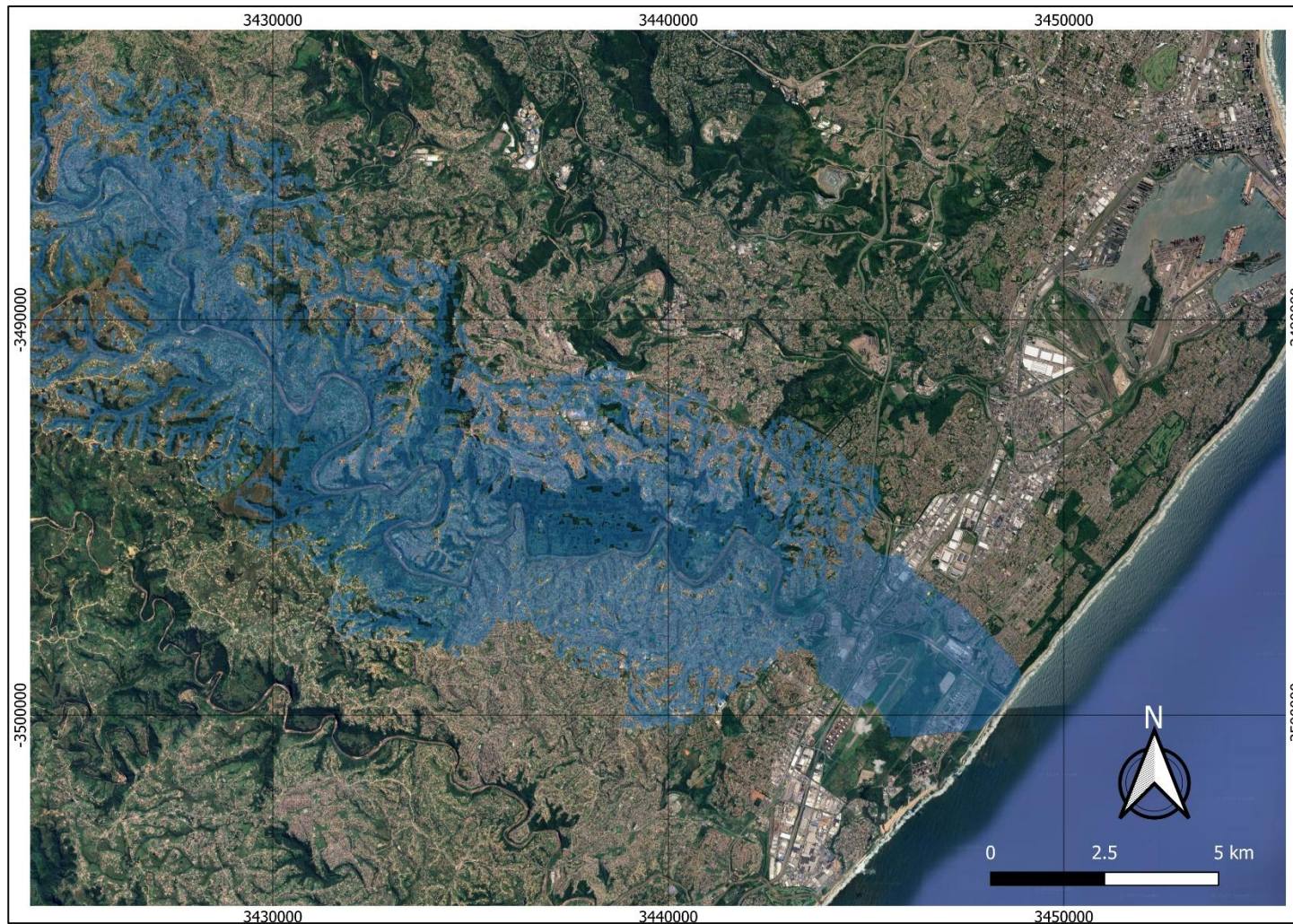


Figure 4–7: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along Umlazi River during the simulated flood event.

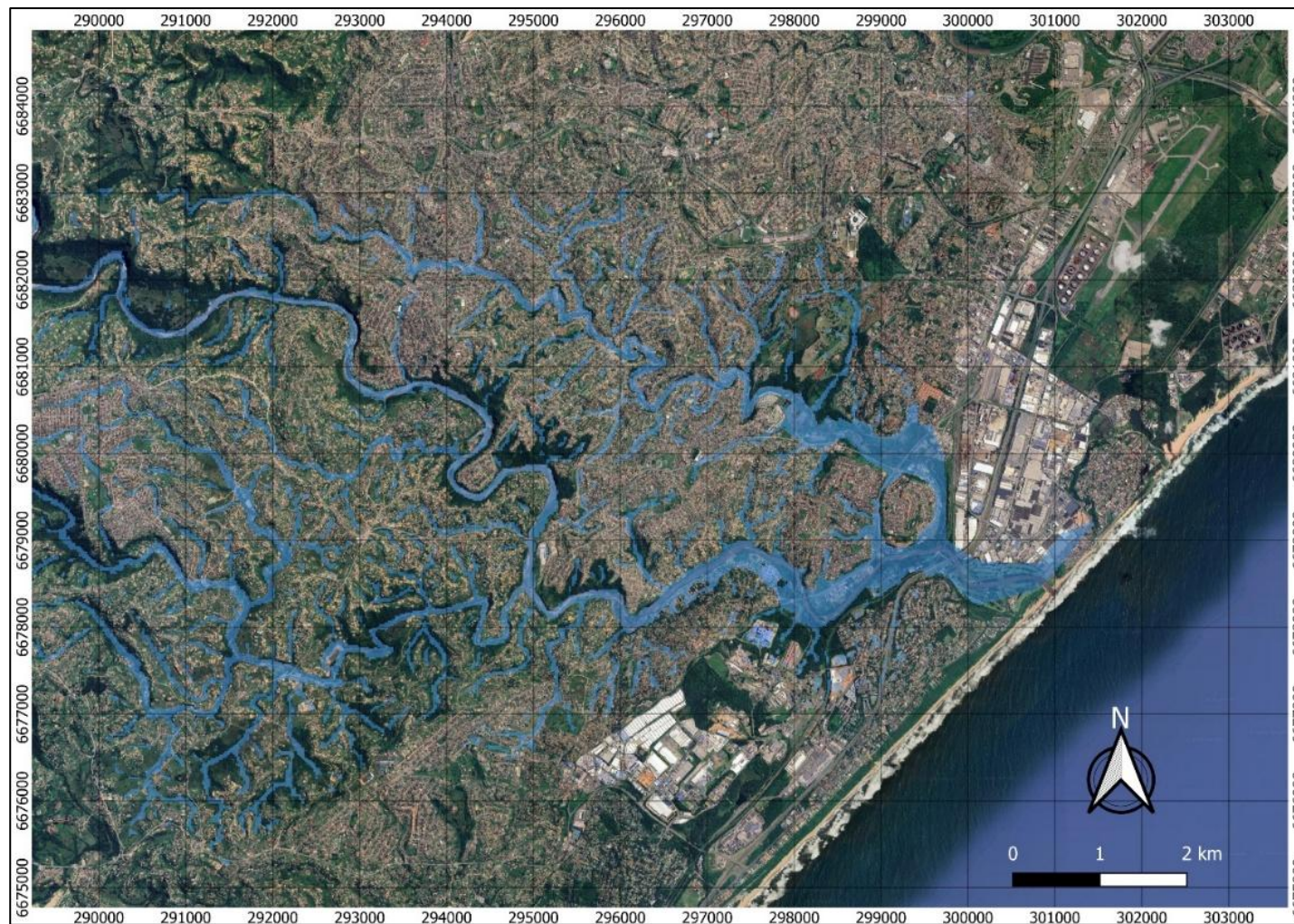


Figure 4–8: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along Mbokodweni River during the simulated flood event.



Figure 4–9: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along uMkomazi River during the simulated flood event.

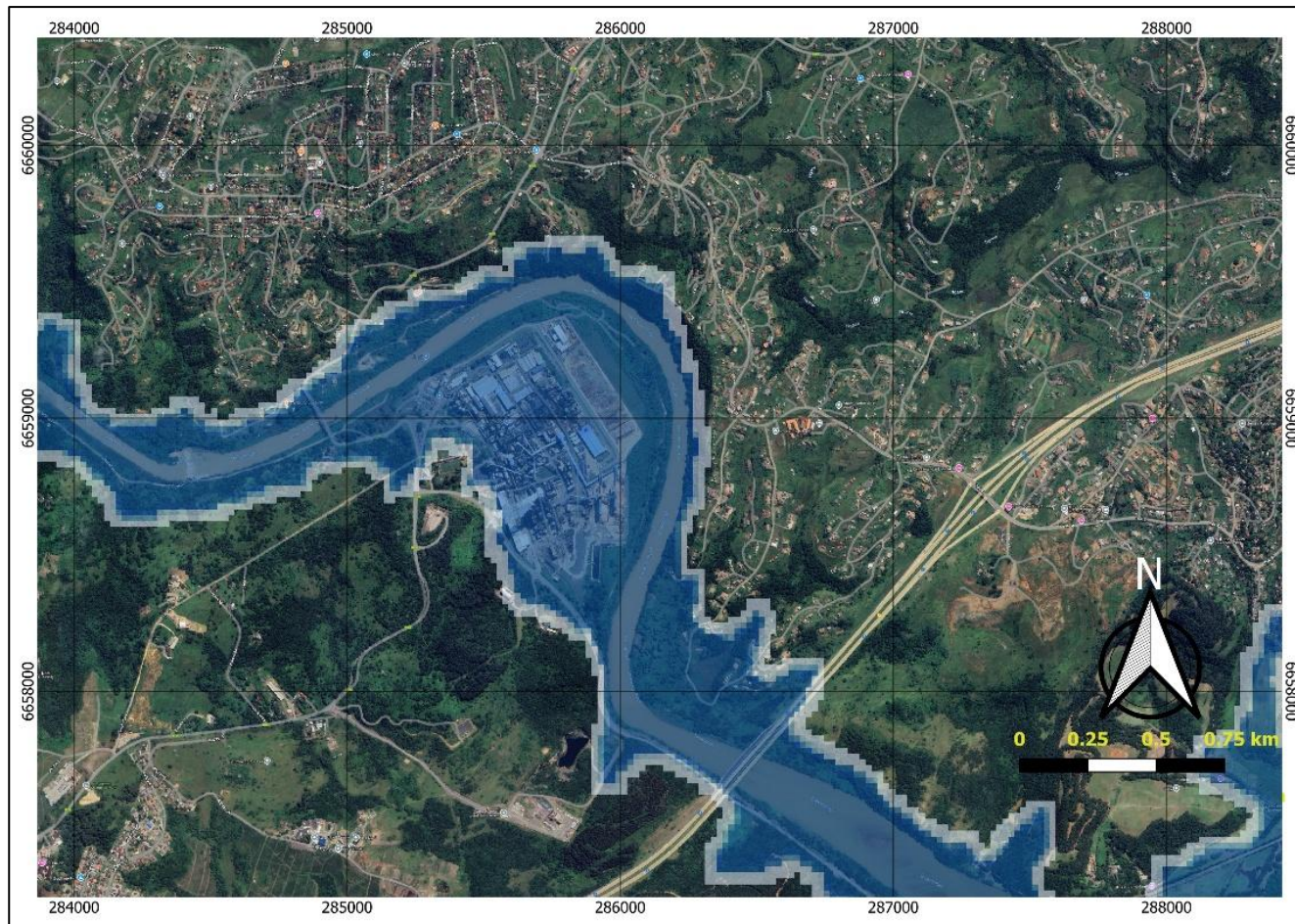


Figure 4–10: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along uMkomazi River during the simulated flood event, and inundation of Sappi Saiccor

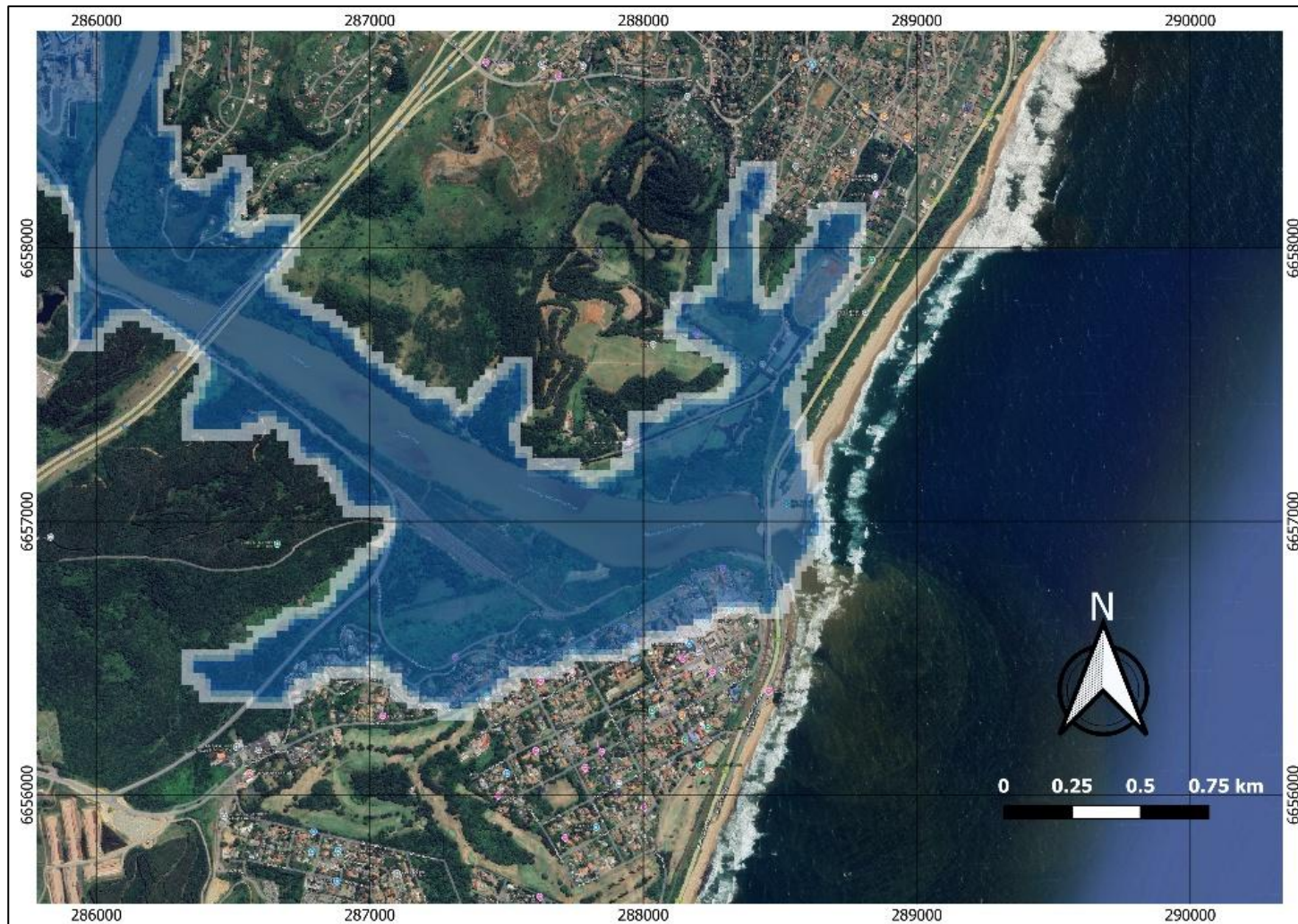


Figure 4–11: Flood extent map generated from HEC-RAS hydraulic modelling, showing the spatial distribution of inundated areas along uMkomazi River at the coast during the simulated flood event.

The flood inundation and extent maps across the study area reveal distinct spatial patterns in flood behaviour, strongly influenced by catchment size, topography, land use, and hydraulic controls. These differences are reflected in the distribution of flood hazard classes, ranging from low to very high hazard zones.

The Mvoti River, shown in Figure 4-2, displays a more rapid hydrological response, with flooding characterised by quick channel overtopping and relatively confined inundation extents. The steeper gradients facilitate faster runoff and shorter lag times, resulting in moderate to high hazard zones concentrated along the river channel. While the spatial extent of flooding is more limited compared to larger systems, localised hotspots of high hazard are evident, particularly in semi-urban areas where increased surface runoff amplifies peak discharges. This can be seen as a rapid incline in the hydrograph (Figure 4-1 A). The flood extent map generated from the HEC-RAS hydraulic model for the Mvoti River indicates significant inundation within low-lying areas of the KwaDukuza Municipality during the simulated flood event, as shown in Figure 4-3. Floodwaters were concentrated along the main river channel and expanded laterally across adjacent floodplains, which occurs in areas characterised by gentle slopes and reduced elevation. The results show that settlements located close to the riverbanks are highly exposed to flooding, with inundation extending into developed areas where infrastructure and access routes are present.

Similarly, the Mdloti River flood extent maps (Figures 4-4 and 4-5) demonstrate extensive flooding along both the broader catchment and the more densely developed Canelands and Verulam areas, where urban expansion and impervious surfaces contribute to rapid runoff generation and elevated flood levels. The lower reaches of the Mdloti River were especially vulnerable due to their flat coastal topography and proximity to the coastline, increasing the likelihood of compounded flood impacts associated with intense rainfall, storm surges, and sea-level influences. In several locations, floodwaters intersected with major road networks and developed properties, indicating the potential for significant socio-economic disruption and infrastructure damage during extreme flood events. The results further suggest that encroachment into floodplain areas and modification of natural drainage systems have reduced the flood attenuation capacity of these catchments, thereby intensified flood propagation and increasing community vulnerability.

In contrast, the uMgeni and uMkomazi Rivers depicted in Figure 4-6 and Figure 4-9, as larger systems, are characterised by extensive floodplain inundation and higher overall flood magnitudes. In the uMgeni River, widespread flooding is observed particularly downstream of Inanda Dam, where regulated flows combine with high inflows during extreme events. The lower

reaches exhibit broad lateral spreading due to gentle gradients, resulting in large areas classified as high to very high hazard zones, especially within low-lying urban and peri-urban areas. Similarly, the uMkomazi River, particularly in the Sappi and coastal sections, as shown in Figure 4-10, shows significant floodplain inundation driven by low-gradient topography and backwater effects near the river mouth. These conditions promote prolonged water retention and deeper flooding, contributing to the expansion of very high hazard zones in coastal floodplains and areas influenced by tidal interactions.

The Mdloti River (Figure 4-5), uMlazi River (Figure 4-7) and Mbokodweni River (Figure 4-8) exhibit flood behaviour typical of smaller, highly urbanised catchments, where land use plays a dominant role in shaping flood dynamics. In the Mbokodweni River, inundation is concentrated within developed areas, where impervious surfaces and constrained drainage systems lead to rapid runoff generation and limited infiltration. This results in intense, localised flooding, with high to very high hazard zones primarily confined to built-up, low-lying areas. Similarly, the Mdloti River, particularly in the Verulam area, shows pronounced localised flooding patterns. The inundation maps indicate that floodwaters accumulate in topographic depressions and densely developed zones, producing discrete pockets of very high hazard, despite the relatively smaller catchment size.

Overall, the results demonstrate a clear distinction between flood regimes: larger river systems (uMgeni and uMkomazi) are dominated by widespread, prolonged inundation with extensive high and very high hazard zones, while smaller and more urbanised catchments (Mbokodweni and Mdloti) exhibit rapid, localised flooding with concentrated high hazard hotspots. The Mvoti River represents an intermediate condition, where flood hazards are more channel-bound but still influenced by land use and runoff dynamics.

These findings highlight the importance of integrating both hydrological processes and land use characteristics in flood risk assessments. The spatial distribution of hazard classes underscores the need for differentiated flood management strategies, with large-scale floodplain management required for major river systems, and targeted urban drainage and infrastructure interventions necessary for smaller, highly developed catchments.

4.4 Vulnerability Assessment

4.4.1 Socio-economic Vulnerability Index

A Multi-Criteria Decision Analysis (MCDA) approach was employed using socio-economic indicators (population density, settlement type, proximity to rivers and Land use). The various indicators were combined using the AHP-weighted overlay method (Saaty, 1980; Phiri and Mazvimavi, 2020). The following weights were assigned:

- **Population density:** 0.20
- **Informal Settlements:** 0.30
- **Proximity to rivers:** 0.40
- **Land use:** 0.10

The resulting Flood Vulnerability Index (FVI) was then categorised on a 1 to 5 scale (1 = Low Vulnerability, 5 = Very High Vulnerability).

4.4.2 Spatial Patterns of Vulnerability

High vulnerability zones were concentrated in informal settlements along uMngeni, uMlazi and Mbokodweni Rivers, as seen in Figure 4-12. These communities exhibit high exposure (proximity to rivers), limited adaptive capacity (poor infrastructure, low income), and high sensitivity (unreinforced housing). Low vulnerability areas correspond to higher-elevation zones and planned urban areas with formal drainage and flood control systems.

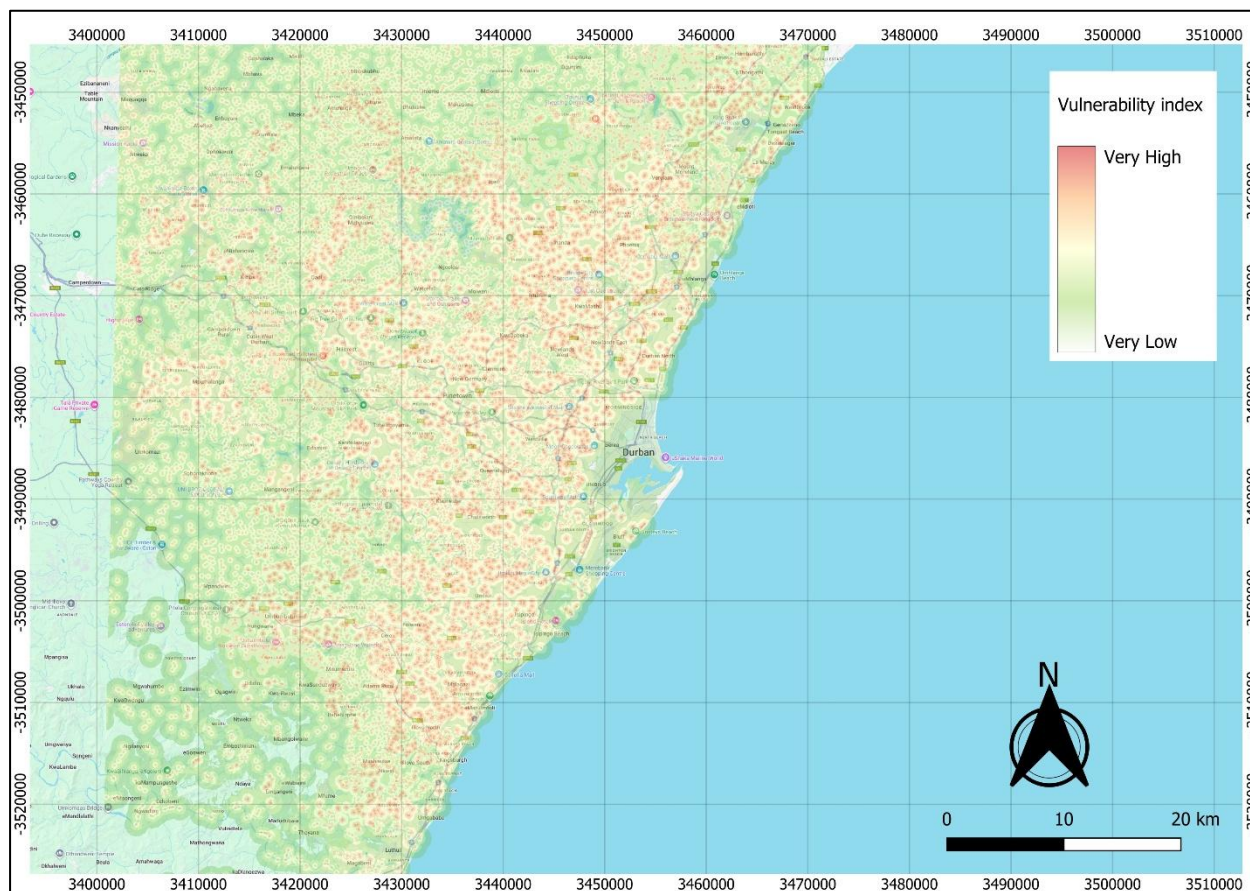


Figure 4-12: Flood vulnerability map of coastal KwaZulu-Natal classifying areas into different hazard levels based on the flood vulnerability index.

4.5 Integrated Flood Risk and Vulnerability Mapping

The vulnerability layer was integrated with the flood depth layer to generate comprehensive flood risk and vulnerability maps. Vulnerability patterns are illustrated in Figures 4-13 to 4-16, where green represents areas of low vulnerability and red represents areas of high vulnerability. The vulnerability assessment was based on a weighted combination of socio-economic and environmental indicators, including population density, settlement type, proximity to rivers, and land use. As a result, vulnerability is not determined solely by distance from river channels.

Consequently, some areas located close to rivers may display relatively low vulnerability because they consist of lower-density developments, formal infrastructure, or land uses with greater adaptive capacity and flood resilience. In contrast, certain areas situated further from river channels may exhibit high vulnerability due to the presence of densely populated informal settlements, inadequate infrastructure, and limited socio-economic capacity to prepare for,

respond to, or recover from flood events. This demonstrates that flood vulnerability is influenced not only by physical exposure to flooding but also by underlying social and developmental conditions that affect community resilience. The results, therefore, highlight the importance of integrating both hydrological hazard and socio-economic vulnerability indicators when assessing overall flood risk within coastal KwaZulu-Natal.

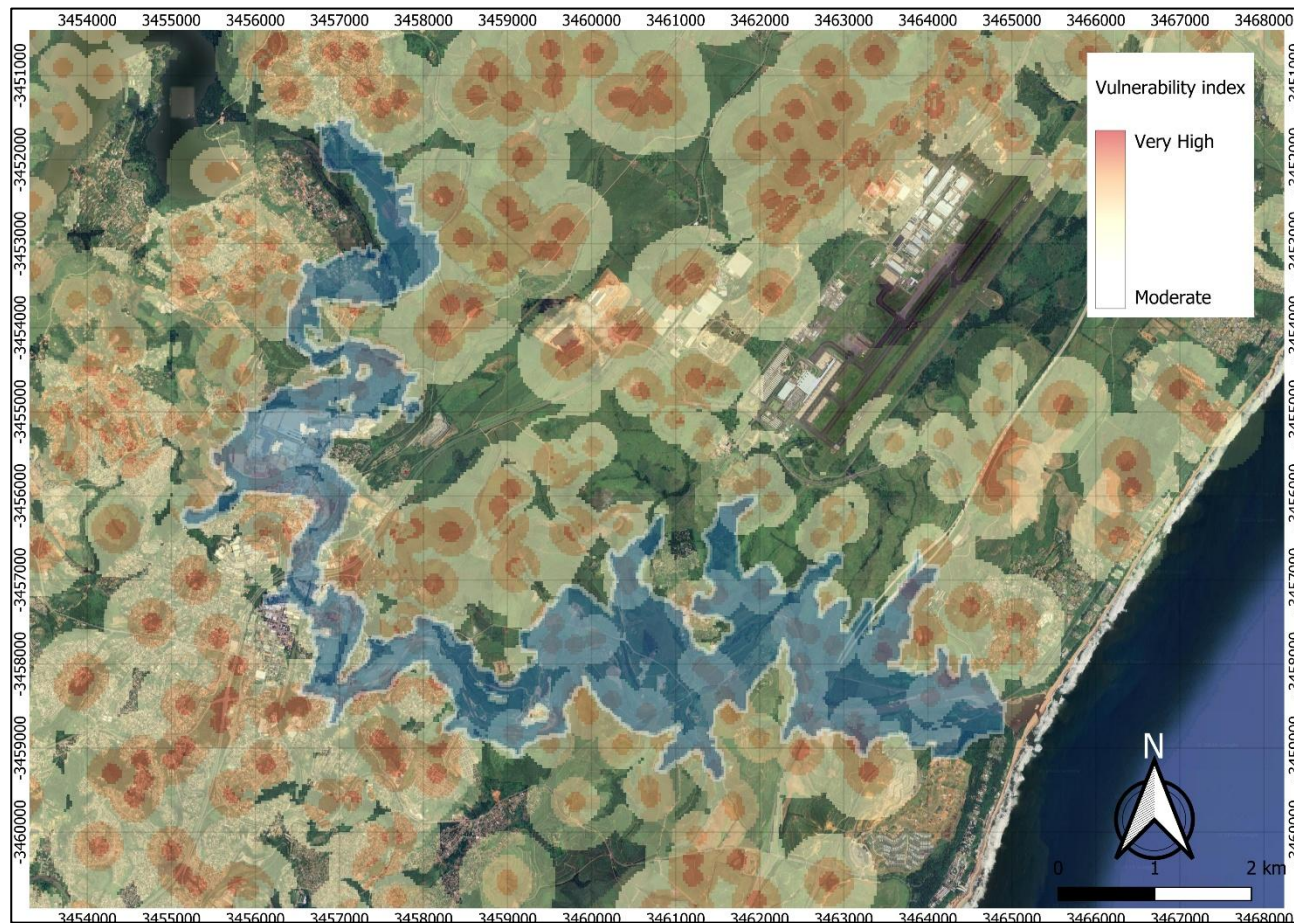


Figure 4-13a: Integrated flood risk map combining hazard and vulnerability to identify moderate to high-risk areas along the Mdloti River.

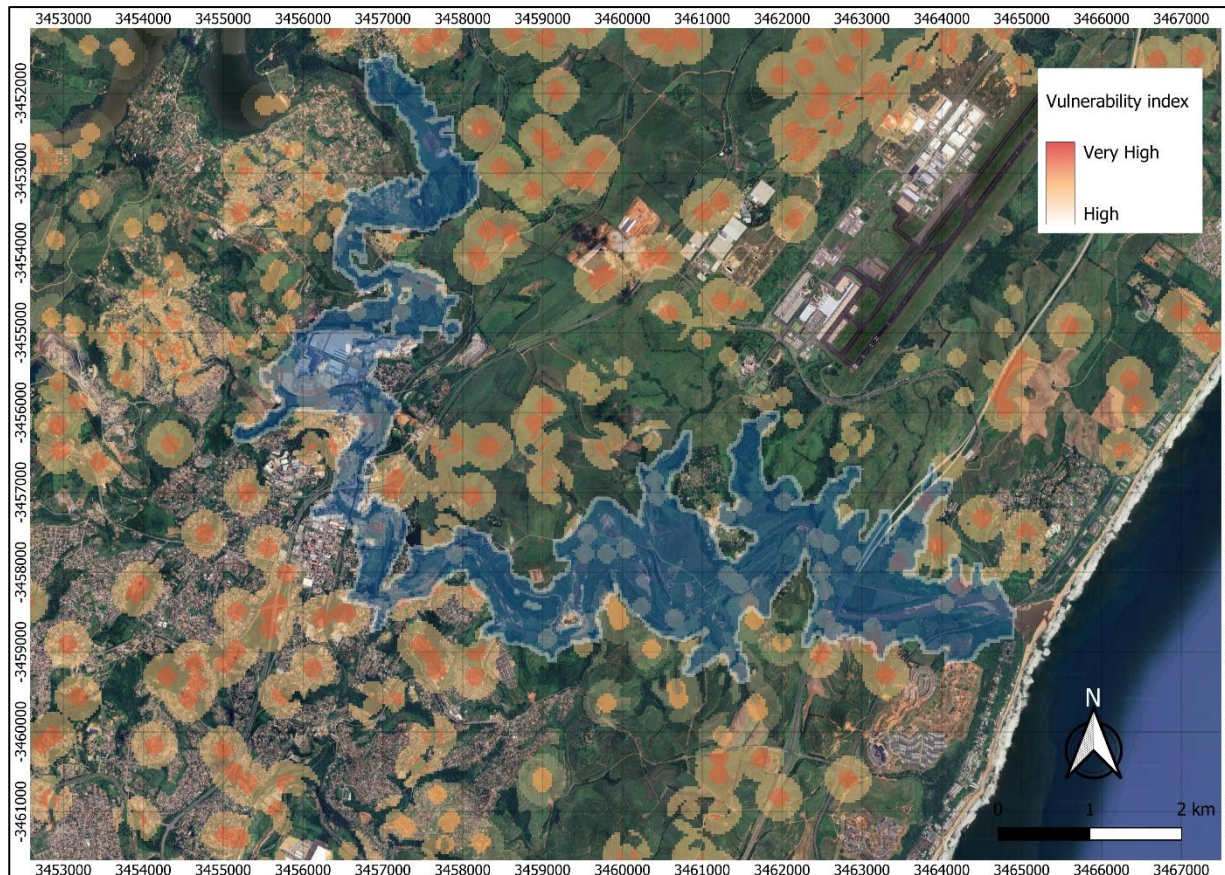


Figure 4-13b: Integrated flood risk map combining hazard and vulnerability to identify high to very high-risk areas along the Mdloti River.

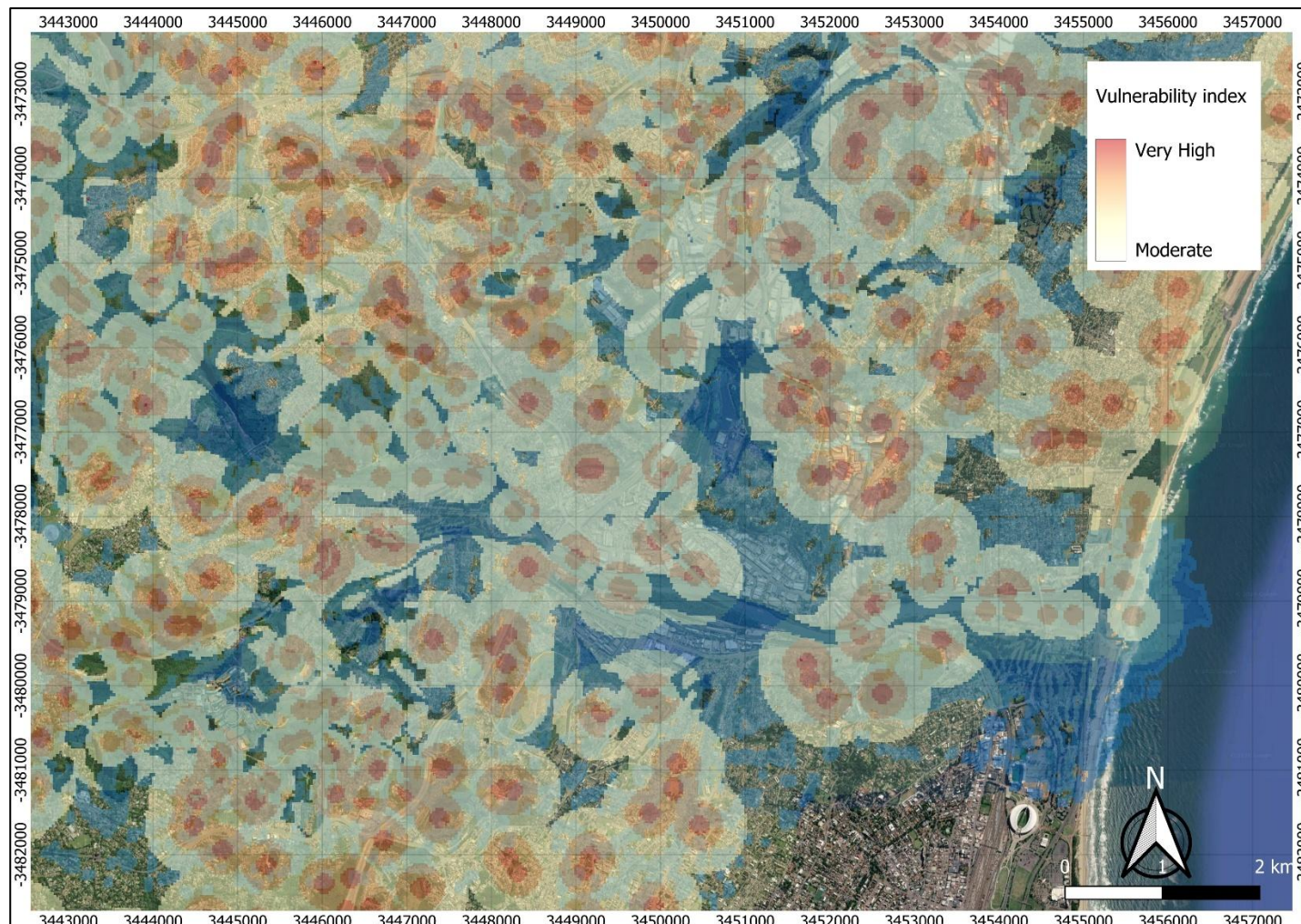


Figure 4-14: Integrated flood risk map combining hazard and vulnerability to identify moderate to high-risk areas along the uMgeni River.

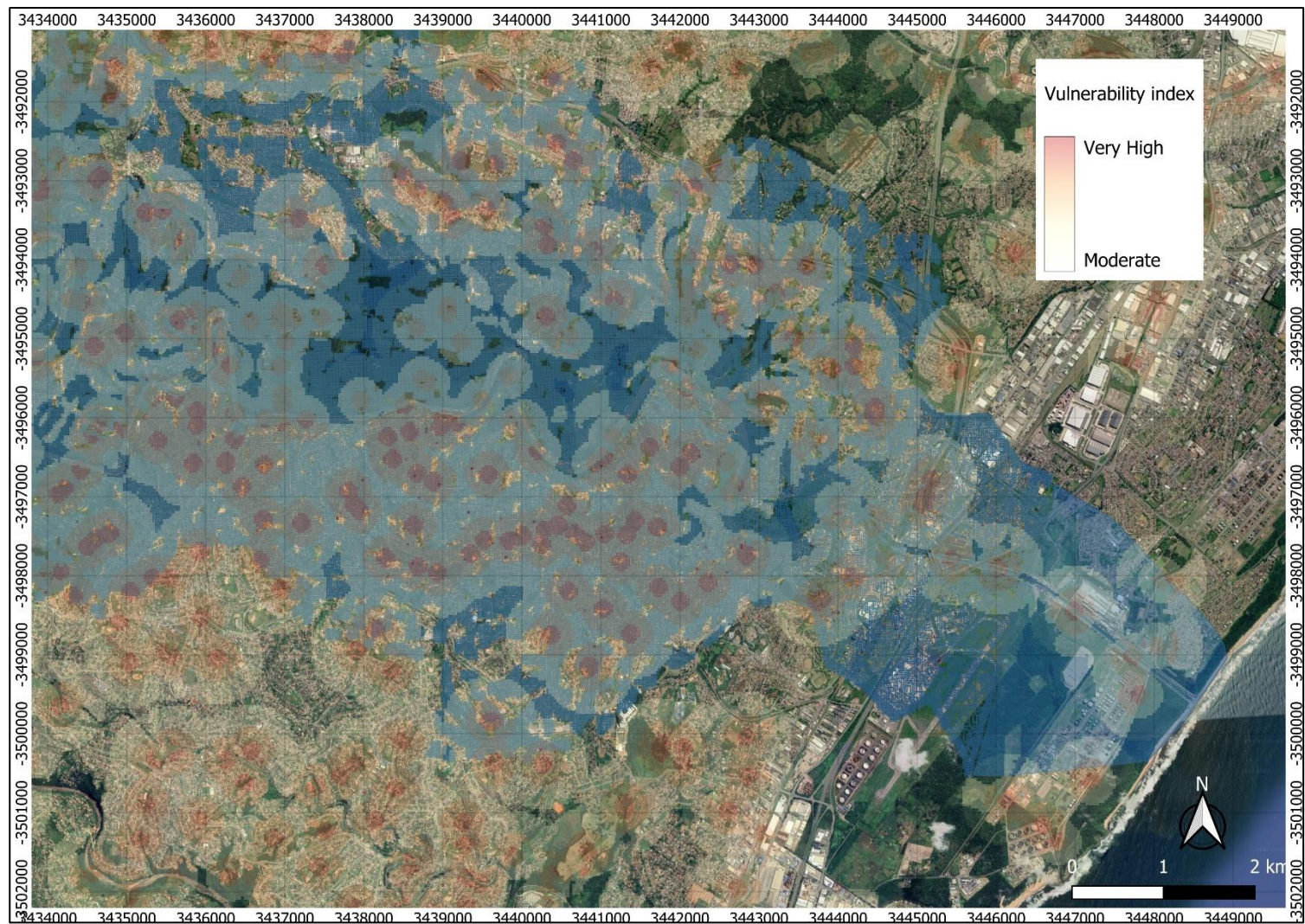


Figure 4-15: Integrated flood risk map combining hazard and vulnerability to identify moderate to very high-risk areas along the uMlazi River.

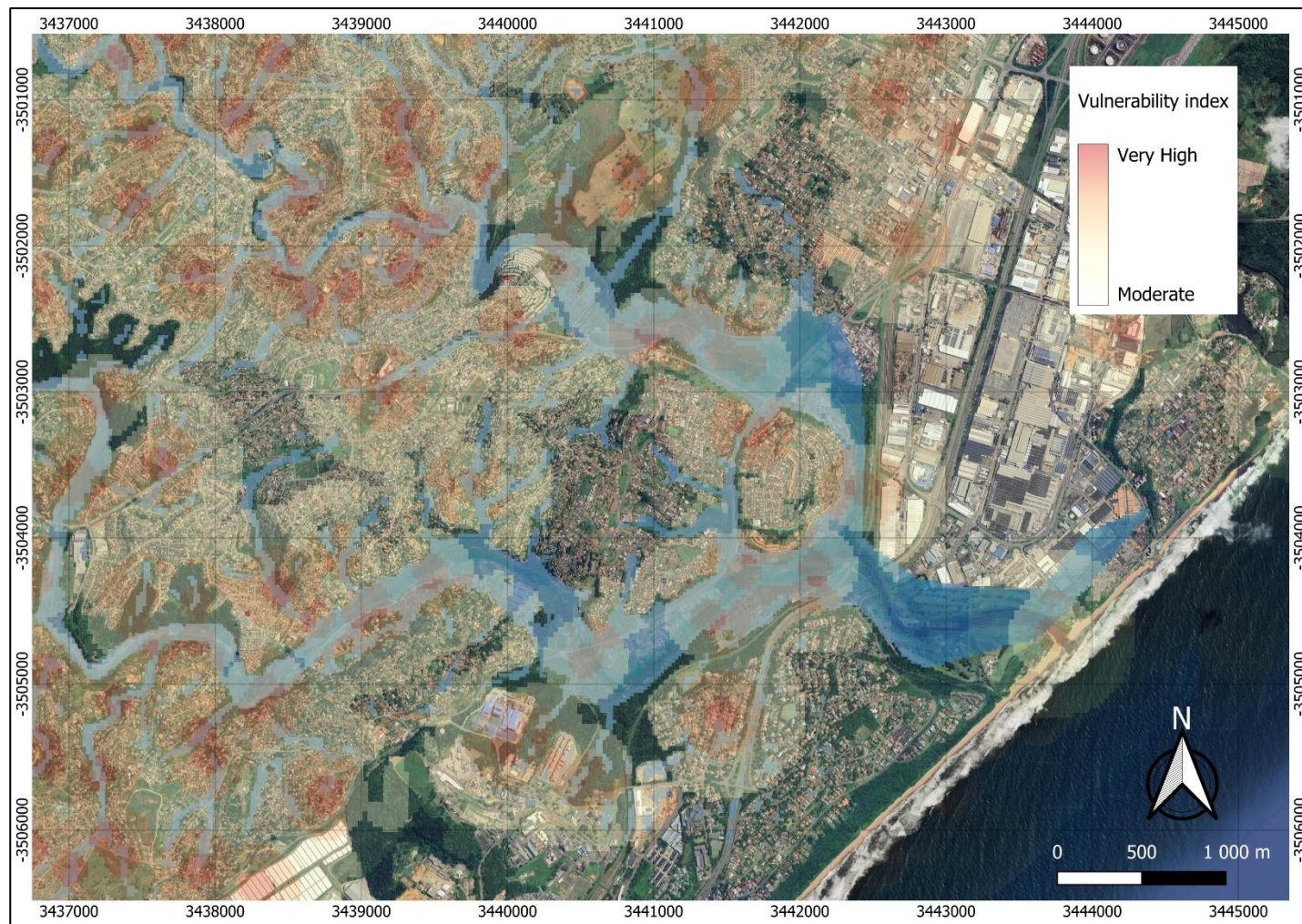


Figure 4-16: Integrated flood risk map combining hazard and vulnerability to identify moderate to very high-risk areas along the Mbokodweni River.

The integration of the flood hazard maps generated using HEC-RAS with the Flood Vulnerability Index produced a comprehensive spatial representation of flood risk across the eThekweni Metropolitan Municipality. The resulting flood risk maps demonstrate that the greatest flood risk occurs where high flood hazard coincides with high levels of socio-economic vulnerability. These areas are predominantly associated with river corridors and floodplains where dense urban development, informal settlements, and high population densities are located in close proximity to major watercourses.

The vulnerability assessment indicates that river proximity is a major determinant of flood risk, particularly where settlements have expanded onto floodplains and low-lying areas adjacent to rivers. Areas characterised by informal settlements generally exhibit higher vulnerability owing to limited infrastructure, poor housing quality, and reduced adaptive capacity. Similarly, densely populated residential areas display elevated vulnerability because a greater number of people and assets are exposed to flooding, increasing the potential for social and economic losses.

When combined with the flood hazard maps, these vulnerable areas correspond closely with locations predicted to experience significant inundation during the simulated flood event. This spatial relationship demonstrates that flood risk is not solely dependent on the magnitude of flooding but also on the characteristics of the exposed communities. Consequently, areas experiencing relatively similar flood depths may exhibit substantially different levels of flood risk depending on their socio-economic conditions and land-use characteristics.

The integrated flood risk maps therefore provide an important decision-support tool for flood risk management by identifying locations where flood mitigation measures, disaster preparedness, and spatial planning interventions should be prioritised. The results further highlight the importance of integrating physically based flood modelling with socio-economic vulnerability assessments to support evidence-based disaster risk reduction and climate adaptation planning within the eThekweni Metropolitan Municipality.

The observed spatial distribution of flood risk is consistent with previous studies that demonstrate that flood risk arises through the interaction of flood hazard, exposure, and vulnerability rather than hazard alone (Balica et al., 2013; Koks et al., 2015; Nasiri et al., 2016; Salami et al., 2017). Similar patterns have also been observed during recent flood events in KwaZulu-Natal, where flood impacts were greatest in densely populated settlements located adjacent to river systems and floodplains (COGTA, 2022; Fitchett, 2023).

4.6 Discussion

4.6.1 Hydrological Response and Catchment Characteristics

The results demonstrate that flood behaviour across the selected coastal catchments of KwaZulu-Natal varies considerably according to catchment size, topography, land cover, degree of urbanisation and drainage characteristics. These factors influence the rate at which rainfall is converted to surface runoff, the movement of water through the catchment and the spatial extent of inundation. Steeper terrain promotes more rapid downslope movement of water, whereas flatter and low-lying floodplain areas favour the lateral spreading and retention of floodwater. Similarly, urbanisation increases impervious surface cover and reduces infiltration, thereby promoting more rapid surface runoff during intense rainfall events (Smithers and Schulze, 2002; Fletcher et al., 2013).

The contrasting responses of the study catchments were evident in the hydrographs and HEC-RAS flood inundation outputs. The smaller and more urbanised uMdloti, uMlazi and Mbokodweni catchments exhibited relatively rapid responses during the April 2022 rainfall event. In these catchments, dense urban development and modified drainage systems increase the concentration of surface runoff into river and stormwater networks. This behaviour was particularly evident within the uMlazi catchment, where the confined drainage network conveys runoff through a densely developed urban environment towards the coast. Rapid increases in flow within such catchments are important from a flood-management perspective because they can reduce the time available for warning and emergency response.

In comparison, the larger uMgeni and uMkomazi systems exhibited broader patterns of inundation associated with their larger drainage areas and extensive downstream floodplains. Within the uMkomazi catchment, floodwater spread across relatively broad low-lying areas towards the coast, producing a more spatially extensive inundation pattern. The uMvoti displayed an intermediate response relative to the larger and smaller catchment systems. These differences demonstrate that flood behaviour cannot be considered uniform across the KwaZulu-Natal coastal region and that the physical characteristics of individual catchments strongly influence the spatial and temporal development of flooding.

Natural vegetation, wetlands and riparian areas can also influence catchment response by slowing surface runoff, promoting infiltration and providing temporary storage. However, urban expansion, modification of natural drainage systems and development within floodplain environments can reduce these functions and increase the potential consequences of extreme rainfall events (Davis-Reddy and Vincent, 2017).

The observed differences between the study catchments have important implications for flood-risk management. Smaller, highly urbanised catchments such as the uMlazi, uMdloti and Mbokodweni require particular attention to rapid warning, stormwater management and maintenance of drainage infrastructure, whereas larger river systems require broader floodplain-management and land-use planning approaches. The results therefore demonstrate the importance of adopting catchment-specific flood-management strategies rather than applying a uniform approach across the KwaZulu-Natal coastal region.

4.6.2 Vulnerability and Socio-economic Dimensions

The vulnerability assessment revealed distinct spatial variations across the areas for which sufficient socio-economic data were available. Higher Flood Vulnerability Index (FVI) values were predominantly associated with densely populated areas, informal settlements and communities situated close to major river corridors. These spatial patterns demonstrate that vulnerability is not determined by a single factor, but by the combined influence of exposure, settlement characteristics, population concentration and land use.

River proximity received the greatest weighting within the vulnerability assessment and consequently had a strong influence on the resulting spatial pattern. However, the highest vulnerability was generally associated with locations where proximity to rivers coincided with other vulnerability factors, particularly high population density and informal settlement areas. This demonstrates the importance of considering multiple interacting indicators rather than using proximity to the flood source alone as a measure of vulnerability. The finding is consistent with GIS-based multi-criteria approaches in which physical exposure and socio-economic characteristics are integrated to represent the spatial variability of flood vulnerability (Nasiri et al. 2016; Tehrany et al. 2017).

Informal settlements contributed substantially to areas classified as more vulnerable. Such settlements may be characterised by limited drainage infrastructure, less resilient housing and reduced access to services and resources required to prepare for and recover from flooding. Their occurrence within or close to river corridors and low-lying areas can further increase potential flood consequences. Similar patterns have been identified within South African cities, where historical spatial inequality, rapid urbanisation and limited access to suitable land have contributed to the development of informal settlements within environmentally hazardous areas (Davis-Reddy and Vincent, 2017; Phiri and Mazvimavi, 2020).

Population density further influenced the spatial distribution of vulnerability because densely populated areas contain greater concentrations of people and assets potentially exposed to flooding. High population concentrations can also create additional challenges for evacuation, emergency response and post-disaster recovery (Koks *et al.*, 2014; Nasiri *et al.*, 2016). Land use had a comparatively lower weighting in the FVI but provided an additional representation of differences in the potential consequences of flooding between developed and less developed areas.

When considered alongside the HEC-RAS flood-depth outputs, the vulnerability results indicate that the greatest potential consequences occur where substantial inundation overlaps with highly vulnerable communities. This is particularly important where densely populated or informal settlement areas occur close to major river corridors. Areas experiencing similar flood conditions may therefore experience different consequences depending on the characteristics and adaptive capacity of the exposed population.

The spatial patterns identified by the vulnerability assessment are also broadly consistent with documented impacts of the April 2022 KwaZulu-Natal floods. Severe impacts were reported within settlements and developed areas located along river corridors and floodplains, including damage to housing, transport infrastructure and public services (COGTA, 2022). This broad correspondence provides contextual support for the spatial patterns represented by the FVI, although it should not be interpreted as formal validation of the vulnerability model.

Overall, the results demonstrate that reducing flood impacts requires attention to both the physical characteristics of flooding and the socio-economic conditions of exposed communities. Flood-management interventions should therefore combine hydraulic and stormwater measures with improved spatial planning, appropriate management of development within flood-prone areas and targeted measures to reduce vulnerability within informal and densely populated settlements.

4.6.3 Model Reliability and Limitations

The models demonstrated strong predictive performance; however, limitations include:

Data availability and spatial resolution: The availability and spatial coverage of rainfall, streamflow and socio-economic datasets varied across the study area. Rainfall-gauge coverage was less dense in some catchments, while consistent population-density and informal-settlement datasets were not available for all study areas. Consequently, vulnerability maps could not be produced for the uMvoti and uMkomazi catchments. The 30 m SRTM DEM also provides a

catchment-scale representation of terrain but may not capture fine-scale features such as small drainage channels, culverts, embankments and detailed urban infrastructure that can influence local flood behaviour.

Hydraulic model representation: The HEC-RAS simulations employed a 2D Rain-on-Grid approach using the Diffusion Wave equation set. Although this provided a spatial representation of rainfall-driven surface flow and floodplain inundation, the model necessarily simplifies complex hydraulic processes. Manning's roughness coefficients and infiltration characteristics were assigned according to the available land-cover and surface information and may not capture all local spatial variability. Processes such as sediment transport, debris blockage, infrastructure failure and the full urban stormwater drainage network were also not explicitly represented.

Model evaluation: Observed rainfall from the April 2022 event was incorporated directly into the Rain-on-Grid simulations. However, comprehensive calibration and independent validation using multiple historical flood events could not be undertaken because consistent high-temporal-resolution rainfall, discharge and observed inundation datasets were not available across all catchments. Where suitable observations were available, the model outputs were compared with observed streamflow records and documented flood impacts to provide a qualitative assessment of model behaviour. The results should therefore be interpreted as a reconstruction of the April 2022 event rather than as a fully calibrated predictive model.

Vulnerability assessment: The FVI incorporated river proximity, informal settlements, population density and land use. While these indicators represent important dimensions of vulnerability, social vulnerability is considerably more complex and may also be influenced by income, age, housing quality, access to services, mobility and adaptive capacity (Salami *et al.*, 2017). The FVI should therefore be interpreted as a spatial representation of selected vulnerability characteristics rather than a complete representation of all socio-economic conditions.

Future and compound flood conditions: The study focused on the April 2022 event and did not explicitly simulate future climate scenarios, future urban development or changes in land use. Coastal water levels, storm surge and other compound flooding processes were also not explicitly incorporated. The results consequently represent the conditions and datasets used for the reconstructed event and should not be interpreted as predictions of future flood magnitude or extent. Nevertheless, the modelling framework provides a basis for future scenario-based analysis using forecast rainfall, design storms, improved terrain data and projected climate conditions.

These limitations do not prevent the results from being used to identify broad catchment-scale patterns of flood hazard and vulnerability, but they should be considered when interpreting local-scale flood depths, inundation boundaries and vulnerability classifications.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Flooding remains a significant natural hazard within the coastal catchments of KwaZulu-Natal, where intense rainfall interacts with urban development, floodplain occupation and socio-economic vulnerability to produce substantial impacts. The April 2022 KwaZulu-Natal flood disaster demonstrated the consequences of these interacting factors and provided the event investigated in this study. The research assessed flood behaviour and vulnerability across selected coastal catchments using terrain and catchment processing, two-dimensional hydraulic modelling and GIS-based spatial analysis.

The study focused on the uMgeni, uMdloti, uMvoti, uMlazi, Mbokodweni and uMkomazi catchments. Terrain processing and catchment delineation were undertaken to define basin and sub-basin boundaries, drainage networks, river reaches and junctions required to establish the spatial framework for the subsequent hydraulic analysis. This catchment-based approach demonstrated the importance of drainage configuration, catchment size, topography, land cover and urban development in understanding differences in flood behaviour between the selected river systems.

Hydraulic modelling was undertaken using HEC-RAS Version 6.6 through a two-dimensional Rain-on-Grid approach. Observed rainfall from the April 2022 event was applied directly to the computational domain, with the Diffusion Wave equation set used to represent the movement of rainfall-generated surface flow across the terrain. The resulting simulations generated spatial outputs of flood depth, velocity and inundation extent for the selected catchments.

The hydraulic results demonstrated clear spatial differences in flood behaviour between the study catchments. Inundation was predominantly concentrated within river corridors, adjacent floodplains and low-lying areas. Smaller and more urbanised catchments, particularly the uMdloti, uMlazi and Mbokodweni, exhibited relatively rapid flood responses, whereas the larger uMgeni and uMkomazi systems were characterised by broader patterns of downstream inundation. These differences emphasise the importance of catchment characteristics in determining the spatial and temporal development of flooding and demonstrate that flood-management requirements vary between catchments.

The simulated flood-depth outputs were subsequently used to identify spatial variations in flood hazard. Areas of greater flood depth were generally concentrated within the main river channels and adjoining low-lying floodplains, while shallower inundation occurred towards the margins of

the flooded areas. The simulated spatial patterns were broadly consistent with documented accounts of severe flooding along river corridors and low-lying developed areas during the April 2022 KwaZulu-Natal disaster. This comparison provides contextual support for the simulated flood patterns but does not constitute formal independent validation of model performance. This cautious interpretation is consistent with the limitations identified in the study regarding the availability of observed inundation and high-temporal-resolution hydrological data.

Vulnerability Assessment

The vulnerability assessment addressed the socio-economic dimension of flood impacts using a GIS-based Multi-Criteria Decision Analysis (MCDA) incorporating the Analytic Hierarchy Process (AHP). Four indicators—river proximity, informal settlements, population density and land use—were standardised and integrated through a weighted raster overlay to generate the Flood Vulnerability Index (FVI). The assessment therefore moved beyond a point-based representation of vulnerability and provided a continuous spatial representation across areas for which sufficient data were available.

The results demonstrated that higher vulnerability was generally concentrated where several contributing factors coincided spatially, particularly within densely populated and informal settlement areas located close to major river corridors. River proximity had the greatest weighting within the assessment, while informal settlements and population density represented important socio-economic contributors. Land use provided an additional representation of differences in the potential consequences of flooding across developed and less developed areas. These findings support the broader understanding that flood vulnerability is produced through the interaction of physical exposure and socio-economic conditions rather than through any single factor (Balica *et al.*, 2013; Nasiri *et al.*, 2016; Salami *et al.*, 2017).

When the vulnerability patterns were considered alongside the HEC-RAS flood-depth outputs, the greatest potential consequences were associated with areas where substantial inundation coincided with highly vulnerable communities. This spatial relationship was particularly important within densely developed and informal settlement areas situated close to river corridors. The results therefore demonstrate that similar levels of flood hazard may produce different consequences depending on the characteristics of the population and land uses exposed.

Vulnerability mapping could not be completed for the uMvoti and uMkomazi catchments because sufficiently consistent population-density and informal-settlement spatial datasets were unavailable. The vulnerability conclusions are therefore restricted to the portions of the study area

for which the required datasets were available and should not be extrapolated to the two excluded catchments without additional socio-economic data.

Achievement of the Research Objectives

The study objectives were addressed through the development of a spatial modelling framework linking catchment preparation, hydraulic modelling and vulnerability assessment. Terrain and drainage processing established the hydrological structure of the selected catchments, while HEC-RAS 2D Rain-on-Grid modelling reconstructed the spatial characteristics of flooding associated with the April 2022 rainfall event. The hydraulic simulations produced flood-depth, velocity and inundation outputs that enabled the spatial distribution of flood hazard to be examined across the selected river systems.

The socio-economic component of the research was addressed through the development of the AHP-based FVI, which integrated population density, informal settlements, land use and river proximity. Consideration of these vulnerability patterns alongside the flood hazard outputs enabled areas where substantial flooding and increased vulnerability coincide to be identified and discussed.

The study therefore achieved its broader purpose of developing an integrated spatial framework for examining the physical and socio-economic dimensions of flooding within the selected coastal catchments. Importantly, the results represent a reconstruction and assessment of the April 2022 event rather than a fully calibrated predictive flood model.

Scientific and Practical Contribution

The principal scientific contribution of the study lies in the integration of catchment-scale terrain processing, HEC-RAS 2D Rain-on-Grid modelling and GIS-based multi-criteria vulnerability assessment within a common spatial framework. The approach demonstrates how physical flood characteristics and socio-economic vulnerability can be examined together to provide a broader understanding of the factors influencing flood consequences.

A further contribution is the use of predominantly accessible geospatial and observational datasets to undertake flood assessment across multiple coastal catchments. This is relevant within data-constrained environments where high-resolution terrain, hydrological and socio-economic information may not be consistently available. However, the study also demonstrates the limitations associated with reliance on such datasets, particularly when detailed local-scale flood prediction or comprehensive model validation is required.

From a practical perspective, the resulting flood hazard and vulnerability information provides spatial evidence that may assist the eThekweni Metropolitan Municipality, KwaZulu-Natal Provincial Disaster Management Centre, Department of Water and Sanitation and other relevant institutions in identifying areas requiring further investigation, flood mitigation, improved preparedness and more flood-sensitive spatial planning.

Limitations and Overall Synthesis

Several limitations should be considered when interpreting the findings. The 30 m SRTM DEM may not fully represent fine-scale terrain, channel geometry, culverts, road embankments and urban drainage infrastructure. Rainfall-gauge and streamflow coverage also varied across the study area, while the availability of consistent socio-economic datasets restricted the spatial extent of the vulnerability assessment. Furthermore, comprehensive calibration and independent validation using multiple historical flood events could not be undertaken.

Accordingly, the hydraulic outputs should be interpreted as a catchment-scale reconstruction of the April 2022 event, rather than precise predictions of flood conditions at individual properties or a fully validated predictive model. Nevertheless, the study provides useful evidence of the spatial variability of flood hazard and vulnerability across the investigated catchments and establishes a framework that can be refined as improved terrain, rainfall, streamflow and socio-economic datasets become available.

Overall, the study demonstrates that flood impacts within coastal KwaZulu-Natal cannot be understood solely through the physical magnitude of flooding. Flood consequences arise through the interaction of rainfall-driven flooding, catchment characteristics, patterns of human settlement and socio-economic vulnerability. Effective flood-risk reduction therefore requires both improved understanding of flood behaviour and targeted interventions addressing the vulnerability and exposure of communities located within flood-prone environments.

5.2 Recommendations and areas of future research

The findings of this study provide a basis for targeted recommendations for flood-risk management within the investigated coastal catchments. Rather than applying uniform interventions across the study area, the results indicate that management responses should reflect differences in catchment behaviour, development patterns and socio-economic vulnerability. The recommendations therefore focus on municipal spatial planning, vulnerable communities, early warning, catchment management and improvements to future modelling.

Integration into Municipal Spatial Planning

The flood hazard and vulnerability maps should be considered within the eThekweni Metropolitan Municipality Spatial Development Framework (SDF), Land Use Scheme and relevant development-control processes. Attention should be given to floodplain areas along the uMgeni, uMdloti, uMlazi and Mbokodweni river systems, where the analysis identified the coincidence of flood-prone areas with densely developed or vulnerable communities.

The mapped information can support the screening of proposed developments, identification of locations requiring more detailed flood investigations and implementation of flood-sensitive land-use controls. Development within river corridors and low-lying floodplain environments should be carefully assessed to avoid increasing future exposure. Where development already exists, the maps can assist in prioritising areas for more detailed local-scale assessment and mitigation.

Targeted Interventions within Vulnerable Communities

The vulnerability assessment identified densely populated and informal settlement areas close to river corridors as particularly important locations for flood-risk reduction. The eThekweni Metropolitan Municipality, KwaZulu-Natal Provincial Disaster Management Centre and Department of Human Settlements should prioritise these communities for targeted interventions.

Interventions should be appropriate to local conditions and may include improvements to stormwater drainage, routine removal of obstructions from drainage systems, improved waste management, riverbank stabilisation and upgrading of vulnerable infrastructure. Where settlements occupy areas subject to substantial flood hazard, longer-term options may include settlement upgrading or appropriately planned relocation where this is socially, economically and legally feasible. Such interventions should be undertaken with meaningful community participation rather than relying solely on engineering responses.

Flood Forecasting and Early Warning

The relatively rapid flood responses identified within the smaller urbanised catchments highlight the importance of effective rainfall and flood-warning systems. Attention should be directed towards the uMdloti, uMlazi and Mbokodweni catchments, where rapid increases in flood flows can reduce the time available for preparedness and emergency response.

The South African Weather Service (SAWS), Department of Water and Sanitation (DWS), eThekweni Disaster Management Centre and KwaZulu-Natal Provincial Disaster Management Centre should continue strengthening the integration of rainfall observations, weather forecasts, river monitoring and flood-modelling information. Warning information should be communicated

rapidly to exposed communities using accessible communication channels, including mobile alerts and community-based warning networks where appropriate (UNDRR, 2022; van Niekerk *et al.*, 2020a).

Catchment and Environmental Management

The contrasting flood behaviour observed between the study catchments demonstrates the need for catchment-specific management strategies. Smaller, highly urbanised systems such as the Mdloti, uMlazi and Mbokodweni require particular attention to stormwater capacity, drainage maintenance, detention measures and management of impervious surface runoff.

Larger river systems such as the uMgeni, uMvoti and uMkomazi require greater emphasis on maintaining floodplain storage, protecting river corridors and controlling inappropriate development within low-lying areas. Wetlands, riparian vegetation and natural floodplains should be protected and, where degraded, considered for rehabilitation because of their contribution to runoff attenuation, temporary flood storage and broader catchment resilience (IPCC, 2022).

These measures require coordination between the eThekweni Metropolitan Municipality, DWS, relevant provincial authorities and environmental management agencies, particularly where catchments extend beyond individual municipal boundaries.

Improvements to Terrain and Hydraulic Modelling

Future research should refine the existing HEC-RAS modelling framework through the incorporation of higher-resolution terrain data. LiDAR-derived DEMs would improve the representation of river channels, floodplain topography, road embankments and other small-scale features that are not fully represented by the 30 m SRTM DEM (Sanders, 2007).

Detailed representation of urban stormwater infrastructure, including culverts, drainage channels and major stormwater networks, should also be incorporated where reliable datasets become available. Improvements in rainfall-gauge coverage and temporal resolution would further strengthen the representation of spatial rainfall variability within Rain-on-Grid simulations, particularly within catchments currently characterised by sparse observational coverage.

Model Calibration and Validation

Future studies should undertake formal calibration and independent validation using multiple historical flood events where suitable observations are available. This should include high-temporal-resolution rainfall and streamflow records, remotely sensed inundation extents, post-event field observations and documented flood depths or damage information.

Such datasets would enable quantitative assessment of model performance and provide a stronger basis for determining the suitability of the framework for predictive and operational applications. The April 2022 reconstruction developed in this study can therefore serve as a foundation for progressively improving the model as additional observational data become available.

Expansion of the Vulnerability Assessment

Future vulnerability assessments should incorporate additional socio-economic indicators where consistent spatial datasets become available. These could include household income, age distribution, disability, housing condition, access to transport and emergency services, and indicators of adaptive capacity (Cutter et al., 2003; Nasiri et al., 2016).

Priority should also be given to obtaining consistent population-density and informal-settlement datasets for the uMvoti and uMkomazi catchments so that vulnerability assessment can be extended across the full study area. This would enable more consistent comparison of vulnerability between the northern, central and southern coastal catchments.

Future Climate and Scenario Modelling

The present study reconstructed the April 2022 flood event and should not be interpreted as a prediction of future flood conditions. Future research should therefore incorporate design rainfall events, forecast rainfall and downscaled climate projections into the HEC-RAS 2D Rain-on-Grid framework to examine how flood depth and inundation extent may change under different rainfall scenarios.

Scenario-based modelling could also incorporate projected urban expansion and land-use change to investigate how continued development may alter future flood behaviour. Such applications would extend the present event-reconstruction framework towards a more predictive decision-support tool for infrastructure planning, disaster preparedness and climate adaptation (DEA, 2019; IPCC, 2022).

Flood risk within coastal KwaZulu-Natal is likely to remain a significant challenge as urban development, settlement within flood-prone areas and climate variability continue to influence both the occurrence and consequences of flooding. The findings of this study demonstrate that effective flood-risk reduction requires an integrated understanding of not only where and how flooding occurs, but also the social and environmental conditions that determine the vulnerability of exposed communities. The contrasting flood responses identified across the study catchments further highlight the need for context-specific interventions, with rapid-response urban catchments

requiring strengthened drainage management and early-warning systems, while larger river systems require careful floodplain and catchment management. Particular attention is also required in densely populated and informal settlement areas located close to river corridors, where physical exposure intersects with increased socio-economic vulnerability. The modelling framework developed in this study provides a basis for identifying such priority areas and supporting evidence-based spatial planning, disaster preparedness and flood-risk management within the eThekweni Metropolitan Municipality and the wider KwaZulu-Natal coastal region. As improved terrain, rainfall, streamflow and socio-economic datasets become available, the framework can be progressively refined and extended to future flood and climate scenarios. Ultimately, reducing future flood losses will depend on translating improved scientific understanding into coordinated and locally appropriate action among government institutions, planners, researchers and affected communities, thereby strengthening the long-term resilience of KwaZulu-Natal's flood-prone communities.

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Annexure A

EMDAT Dataset listing natural disasters that occurred in KwaZulu Natal over the past decade, and associated data

DisNo.	Hist oric	Disaster Subgrou p	Disaster Type	Disaster Subtype	Location	Origin	Magnitu de	Magnit ude Scale	River Basin	Start Year	Start Mon th	Start Day	End Year	End Mon th	End Day	Total Deaths	No. Injur ed	No. Affe cted	No. Hom eless	Total Affe cted	Total Damag e, Adjust ed ('000 US\$)
2014-0099-ZAF	No	Hydrolog ical	Flood	Riverine flood	Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, North West provinces	Heavy rain; extente d rainfall	1037639	Km2		2014	3	1	2014	3	18	32		7185		7185	112630
2016-0305-ZAF	No	Hydrolog ical	Flood	Flood (General)	Kwazulu Natal (Durban, Cato Manor, Amanzimtoti, Inanda, Ntuzuma, KwaMashu, uMlazi, Yellow Wood Park, Chatsworth - eThekweni Metropolitan Municipality, Ugu district)	Heavy rains		Km2		2016	7	25	2016	8	3	7		6900		6900	235260
2016-0478-ZAF	No	Hydrolog ical	Flood	Flash flood	Gauteng, KwaZulu Natal provinces			Km2	Jukskei Rive	2016	11	9	2016	11	9	6		600		600	130700
2017-0217-ZAF	No	Hydrolog ical	Flood	Flood (General)	KwaZulu-Natal, Nquthu (Umzinyathi District), Zinkwazi (Ilembe District), Mzingwenya (Uthungulu District), uMzumbe municipality		213686,9	Km2		2017	5	14	2017	5	19	3		200		200	
2019-0106-ZAF	No	Hydrolog ical	Flood	Flood (General)	Ntuzuma, Verusalam, Inanda and KwaMashu towns (north of Durban city, KwaZulu-Natal Province)	Heavy rains		Km2		2019	3	8	2019	3	12	10					
2019-0176-ZAF	No	Hydrolog ical	Flood	Flood (General)	KwaZulu-Natal, Eastern Cape, Free state provinces	Heavy rains		Km2		2019	4	21	2019	4	25	73		1000		1000	61349
2019-0548-ZAF	No	Meteorol ogical	Storm	Severe weather	KwaZulu-Natal Province, Inanda Town (North of Durban City)			Kph		2019	11	11	2019	11	12	4	20			20	

DisNo.	Historic	Disaster Subgroup	Disaster Type	Disaster Subtype	Location	Origin	Magnitude	Magnitude Scale	River Basin	Start Year	Start Month	Start Day	End Year	End Month	End Day	Total Deaths	No. Injured	No. Affected	No. Homeless	Total Affected	Total Damage, Adjusted ('000 US\$)
2020-0489-ZAF	No	Meteorological	Storm	Severe weather	KwaZulu-Natal Province; Tshwane City (Gauteng Province); Mthaha (Eastern Cape); Free state			Kph		2020	11	17	2020	11	21	10		210		210	
2021-0036-ZAF	No	Meteorological	Storm	Tropical cyclone	Umkhanyakude, Zululand (Kwa Zulu Natal province) , Ehlanzeni, Mbombela, Bushbuckridge, Nkomazi, Thaba Chweu, Gert Sibande, Chief Albert Luthuli (Mpumalanga province); Limpopo province	Tropical cyclone 'Eloise'		Kph		2021	1	24	2021	1	24	4		3200		3200	
2021-0075-ZAF	No	Hydrological	Flood	Flood (General)	Mpumalanga Province, , Limpopo, Mpumalanga, KwaZulu-Natal and Northern Cape Provinces	Heavy rains		Km2		2021	2	1	2021	2	15	31		400		400	86824
2022-0035-ZAF	No	Hydrological	Flood	Flood (General)	Ladysmith and Msinga (KwaZulu-Natal Province)	Heavy rains		Km2		2022	1	15	2022	1	16	1		100		100	112547
2022-0077-ZAF	No	Hydrological	Flood	Flood (General)	Gauteng Province; KwaZulu-Natal	Heavy rains		Km2		2022	2	4	2022	2	5	3			138	138	
2022-0205-ZAF	No	Hydrological	Flood	Flood (General)	uMkhanyakude, uThukela, uMzinyathi, uMgungundlovu, Zululand, eThekweni, Ilembe, Harry Gwala, King Cetshwayo, Ugu, Amajuba municipalities uMlazi Town (Durban, KwaZulu-Natal Province)	Heavy rains		Km2		2022	4	8	2022	4	18	544	50	135345	6895	142290	3751557
2022-0313-ZAF	No	Hydrological	Flood	Flood (General)	Durban (KwaZulu-Natal province)	Heavy rains		Km2		2022	5	22	2022	5	22			200		200	

DisNo.	Hist oric	Disaster Subgrou p	Disaster Type	Disaster Subtype	Location	Origin	Magnitu de	Magnit ude Scale	River Basin	Start Year	Start Mon th	Start Day	End Year	End Mon th	End Day	Total Deaths	No. Injur ed	No. Affe cted	No. Hom eless	Total Affe cted	Total Damag e, Adjust ed ('000 US\$)
2023-0080-ZAF	No	Hydrolog ical	Flood	Flood (General)	Mpumalanga, the Eastern Cape, Gauteng, KwaZulu-Natal, Limpopo, the Northern Cape, and North West	Heavy rains		Km2		2023	2	8	2023	2	21	17		1000		1000	
2023-0352-ZAF	No	Meteorol ogical	Storm	Severe weather	Phoenix, Inanda, Ntuzuma, KwaMashu, Pinetown, Folweni, and the north of Durban (KwaZulu-Natal Province)			Kph		2023	6	27	2023	6	29	5			150	150	
2023-0847-ZAF	No	Meteorol ogical	Storm	Severe weather	Dundee City area (KwaZulu-Natal Province)			Kph		2023	12	19	2023	12	21	1	6	1211		1217	
2023-0855-ZAF	No	Hydrolog ical	Flood	Flood (General)	Ladysmith, Mandeni (KwaZulu-Natal province)	Heavy rains		Km2		2023	12	24	2023	12	26	34		1800		1800	
2024-0015-ZAF	No	Hydrolog ical	Flood	Flash flood	eThekwin Metro, KwaDukuza, and Ndwedwe Local Municipality (KwaZulu-Natal); Durban	Heavy rains		Km2		2024	1	12	2024	1	19	13	6	750		756	10000
2024-0074-ZAF	No	Meteorol ogical	Storm	Storm surge	uThukela (Ladysmith), uMzinyathi, Amajuba district Municipality (Kwazulu Natal); Free state; North West			Kph		2024	1	7	2024	1		46		7813		7813	
2024-0302-ZAF	No	Hydrolog ical	Flood	Flood (General)	Eastern Cape, KwaZulu-Natal, and Western Cape provinces	Heavy rains		Km2		2024	6	1	2024	6	3	21	55	46565		46620	50000

ANNEXURE B

DWS Monitoring station locations:

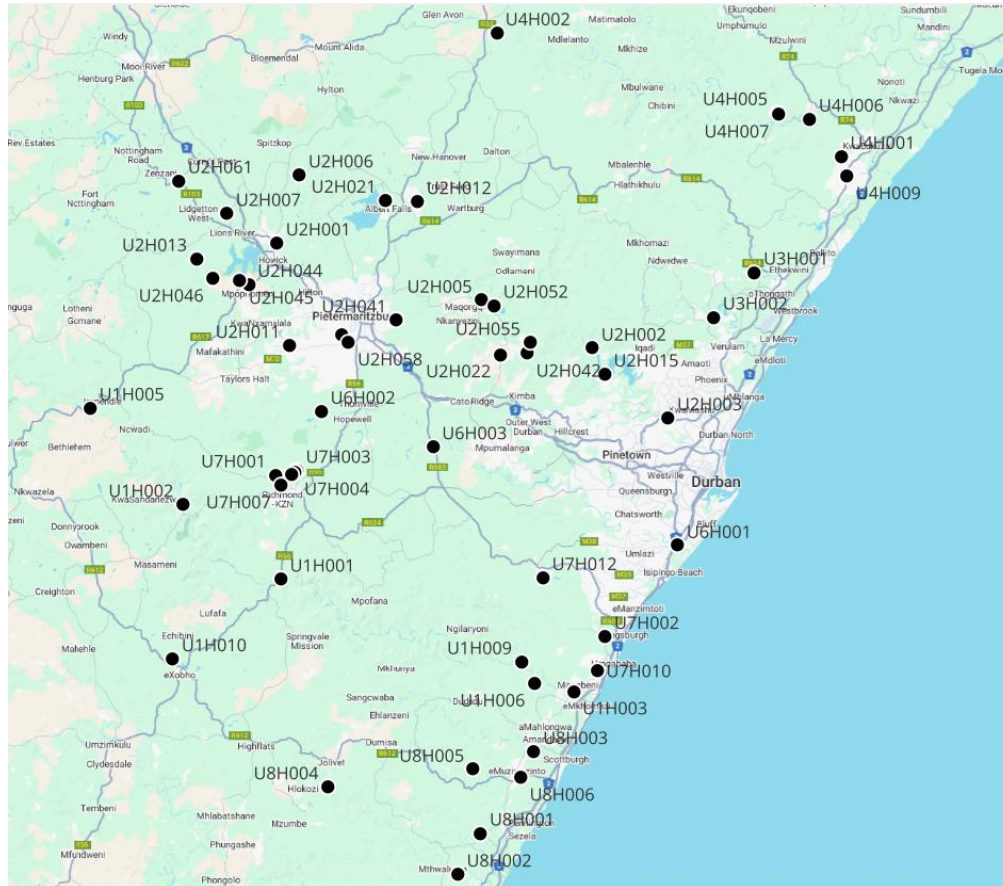


Figure B1: DWS monitoring stations for the study area