Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Social and Educational Sciences
Department of Geography and Social Anthropology

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Spatial Inequalities in Healthcare Accessibility Following Cyclone Idai (2019)

A GIS-Based Analyze of Flood Exposure and Transport Connectivity in Sofala Province, Mozambique

Master's thesis in Geography
Supervisor: Sabrina Scherzer
Co-supervisor: Martina Calovi
May 2026

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Abstrakt (Norsk)

Denne masteroppgaven undersøker hvordan syklonen Idai (2019) påvirket tilgjengeligheten til helsetjenester i Sofala-provinsen i Mosambik. Studien fokuserer på hvordan flom, transportinfrastruktur og eksisterende romlige ulikheter påvirket tilgangen til helsetjenester før og etter syklonen. For å analysere tilgjengelighet ble det brukt GIS-baserte metoder, inkludert Euclidean avstandsanalyse, service area-analyse og closest facility-nettverksanalyse. Data om helseinstitusjoner, veinettverk, flomutbredelse og befolkning ble kombinert for å undersøke hvordan flom påvirket transportforbindelser og tilgang til helsetjenester i provinsen. Resultatene viser at helsetilgjengeligheten i Sofala-provinsen er ujevnt fordelt. Urbane områder, spesielt rundt Beira, har generelt bedre tilgang til helsetjenester, mens rurale og mer avsidesliggende områder har lengre reiseavstander og svakere transportforbindelser. Etter syklonen Idai førte flom til store forstyrrelser i transportnettverket, noe som reduserte tilgjengeligheten i flere deler av provinsen. Områder som allerede hadde dårlig tilgjengelighet var ofte de samme områdene som ble hardest rammet av flom, noe som skapte økt sårbarhet. Studien viser at konsekvensene av naturkatastrofer ikke bare handler om selve flommen, men også om eksisterende ulikheter i infrastruktur og tilgang til helsetjenester. Ved å kombinere analyser av flomeksponering, tilgjengelighet og befolkning bidrar oppgaven til økt forståelse av hvordan katastrofer kan forsterke eksisterende romlige sårbarheter i utsatte områder.

Abstract (English)

This thesis examines how Cyclone Idai (2019) affected healthcare accessibility in Sofala Province, Mozambique. The study focuses on how flooding, transport infrastructure, and existing spatial inequalities influenced access to healthcare services before and after the cyclone. To analyze accessibility, the study used GIS-based methods including Euclidean distance analyze, service area analyze, and closest facility network analyze. Healthcare facility data, road networks, flood extent data, and population data were combined to examine how flooding disrupted transport connectivity and access to healthcare across the province. The results show that healthcare accessibility in Sofala Province is unevenly distributed. Urban areas, particularly around Beira, generally have better access to healthcare services, while rural and remote areas experience longer travel distances and lower connectivity. Following Cyclone Idai, flooding caused major disruptions to the transport network, reducing accessibility in several parts of the province. Areas already characterized by poor accessibility were often the same areas most affected by flooding, creating patterns of increased vulnerability. The study highlights that disaster impacts are shaped not only by the flood itself, but also by existing inequalities in infrastructure and healthcare access. By combining flood exposure, accessibility analyze, and population data, the thesis contributes to understanding how disasters can intensify existing spatial vulnerabilities in hazard-prone regions.

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1. Introduction

Extreme weather events are increasingly recognized not only as environmental hazards, but also as processes that interact with and intensify existing social and spatial inequalities. In many low- and middle-income countries, disasters such as floods and cyclones do not affect all populations equally. Rather, their impacts are shaped by pre-existing conditions including uneven infrastructure distribution, limited access to essential services, socio-economic marginalization, and geographic isolation. Among these factors, access to healthcare is particularly important, as it directly influences the ability of populations to respond to, survive, and recover from disaster events.

Healthcare accessibility is strongly shaped by geography. The spatial distribution of healthcare facilities, transport infrastructure, and population settlements determines how easily people can reach medical services under both normal and crisis conditions. In many parts of sub-Saharan Africa, healthcare access is already constrained by long travel distances, weak transport networks, and uneven infrastructure development, particularly in rural and hazard-prone regions (Ouma et al., 2018; Weiss et al., 2020). During disasters, these existing inequalities may intensify as flooding, infrastructure damage, and mobility disruptions reduce the functional accessibility of healthcare services. Disaster impacts on healthcare systems are therefore not only a question of physical damage to facilities, but also of whether affected populations are able to reach essential services when they are most needed.

Cyclone Idai, which made landfall in central Mozambique in March 2019, represents one of the most severe tropical cyclones recorded in the Southern Hemisphere. The cyclone caused extensive flooding, widespread infrastructure destruction, displacement, and major disruptions to transportation and public services, particularly in Sofala Province and the city of Beira (World Bank, 2019). The event exposed the vulnerability of both infrastructure systems and communities across central Mozambique, especially in low-lying flood-prone areas where large populations depend on limited transport connectivity and unevenly distributed public services. In this context, Cyclone Idai provides a highly relevant case for examining how disaster events interact with pre-existing spatial inequalities in healthcare accessibility.

Existing research has demonstrated that disasters can significantly disrupt access to healthcare by damaging roads, isolating communities, and reducing mobility (Koks et al., 2019; Petricola et al., 2022; Dewi et al., 2024). Other studies have shown that healthcare accessibility is already highly uneven across many parts of sub-Saharan Africa due to disparities in infrastructure, settlement distribution, and service provision (Ouma et al., 2018; Weiss et al., 2020). However, fewer studies have explicitly examined how disaster events reshape pre-existing spatial inequalities in healthcare accessibility at subnational scales. Much of the existing literature either focuses on hazard exposure and infrastructure damage or examines baseline healthcare accessibility separately from disaster impacts. As a result, there remains limited understanding of how environmental hazards and healthcare accessibility interact spatially to produce compounded patterns of vulnerability.

This thesis addresses that gap by examining how Cyclone Idai reshaped spatial inequalities in healthcare accessibility in Sofala Province, Mozambique. Using Geographic Information Systems (GIS) and spatial analyze, the study combines data on healthcare facility locations, transport infrastructure, population distribution, and observed flood extent to analyze how accessibility conditions changed following the cyclone. By integrating accessibility analyze with hazard exposure data, the study identifies areas where populations were simultaneously exposed to flooding and constrained by limited access to healthcare services.

The study applies multiple spatial accessibility approaches, including Euclidean distance analyze, service area analyze, and closest facility network analyze, in order to compare baseline accessibility conditions with post-flood accessibility patterns. This multi-method approach allows for a more nuanced understanding of how both spatial proximity and transport connectivity influence healthcare accessibility during disaster conditions. In doing so, the thesis contributes to broader discussions within health geography, disaster risk reduction (DRR), and spatial vulnerability research by demonstrating how environmental hazards interact with existing infrastructural inequalities across space.

Beyond its empirical contribution, the study also has practical relevance for disaster risk reduction and health system planning. Identifying areas where flood exposure overlaps with limited healthcare accessibility can support more spatially informed approaches to emergency preparedness, infrastructure planning, and resilience-building in hazard-prone regions. In contexts where climate-related extreme weather events are expected to increase in frequency and intensity, understanding the spatial dimensions of healthcare accessibility becomes

increasingly important for reducing vulnerability and strengthening adaptive capacity. Against this background, the present study examines how Cyclone Idai interacted with pre-existing spatial inequalities in healthcare accessibility in Sofala Province, Mozambique. Rather than analysing flood exposure or healthcare distribution separately, the study investigates how these dimensions intersect spatially to produce differentiated patterns of vulnerability across the landscape.

The thesis is guided by the following overarching research question:

How did Cyclone Idai reshape spatial inequalities in healthcare accessibility in Sofala Province, Mozambique?

To address this question, the study explores four related sub-questions:

1. What were the spatial patterns of healthcare accessibility in Sofala Province before Cyclone Idai?
2. How did flooding associated with Cyclone Idai affect healthcare accessibility across Sofala Province?
3. Which populations and areas experienced the greatest overlap between flood exposure and limited healthcare accessibility?
4. What do these spatial patterns reveal about disaster vulnerability and infrastructure inequality in Sofala Province?

This thesis argues that Cyclone Idai did not affect healthcare accessibility uniformly across Sofala Province, but instead intensified pre-existing spatial inequalities by disproportionately disrupting already underserved and hazard-prone areas.

1.1. Structure of the Thesis

The thesis is structured into seven chapters. Following this introduction, Chapter 2 reviews literature on disaster risk reduction, healthcare accessibility, health system vulnerability, GIS and spatial analyze, and empirical studies on disaster-related healthcare access. Chapter 3 introduces the study area and outlines the geographic and environmental characteristics of Sofala Province. Chapter 4 presents the methodological framework, including data sources, accessibility modelling, flood mapping, and spatial analyze techniques. Chapter 5 presents the results of the spatial Analyzes, focusing on healthcare accessibility before and after

Cyclone Idai. Chapter 6 discusses the findings in relation to disaster vulnerability, spatial inequality, and disaster risk reduction theory. Finally, Chapter 7 concludes the thesis by summarizing the main findings, discussing limitations, and outlining implications for future research and planning.

2. Literature Review

This chapter reviews the literature that forms the theoretical and empirical foundation of the thesis. The study examines how flood exposure associated with Cyclone Idai intersected with healthcare accessibility in Sofala Province, Mozambique, and therefore draws on scholarship from several related fields. These include disaster risk reduction (DRR), critical infrastructure, geographic accessibility to healthcare, health system vulnerability in disaster contexts, and the use of GIS and spatial analyze in disaster and accessibility research. Bringing these strands together is necessary for understanding how environmental hazards and uneven service accessibility interact to produce spatially differentiated patterns of vulnerability.

The chapter is structured in five parts. It begins by discussing disaster risk reduction and critical infrastructure as a broader conceptual framework for analysing vulnerability, resilience, and the role of essential services in disaster contexts. It then examines geographic accessibility as a concept within health and spatial research, before reviewing literature on health system vulnerability during disasters. The chapter also considers the role of GIS and spatial analyze in measuring accessibility, mapping hazard exposure, and identifying compounded vulnerability. Finally, it reviews empirical studies on disaster-related health accessibility and identifies the research gap to which this thesis responds. Together, these perspectives provide the basis for the methodological approach and analytical focus of the study.

2.1. Disaster Risk Reduction (DRR) and Critical Infrastructure

Disaster risk reduction (DRR) provides an important framework for understanding why disasters affect populations unevenly across space. Rather than viewing disasters as isolated natural events, DRR research emphasizes that disaster impacts emerge through the interaction between hazards, vulnerability, exposure, and infrastructure systems (Wisner et al., 2012; UNDRR, 2015; IPCC, 2022). This perspective is particularly relevant for understanding healthcare accessibility in disaster contexts, as access to essential services is strongly shaped

by the spatial distribution of infrastructure, transport connectivity, and pre-existing social inequalities.

Within this framework, healthcare systems and transport networks can be understood as forms of critical infrastructure that influence both vulnerability and capacity to cope during hazard events. In flood-prone regions such as Sofala Province, disruptions to roads, mobility, and service accessibility may therefore disproportionately affect already underserved populations. DRR perspectives are consequently important for this study because they provide a theoretical basis for analysing how Cyclone Idai interacted with pre-existing spatial inequalities in healthcare accessibility.

2.1.1. Conceptual Disaster Risk Reduction

The concept of Disaster Risk Reduction (DRR) has evolved significantly over recent decades, shifting from a predominantly hazard-centered and emergency-oriented approach toward a broader understanding of how disasters are socially and spatially produced. Contemporary DRR research emphasizes that disasters are not simply the result of extreme natural events, but emerge through the interaction between hazards, vulnerability, exposure, and institutional capacity (Wisner et al., 2012; UNDRR, 2015; IPCC, 2022). From this perspective, disaster impacts are uneven because populations differ in their ability to anticipate, cope with, and recover from hazardous events.

A central contribution within DRR theory is the Pressure and Release (PAR) model developed by Wisner et al. (2012), which conceptualizes disasters as the outcome of long-term structural processes rather than isolated environmental events. The model argues that root causes such as poverty, marginalization, uneven development, and weak governance create “unsafe conditions” that increase vulnerability to hazards. These vulnerabilities are reproduced through dynamic pressures including limited infrastructure investment, inadequate planning, and uneven access to services. In hazard-prone environments, such conditions amplify the impacts of floods, cyclones, and other extreme events.

This perspective is particularly relevant for understanding healthcare accessibility in Sofala Province. Spatial inequalities in access to healthcare services should not be understood solely as technical or infrastructural issues, but as the outcome of broader socio-spatial processes that shape where services, infrastructure, and populations are located. Rural isolation, uneven

transport connectivity, and limited healthcare provision may therefore be interpreted as forms of structural vulnerability that increase disaster risk. From a PAR perspective, populations living far from healthcare facilities and dependent on fragile transport networks may experience disproportionate impacts during flood events because pre-existing accessibility constraints reduce their capacity to access essential services during crises.

While the PAR model, primarily emphasizes the social production of vulnerability, contemporary DRR frameworks increasingly integrate social and physical-geographical dimensions of risk. The Sendai Framework for Disaster Risk Reduction defines disaster risk as the interaction between hazard, exposure, vulnerability, and capacity (UNDRR, 2015). This understanding highlights that disaster impacts are shaped not only by the severity of the hazard itself, but also by the spatial distribution of populations, infrastructure systems, and critical services within hazard-prone landscapes (IPCC, 2022; IPCC, 2023). While the PAR model emphasizes the social production of vulnerability, contemporary DRR frameworks increasingly conceptualize disaster risk as the interaction between multiple interconnected components.

$$Risk = Hazard \times Exposure \times Vulnerability \times (Lack\ of)\ Capacity$$

This formulation highlights that disaster impacts are shaped not only by the hazard itself, but also by the spatial distribution of exposed populations, infrastructure systems, and the capacity of communities to access essential services during crises. Within this study, these components are operationalized through a spatial analytical framework. Flood extent associated with Cyclone Idai represents the hazard dimension, while population distribution is used as a proxy for exposure. Geographic accessibility to healthcare services is interpreted as both a dimension of vulnerability and an indicator of coping capacity, since accessibility influences the ability of populations to reach essential medical services during and after disaster events. This approach allows disaster vulnerability to be examined not only as a social condition, but also as a spatially differentiated process shaped by infrastructure distribution, transport connectivity, and environmental exposure.

Recent DRR research further emphasizes that vulnerability is inherently place-based and uneven across space. Cutter et al. (2003) argue that disaster risk is shaped by the interaction between environmental conditions and socially produced inequalities, meaning that some places become systematically more vulnerable than others. In flood-prone regions such as

central Mozambique, low-lying floodplains, weak transport infrastructure, and dispersed rural settlements may interact to produce compounded forms of vulnerability. Such areas may simultaneously experience high hazard exposure and limited access to healthcare services, thereby increasing the potential severity of disaster impacts.

Twigg (2015) similarly highlights that critical infrastructure plays a central role in shaping disaster outcomes. Infrastructure systems such as roads, bridges, communication networks, and healthcare facilities influence both exposure and the ability of populations to respond to hazards. Importantly, infrastructure vulnerability is not only determined by physical damage, but also by functionality and connectivity. In disaster contexts, healthcare facilities may remain operational while still becoming effectively inaccessible if surrounding transport routes are disrupted by flooding. This distinction between the physical presence of infrastructure and its functional accessibility is particularly important for the present study, as Cyclone Idai disrupted mobility and transport connectivity across large parts of Sofala Province.

More recent research also demonstrates that climate-related hazards increasingly interact with existing socio-spatial inequalities, reinforcing uneven patterns of vulnerability and risk (IPCC, 2023; Dewi et al., 2024). Rather than creating entirely new vulnerabilities, disaster events often intensify pre-existing inequalities linked to infrastructure distribution, poverty, and accessibility constraints. This perspective is central to the argument of this thesis, which examines how Cyclone Idai disproportionately affected already underserved and hazard-prone areas within Sofala Province.

The DRR perspectives provide an important conceptual foundation for understanding how healthcare accessibility, infrastructure systems, and flood exposure interact across space. By framing disaster impacts as the outcome of both environmental hazards and pre-existing socio-spatial inequalities, DRR theory helps explain why disruptions to healthcare accessibility are often unevenly distributed and why certain populations experience greater vulnerability during disaster events.

2.1.2. Translating Theory into Practice: DRR in Mozambique

Mozambique is widely recognized as one of the most disaster-prone countries in sub-Saharan Africa, experiencing recurrent floods, cyclones, droughts, and storm-related disasters that are

intensified by climate variability, environmental exposure, and socio-economic vulnerability (Djalante & Thomalla, 2012; World Bank, 2019; IPCC, 2022). The country's geographic location along the southwest Indian Ocean, combined with extensive river basins, low-lying coastal plains, and limited infrastructure capacity, contributes to high levels of disaster risk, particularly in central and coastal regions such as Sofala Province.

Following the catastrophic floods of 2000, Mozambique gradually shifted from a primarily reactive disaster response approach toward a broader disaster risk reduction (DRR) framework emphasizing preparedness, resilience, and institutional coordination (Djalante & Thomalla, 2012). This transition was influenced by broader international developments in DRR policy, particularly through the Hyogo Framework for Action and later the Sendai Framework, which promoted the integration of disaster risk reduction into governance and development planning (UNDRR, 2015).

As part of this transition, Mozambique established the National Institute for Disaster Management (INGC) and introduced legal and institutional reforms aimed at strengthening disaster preparedness, response coordination, and risk management capacity. Law No. 15/2014 further formalized the country's disaster risk management framework by regulating prevention, mitigation, preparedness, response, and recovery processes. In addition, national DRR strategies increasingly emphasized local participation, early-warning systems, hazard mapping, and coordination between national and district-level institutions (World Bank, 2019; UNDRR, 2015).

Despite these institutional developments, research consistently highlights substantial gaps between formal DRR policy and implementation capacity at local scales (Djalante & Thomalla, 2012; World Bank, 2019). In practice, the effectiveness of disaster risk reduction is strongly shaped by uneven infrastructure distribution, regional disparities, and limited technical and financial resources. These challenges are particularly pronounced in rural and hazard-prone areas, where weak transport connectivity, dispersed settlements, and limited access to essential services may constrain both disaster preparedness and post-disaster response capacity.

From a spatial perspective, these conditions are highly relevant for understanding vulnerability in Sofala Province. Central Mozambique is characterized by large floodplains, river systems, and extensive rural areas where infrastructure networks are often sparse and

highly sensitive to disruption during extreme weather events. In such contexts, the ability of populations to access healthcare services depends not only on the existence of healthcare facilities, but also on the resilience and connectivity of surrounding transport infrastructure. Flood-related road disruption may therefore transform already underserved areas into functionally isolated spaces during disasters.

Research on Cyclone Idai further illustrates how infrastructural vulnerability and uneven accessibility contributed to differentiated disaster impacts across central Mozambique. Flooding damaged roads, bridges, communication systems, and public infrastructure, significantly reducing mobility and access to essential services across affected districts (World Bank, 2019; Petricola et al., 2022). These disruptions disproportionately affected rural and peripheral populations that were already characterized by limited healthcare accessibility and weak transport connectivity prior to the cyclone.

This highlights an important issue within disaster risk reduction: vulnerability reduction is not only a question of emergency preparedness or institutional policy, but also of spatial inequality and infrastructure distribution. Areas with limited transport connectivity, dispersed settlements, and low accessibility to healthcare services may experience greater disaster impacts because pre-existing infrastructural constraints reduce coping capacity during crises. In this sense, healthcare accessibility becomes closely connected to broader patterns of uneven development and regional marginalization.

Mozambique therefore provides a particularly important context for examining the relationship between disasters, infrastructure vulnerability, and healthcare accessibility. While the country has made significant progress in strengthening national DRR frameworks, the impacts of Cyclone Idai demonstrate that substantial spatial inequalities in infrastructure and service accessibility remain. For the present study, these conditions are central because they help explain why flood impacts on healthcare accessibility were unevenly distributed across Sofala Province and why vulnerable areas may have experienced disproportionate disruption during and after the cyclone.

2.1.3. Community-Based and Ecosystem-Based Approaches

A central theme within disaster risk reduction (DRR) research is that vulnerability reduction cannot rely solely on top-down institutional planning, but also depends on local knowledge,

community participation, and environmental management practices. Community-based disaster risk reduction (CBDRR) has therefore become an important approach within contemporary DRR frameworks because it emphasizes the role of local actors in identifying risks, strengthening preparedness, and improving adaptive capacity (Wisner et al., 2012; Twigg, 2015).

CBDRR approaches are based on the understanding that local communities often possess detailed knowledge of environmental conditions, seasonal hazards, mobility constraints, and infrastructural limitations that may not be fully captured within centralized disaster management systems. Twigg (2015) argues that disaster preparedness measures such as evacuation planning, early-warning dissemination, and local risk assessment are generally more effective when communities are directly involved in decision-making processes. Similarly, Wisner et al. (2012) emphasize that vulnerability is experienced unevenly at local scales and that disaster risk reduction strategies must therefore account for place-specific social and environmental conditions.

In Mozambique, community-based approaches have become increasingly integrated into national disaster risk reduction strategies, particularly following the major flood disasters of the early 2000s. Community Disaster Risk Management Committees (CLGRs) have been established in several hazard-prone regions to support local preparedness, hazard monitoring, evacuation coordination, and risk communication (World Bank, 2019; UNDRR, 2015). Such initiatives reflect broader efforts to strengthen local adaptive capacity in regions where institutional resources and infrastructure systems remain limited.

From the perspective of this study, community-based approaches are particularly relevant because they highlight how vulnerability and accessibility are shaped differently across space. In rural and flood-prone regions such as Sofala Province, communities may rely heavily on informal mobility routes, local transport systems, and community networks to access healthcare services during crises. When formal infrastructure systems are disrupted by flooding, local coping strategies and community-level adaptation may become essential for maintaining access to care. At the same time, the capacity of communities to adapt is often uneven, reflecting broader inequalities in infrastructure, resources, and geographic isolation.

Alongside community-based approaches, ecosystem-based disaster risk reduction (Eco-DRR) has gained increasing attention within both disaster and climate adaptation research. Eco-

DRR emphasizes the role of natural ecosystems in reducing hazard exposure and supporting resilience. Coastal ecosystems such as mangroves, wetlands, and floodplains can reduce storm surge impacts, improve water retention, and limit erosion, thereby contributing to both environmental protection and disaster mitigation (IPCC, 2022; Dewi et al., 2024).

In coastal Mozambique, mangrove systems and wetland environments play an important role in moderating cyclone and flood impacts. However, environmental degradation, urban expansion, and land-use change have reduced the protective capacity of some ecosystems, increasing exposure in vulnerable coastal and riverine areas (World Bank, 2019; IPCC, 2022). This is particularly significant in Sofala Province, where low-lying floodplains and coastal settlements are highly exposed to both river flooding and cyclone-related storm surge.

Eco-DRR perspectives are relevant to this thesis because they reinforce the idea that disaster vulnerability is shaped through the interaction between environmental processes, infrastructure systems, and human settlement patterns. Flood risk is therefore not only a product of extreme weather events, but also of how populations and infrastructure are distributed within environmentally vulnerable landscapes. In areas where settlements, roads, and healthcare services are concentrated in flood-prone zones, disruptions to accessibility may become especially severe during disasters.

Together, community-based and ecosystem-based approaches broaden the understanding of disaster risk reduction beyond emergency response and technical infrastructure protection alone. They emphasize that vulnerability reduction depends on both local adaptive capacity and the management of environmental systems that shape hazard exposure. For the present study, these perspectives are important because they help explain why healthcare accessibility during Cyclone Idai was influenced not only by flooding itself, but also by the interaction between infrastructure vulnerability, environmental conditions, and uneven local capacity across Sofala Province.

2.1.4. The Role of Technology and Spatial Analyze

Recent disaster risk reduction (DRR) research increasingly emphasizes the importance of technological and spatial tools for understanding hazard exposure, infrastructure vulnerability, and disaster impacts across space. Advances in Geographic Information Systems (GIS), remote sensing, and spatial modelling have significantly improved the ability

of researchers and decision-makers to analyze how hazards interact with populations, infrastructure systems, and critical services (Hoque, 2017; Koks et al., 2019; Tellman et al., 2021).

Within disaster research, GIS is particularly valuable because it allows hazards, infrastructure, and social vulnerability to be analyzed within a shared spatial framework. Rather than treating disasters as geographically uniform events, spatial analyze makes it possible to identify how impacts vary across landscapes depending on settlement distribution, transport connectivity, environmental exposure, and accessibility conditions. This perspective aligns closely with contemporary DRR frameworks, which emphasize that disaster risk is spatially differentiated and shaped by the interaction between hazard, exposure, vulnerability, and capacity (UNDRR, 2015; IPCC, 2022).

Remote sensing technologies have become especially important in flood and cyclone research because they enable rapid mapping of inundation extent and environmental change using satellite imagery. Tellman et al. (2021), for example, demonstrates how satellite-derived flood data can reveal changing patterns of flood exposure at global scale, while Hoque (2017) highlights the role of GIS and remote sensing in cyclone monitoring, hazard mapping, and disaster response planning. In data-constrained environments such as central Mozambique, remotely sensed flood data are particularly valuable because ground-based observations and infrastructure datasets may be incomplete or difficult to access following major disasters.

At the same time, spatial technologies are increasingly used to analyze critical infrastructure and accessibility under disaster conditions. Infrastructure systems such as roads, bridges, healthcare facilities, and communication networks function as interconnected spatial systems that shape mobility and access to essential services. Research shows that disaster impacts are often amplified when disruptions to transport infrastructure reduce connectivity between populations and critical services (Koks et al., 2019; Pozo et al., 2025). This means that healthcare accessibility during disasters depends not only on the location of healthcare facilities themselves, but also on the resilience and functionality of surrounding transport networks.

This distinction between infrastructure presence and functional accessibility is particularly important in flood-prone regions. Healthcare facilities may remain physically intact while still becoming effectively inaccessible if roads, bridges, or transport routes are disrupted by

flooding. Spatial analyze therefore provides a way to examine how hazards reshape accessibility patterns by altering network connectivity and mobility conditions across affected areas.

Recent studies further demonstrate the growing importance of integrating hazard mapping with accessibility analyze. Petricola et al. (2022), examining healthcare accessibility during Cyclone Idai, show that flooding significantly reduced functional access to healthcare services across central Mozambique, particularly in rural and poorly connected areas. Their findings illustrate how flood exposure and infrastructure disruption can combine to intensify existing spatial inequalities in access to care. Similar studies increasingly emphasize that disaster vulnerability emerges not only from hazard exposure itself, but from the spatial overlap between hazards, infrastructure fragility, and limited accessibility (Koks et al., 2019; Dewi et al., 2024).

Within healthcare accessibility research, GIS-based methods are widely used to model distance, travel time, and network connectivity between populations and healthcare facilities. Approaches such as Euclidean distance analyze, service area modelling, and closest facility network analyze allow researchers to examine how accessibility varies across space and how infrastructure disruptions may alter access conditions during hazard events (Guagliardo, 2004; Weiss et al., 2020). While more advanced accessibility models may provide highly detailed estimates of travel conditions, they also depend on high-quality spatial datasets that are often incomplete in low-resource and disaster-affected settings. Simpler spatial methods may therefore offer a more transparent and robust basis for identifying broader patterns of accessibility inequality in data-constrained environments.

For the present study, spatial technologies and GIS-based analyze are central because they provide the methodological tools needed to examine how Cyclone Idai reshaped healthcare accessibility across Sofala Province. By combining flood extent data with healthcare facility locations, transport infrastructure, and population distribution, GIS makes it possible to identify areas where environmental exposure and limited accessibility overlap spatially. This allows disaster vulnerability to be analyzed not only as a social or environmental condition, but also as a geographically differentiated process shaped by infrastructure connectivity and uneven access to essential services.

The technological and spatial approaches have become increasingly important within DRR because they support more spatially explicit understandings of vulnerability, accessibility, and infrastructure resilience. Rather than focusing solely on hazard occurrence, these approaches make it possible to examine how disasters disrupt the functional relationships between populations, mobility systems, and critical services across space. For this thesis, such perspectives are essential for understanding how Cyclone Idai altered healthcare accessibility and intensified pre-existing spatial inequalities within Sofala Province.

2.1.5. Persistent Challenges and Structural Vulnerabilities

Despite significant progress in disaster risk reduction policy and institutional development, structural vulnerability remains a major challenge in Mozambique and other hazard-prone low-income contexts. Contemporary DRR research emphasizes that disaster impacts are often shaped less by hazards alone than by long-term socio-economic inequalities, uneven infrastructure development, and limited institutional capacity (Wisner et al., 2012; IPCC, 2022; Dewi et al., 2024). These structural conditions influence both exposure to hazards and the ability of populations to cope with and recover from disaster events.

In Mozambique, vulnerability is closely connected to spatial inequalities in infrastructure, service accessibility, and regional development. Large parts of the country, particularly rural and peripheral regions, are characterized by weak transport connectivity, dispersed settlement patterns, and limited access to essential services such as healthcare, communication systems, and emergency infrastructure (World Bank, 2019; Ouma et al., 2018). These conditions increase the susceptibility of communities to disruption during floods and cyclones because infrastructure systems may already operate with limited redundancy and low adaptive capacity before disasters occur.

From a spatial perspective, such inequalities are particularly important in flood-prone regions such as Sofala Province. Many settlements are located within low-lying floodplains where exposure to flooding is high, while transport infrastructure and healthcare services are unevenly distributed across the landscape. In these areas, physical distance, poor road quality, and limited transport alternatives may already constrain healthcare accessibility under normal conditions. During flood events, these constraints may intensify as roads become impassable, bridges are damaged, and communities become physically isolated.

Research increasingly shows that disaster vulnerability is strongly influenced by infrastructure connectivity and mobility systems (Koks et al., 2019; Pozo et al., 2025). Infrastructural vulnerability is therefore not only a question of whether facilities exist, but whether populations are able to access them during crises. Healthcare facilities may remain operational while still becoming functionally inaccessible because surrounding transport networks are disrupted. This distinction between nominal infrastructure presence and functional accessibility is particularly relevant for understanding healthcare access during Cyclone Idai.

Structural vulnerability is also reinforced through broader patterns of uneven development and marginalization. Wisner et al. (2012) argue that disaster risk is deeply connected to political-economic processes that shape how resources, infrastructure, and opportunities are distributed across society. More recent climate risk research similarly demonstrates that climate-related hazards often amplify pre-existing inequalities rather than producing entirely new forms of vulnerability (IPCC, 2022; IPCC, 2023). In practice, this means that populations already characterized by poor infrastructure access, limited mobility, and weak service provision may experience disproportionately severe impacts during disaster events.

Climate change further intensifies these challenges by increasing the frequency and severity of extreme weather events, particularly in coastal and flood-prone regions (IPCC, 2022; IPCC, 2023). For countries such as Mozambique, where many infrastructure systems are already fragile and unevenly distributed, recurrent flooding and cyclones place additional pressure on transport networks, healthcare systems, and emergency response capacity. This creates a situation in which vulnerability is both environmentally and structurally produced through the interaction between hazard exposure and existing socio-spatial inequalities.

These perspectives are highly relevant for the present study because they help explain why the impacts of Cyclone Idai on healthcare accessibility were unevenly distributed across Sofala Province. Rather than affecting all populations equally, flood-related disruptions likely intensified pre-existing inequalities by disproportionately reducing accessibility in already underserved and poorly connected areas. Understanding these patterns therefore requires attention not only to flood extent itself, but also to the structural and spatial conditions that shaped vulnerability before the disaster occurred.

2.1.6. Knowledge, Learning, and Evaluation

Contemporary disaster risk reduction (DRR) research increasingly emphasizes that effective risk reduction depends not only on infrastructure and emergency response capacity, but also on the ability of institutions and communities to learn from past disasters and adapt over time. DRR is therefore understood as an ongoing and iterative process involving knowledge production, monitoring, evaluation, and institutional learning (Twigg, 2015; UNDRR, 2015).

Within this perspective, disasters are not viewed as isolated events, but as opportunities to identify structural weaknesses, improve preparedness strategies, and strengthen resilience. Twigg (2015) argues that monitoring and evaluation are essential components of effective DRR because they allow institutions to assess how vulnerabilities are distributed, how interventions perform under crisis conditions, and where gaps in preparedness and infrastructure remain. Similarly, the Sendai Framework emphasizes the importance of evidence-based planning, risk information, and the use of scientific knowledge to support disaster preparedness and resilience-building (UNDRR, 2015).

At the same time, DRR scholars stress that knowledge production is not politically neutral. Wisner et al. (2012) highlight that vulnerability assessments and disaster planning may overlook marginalized populations if social and spatial inequalities are not explicitly considered. This means that disaster risk reduction requires not only technical knowledge about hazards, but also critical understanding of how vulnerability is unevenly distributed across space and society. Populations living in peripheral, underserved, or hazard-prone areas may face risks that remain insufficiently represented within national datasets and planning frameworks.

Recent advances in GIS, remote sensing, and spatial analyze have significantly expanded the ability of researchers and institutions to identify vulnerable populations and infrastructure systems more precisely (Hoque, 2017; Weiss et al., 2020). Spatial data can support disaster preparedness by identifying hazard-prone areas, mapping infrastructure gaps, and analysing how accessibility conditions may change during disasters. In this sense, spatial analyze contributes not only to academic understanding, but also to more targeted and evidence-based disaster planning.

However, the usefulness of such analyzes depends heavily on data quality, scale, and accessibility. In many low-income and disaster-prone regions, infrastructure datasets, transport information, and population data may be incomplete or unevenly distributed (Petricola et al., 2022). These limitations can affect both disaster response and research outcomes, particularly in rural regions where mapping coverage and institutional capacity are often weakest. Methodological transparency therefore becomes especially important in spatial disaster research, as analytical choices and data constraints may significantly shape conclusions about accessibility and vulnerability.

For the present study, these perspectives are important because they highlight the value of spatial accessibility analyze as a tool for identifying uneven disaster impacts and infrastructure vulnerability. By combining healthcare accessibility modelling with flood extent analyze, the study contributes to a more spatially explicit understanding of how vulnerability was distributed across Sofala Province during Cyclone Idai. At the same time, the study recognizes that accessibility modelling is shaped by methodological choices and data availability, particularly in disaster-affected and data-constrained environments.

Overall, knowledge, monitoring, and spatial analyze play a central role in strengthening disaster risk reduction by improving understanding of where vulnerability is concentrated and how infrastructure systems function under stress. These approaches are particularly important in hazard-prone regions such as central Mozambique, where uneven accessibility and limited infrastructure connectivity may significantly influence disaster impacts and recovery capacity.

2.1.7. Synthesis and Implications

The literature on disaster risk reduction (DRR) demonstrates that disaster impacts are shaped not only by hazards themselves, but by the interaction between environmental exposure, infrastructure systems, socio-economic vulnerability, and institutional capacity (Wisner et al., 2012; UNDRR, 2015; IPCC, 2022). Across conceptual, operational, and empirical perspectives, a consistent theme emerges. Disasters affect populations unevenly because vulnerability and coping capacity are spatially differentiated.

A central insight from the literature is that disaster vulnerability is closely connected to patterns of uneven infrastructure distribution and accessibility. Roads, healthcare facilities,

communication systems, and transport networks function as critical infrastructure that influence both exposure and the ability of populations to respond to and recover from hazard events (Twigg, 2015; Koks et al., 2019). Importantly, disaster impacts are often shaped not only by whether infrastructure exists, but by whether it remains functionally accessible during crises. In flood-prone regions, disruptions to transport connectivity may therefore significantly reduce access to essential services even when facilities themselves remain operational.

The literature further highlights that vulnerability is strongly place-based and shaped by broader socio-spatial inequalities. Populations living in peripheral, underserved, and hazard-prone areas often experience compounded forms of vulnerability linked to weak infrastructure, limited mobility, and constrained access to services (Wisner et al., 2012; Cutter et al., 2003; IPCC, 2023). In this sense, disasters frequently intensify pre-existing inequalities rather than creating entirely new patterns of vulnerability.

These perspectives are particularly relevant for understanding healthcare accessibility in Sofala Province. In regions characterized by dispersed rural settlements, weak transport connectivity, and extensive flood exposure, access to healthcare services is highly sensitive to infrastructure disruption and mobility constraints. Cyclone Idai therefore represents not only an environmental hazard event, but also a disruption to the spatial systems that connect populations to essential healthcare services.

The literature also emphasizes the growing importance of GIS, remote sensing, and spatial analyze within disaster research. These approaches allow researchers to examine how hazard exposure, infrastructure vulnerability, and accessibility interact across space, thereby supporting more spatially explicit understandings of disaster risk (Hoque, 2017; Tellman et al., 2021; Weiss et al., 2020). Integrating flood extent data with healthcare accessibility analyze therefore provides an important framework for identifying areas where vulnerability may be compounded by both environmental exposure and limited access to services.

Taken together, the DRR literature provides a conceptual foundation for analysing how Cyclone Idai reshaped healthcare accessibility across Sofala Province. Rather than viewing disaster impacts as geographically uniform, these perspectives suggest that flood-related disruptions were likely mediated through pre-existing spatial inequalities in infrastructure and accessibility. This understanding forms the basis for the following section, which examines

geographic accessibility more directly as a concept within health geography and spatial analyze research.

2.2. Geographic Accessibility: Concepts and Theoretical Frameworks

Geographic accessibility to healthcare services is a central concept within both health geography and disaster risk reduction research because it shapes the ability of populations to obtain timely medical care under both normal and crisis conditions. Accessibility is not only determined by physical distance to healthcare facilities, but by the broader interaction between population distribution, transport infrastructure, mobility conditions, and environmental context (Guagliardo, 2004; Levesque et al., 2013). In hazard-prone environments, these relationships become particularly important because disasters may disrupt transport systems, isolate communities, and significantly alter the functional accessibility of essential services.

Within health geography, accessibility is generally understood as a multidimensional concept that includes spatial, economic, organizational, and social dimensions of access (Levesque et al., 2013). However, geographic accessibility remains especially important in low- and middle-income countries where physical distance, transport availability, and infrastructure quality often represent major barriers to healthcare utilization (Ouma et al., 2018; Weiss et al., 2020). In such contexts, populations located far from healthcare facilities or dependent on weak transport networks may face significant constraints in reaching medical care, particularly during emergencies.

Recent research increasingly emphasizes that geographic accessibility should not be understood as a static condition, but as a dynamic spatial process that may change rapidly during disasters and environmental shocks (Dewi et al., 2024). Flooding, cyclone impacts, and infrastructure disruption can alter mobility conditions, damage transport networks, and isolate settlements, thereby reshaping accessibility patterns across affected regions. Accessibility during disasters therefore depends not only on the spatial distribution of healthcare facilities, but also on whether infrastructure systems remain functional under crisis conditions.

This distinction between nominal and functional accessibility is particularly important for the present study. Healthcare facilities may exist within reasonable geographic proximity while

still becoming effectively inaccessible if roads, bridges, or transport routes are disrupted by flooding. Functional accessibility therefore reflects the actual ability of populations to reach healthcare services within specific environmental and infrastructural conditions. In flood-prone regions such as Sofala Province, healthcare accessibility is highly dependent on transport connectivity and mobility systems that may be vulnerable to disruption during extreme weather events.

From a disaster risk reduction perspective, geographic accessibility is closely linked to vulnerability and coping capacity. The Sendai Framework conceptualizes disaster risk as the interaction between hazard, exposure, vulnerability, and capacity (UNDRR, 2015). Within this framework, healthcare accessibility can be understood as a critical dimension of coping capacity because it influences the ability of populations to receive treatment, emergency care, and health support during and after disasters. Limited accessibility may therefore increase vulnerability by reducing the capacity of communities to respond effectively to hazard events (IPCC, 2022).

Contemporary vulnerability research further emphasizes that accessibility inequalities are socially and spatially produced rather than randomly distributed. Wisner et al. (2012) argue that limited access to services and infrastructure constitutes an “unsafe condition” that may intensify disaster impacts. More recent studies similarly demonstrate that healthcare accessibility is strongly shaped by broader patterns of uneven development, infrastructural inequality, and regional marginalization (IPCC, 2023; Dewi et al., 2024). Rural populations, peripheral settlements, and hazard-prone communities often experience lower accessibility due to weak transport infrastructure and uneven service provision, making them particularly vulnerable during disasters.

Infrastructure systems therefore play a fundamental role in shaping healthcare accessibility. Transport networks, roads, bridges, and mobility systems determine whether healthcare services can be reached in practice, especially during emergencies. Twigg (2015) emphasizes that critical infrastructure resilience is essential for disaster preparedness and response, while Koks et al. (2019) demonstrate that disruptions to transport connectivity can significantly reduce access to essential services during hazard events. In this sense, healthcare accessibility depends not only on healthcare systems themselves, but also on the resilience and functionality of broader infrastructure systems.

Advances in GIS and spatial accessibility modelling have significantly improved the ability to measure and analyze healthcare accessibility across different spatial contexts. GIS-based approaches allow accessibility to be modelled through distance analyze, network connectivity, service areas, and travel-time estimation (Guagliardo, 2004; Weiss et al., 2020). Recent high-resolution accessibility studies further demonstrate how spatial analyze can identify underserved populations and reveal inequalities in healthcare access with increasing precision (Hierink et al., 2023; Ye et al., 2024).

At the same time, accessibility modelling involves important methodological considerations. More advanced network and travel-time approaches may provide more realistic estimates of mobility conditions, but they also require detailed and reliable spatial datasets on roads, transport conditions, and travel speeds. In data-constrained environments such as central Mozambique, such information may be incomplete or rapidly altered during disasters. Simpler spatial measures such as Euclidean distance may therefore still provide valuable insights into broader accessibility inequalities, particularly when the objective is to compare relative spatial conditions across regions (Guagliardo, 2004; Weiss et al., 2020). This creates an important methodological trade-off between analytical realism and data availability.

These perspectives are highly relevant for understanding healthcare accessibility in Sofala Province. The province is characterized by dispersed rural settlements, uneven healthcare distribution, weak transport connectivity, and extensive flood-prone areas. Under normal conditions, many populations may already experience limited access to healthcare services due to distance and infrastructure constraints. During Cyclone Idai, flooding likely intensified these inequalities by disrupting mobility systems and reducing functional accessibility across affected districts.

The literature demonstrates that geographic accessibility is both a spatial and infrastructural dimension of disaster vulnerability. Accessibility is shaped not only by proximity to healthcare facilities, but by the interaction between infrastructure systems, environmental conditions, and uneven socio-spatial development. These perspectives provide an important conceptual foundation for the present study, which examines how Cyclone Idai reshaped healthcare accessibility and intensified spatial inequalities across Sofala Province through the disruption of transport connectivity and essential service access.

2.3. Health System Vulnerability in Disaster Contexts

Understanding how health systems function during disasters is essential for analysing the impacts of environmental hazards on healthcare accessibility. During hazard events, healthcare systems are required not only to maintain routine service delivery, but also to respond to increased medical demand, infrastructure disruption, population displacement, and logistical constraints. The concept of health system vulnerability therefore provides an important framework for understanding how disasters affect the availability, functionality, and accessibility of healthcare services across space.

Health system vulnerability refers to the susceptibility of healthcare systems to disruption when exposed to external shocks such as floods, cyclones, disease outbreaks, or infrastructural failure (IPCC, 2022). Within disaster research, vulnerability is increasingly understood not only as an institutional or technical issue, but also as a spatial condition shaped by the distribution of healthcare infrastructure, transport connectivity, and population accessibility. In geographically dispersed and infrastructure-constrained regions, healthcare systems may become vulnerable because populations are unevenly connected to essential services even before disasters occur (Ouma et al., 2018; Dewi et al., 2024).

A key concept within health systems research is resilience, often defined as the ability of healthcare systems to absorb shocks, maintain core functions, and adapt under changing conditions (Kruk et al., 2015). Conversely, vulnerable health systems are characterized by limited infrastructure capacity, weak transport networks, workforce shortages, and uneven service distribution, all of which may reduce the ability of populations to access healthcare during crises. This distinction is particularly important in disaster-prone low- and middle-income contexts where healthcare systems often operate under existing infrastructural and resource constraints prior to hazard events.

From a spatial perspective, healthcare systems are inherently dependent on infrastructure connectivity. Healthcare accessibility relies not only on the existence of facilities, but also on roads, bridges, transport systems, communication infrastructure, and mobility conditions that enable populations to physically reach care. In rural and hazard-prone regions, these infrastructural systems may already be fragile under normal conditions and become highly vulnerable during floods and cyclones.

Research increasingly demonstrates that disaster impacts on healthcare systems are often indirect and mediated through infrastructure disruption rather than direct damage to facilities themselves (Koks et al., 2019; Dewi et al., 2024). Flooding may isolate communities, sever transport links, and reduce mobility, thereby limiting access to healthcare even when medical facilities remain operational. This highlights an important distinction between healthcare availability and healthcare accessibility. A facility may continue functioning physically while still becoming effectively inaccessible to surrounding populations due to disrupted connectivity.

This distinction between nominal and functional healthcare access is central to understanding health system vulnerability during disasters. Functional accessibility reflects the actual ability of populations to reach healthcare services within specific infrastructural and environmental conditions. In flood-prone landscapes, healthcare systems may therefore experience reduced functionality not only because facilities are damaged, but because populations become spatially disconnected from services. Such disruptions may disproportionately affect rural, peripheral, and already underserved populations that rely on limited transport infrastructure and have few alternative access routes.

Empirical studies increasingly document these patterns in disaster-affected regions. Following Cyclone Idai, widespread flooding in central Mozambique disrupted roads, damaged infrastructure, and reduced access to healthcare services across affected districts (World Bank, 2019; Petricola et al., 2022). Similar findings have been reported in other flood-prone contexts where mobility disruptions significantly constrained healthcare access during and after disasters (Wu et al., 2024; Mroz et al., 2023). These studies suggest that healthcare vulnerability during disasters is strongly linked to transport connectivity and infrastructure resilience rather than solely to the distribution of healthcare facilities themselves.

Recent climate risk research further highlights that health system vulnerability is likely to intensify under increasing climate-related hazard exposure (IPCC, 2022; IPCC, 2023). Floods, cyclones, and extreme weather events place additional pressure on already constrained healthcare systems, particularly in low-income regions characterized by uneven infrastructure and limited adaptive capacity. Climate-related hazards may therefore reinforce pre-existing healthcare inequalities by disproportionately affecting populations with limited accessibility and weak infrastructure connectivity.

These perspectives are particularly relevant for Sofala Province, where healthcare accessibility is shaped by dispersed settlement patterns, uneven infrastructure distribution, and extensive flood exposure. In such contexts, disaster impacts on healthcare systems cannot be understood solely through physical damage assessments, but must also consider how environmental hazards alter mobility, transport connectivity, and functional accessibility across space. Cyclone Idai therefore represents not only a health emergency, but also a disruption to the spatial systems that connect populations to essential healthcare services.

The literature demonstrates that health system vulnerability in disaster contexts is fundamentally connected to infrastructure resilience, spatial accessibility, and socio-spatial inequality. Healthcare systems become vulnerable not only when facilities are damaged, but when populations lose the ability to physically access care during crises. These insights provide an important foundation for the present study, which examines how flooding associated with Cyclone Idai reshaped healthcare accessibility and intensified spatial inequalities across Sofala Province.

2.3.1. Conceptualizing Health System Vulnerability

Health system vulnerability refers to the susceptibility of healthcare systems to disruption when exposed to external shocks such as floods, cyclones, disease outbreaks, or infrastructural failure. Within disaster research, vulnerability is increasingly understood not only as a technical or institutional condition, but also as a spatial and socio-economic process shaped by infrastructure distribution, accessibility, and uneven development (IPCC, 2022; Dewi et al., 2024). This perspective is particularly relevant in disaster-prone low- and middle-income regions where healthcare systems often operate under existing infrastructural and resource constraints prior to hazard events.

A central concept within health systems research is resilience, commonly defined as the ability of healthcare systems to absorb shocks, maintain core functions, and adapt to changing conditions during crises (Kruk et al., 2015). Vulnerability and resilience are therefore closely connected. Health systems characterized by weak infrastructure, workforce shortages, limited resources, and uneven service distribution may experience greater difficulty maintaining healthcare accessibility during disasters. Conversely, resilient systems are generally better able to sustain service delivery and adapt under disrupted conditions.

Recent research increasingly emphasizes that health system vulnerability is strongly spatial in nature. Healthcare systems rely on interconnected infrastructure networks including roads, bridges, transport systems, communication systems, and healthcare facilities that together enable populations to physically access medical care. Vulnerability therefore depends not only on the quality or availability of healthcare facilities themselves, but also on the broader infrastructural systems that support mobility and connectivity across space.

This spatial perspective is particularly important in rural and hazard-prone regions where healthcare accessibility may already be constrained by long travel distances, poor transport infrastructure, and uneven facility distribution (Ouma et al., 2018; Weiss et al., 2020). In such contexts, populations often rely on limited transport routes and fragile infrastructure systems that are highly sensitive to environmental disruption. Flooding, damaged roads, and mobility constraints may therefore significantly reduce the functional capacity of healthcare systems during disasters.

Within disaster risk reduction frameworks, healthcare accessibility can also be understood as a dimension of coping capacity. The ability of populations to reach healthcare services influences emergency response, treatment access, and recovery potential during crises (UNDRR, 2015; IPCC, 2022). Limited accessibility may therefore increase disaster vulnerability by reducing the capacity of communities to obtain timely healthcare under hazardous conditions. This means that healthcare accessibility is not only a public health issue, but also a key component of disaster resilience.

Wisner et al. (2012) further argue that vulnerability is socially produced through long-term structural inequalities linked to poverty, marginalization, and uneven infrastructure development. From this perspective, limited healthcare accessibility represents a form of structural vulnerability that may intensify disaster impacts. Communities already characterized by poor infrastructure connectivity and limited service access are therefore likely to experience disproportionate disruption during hazard events because pre-existing inequalities reduce adaptive capacity before disasters occur.

This conceptualization is particularly relevant for understanding health system vulnerability in Sofala Province. The combination of dispersed rural populations, flood-prone landscapes, and uneven infrastructure distribution creates conditions where healthcare accessibility is highly sensitive to environmental disruption. Cyclone Idai therefore did not affect healthcare

systems in isolation, but interacted with existing spatial inequalities that shaped how populations were able to access care during and after the disaster.

Overall, conceptualizing health system vulnerability as both a spatial and infrastructural condition provides an important framework for understanding how disasters reshape healthcare accessibility. Rather than focusing solely on physical damage to healthcare facilities, this perspective highlights how vulnerability emerges through the interaction between infrastructure systems, mobility conditions, environmental exposure, and uneven access to essential services across space.

2.3.2. Infrastructure and Spatial Vulnerability

Healthcare systems are inherently spatial because they depend on interconnected infrastructure systems that enable populations to physically access medical services. Hospitals, clinics, roads, bridges, transport routes, communication systems, and mobility networks together shape the functional accessibility of healthcare across different geographic contexts. The spatial distribution and resilience of this infrastructure therefore play a critical role in determining how healthcare systems function during disasters.

In many low- and middle-income regions, healthcare infrastructure is unevenly distributed across urban and rural areas. Urban centers often benefit from higher concentrations of healthcare facilities, transport connectivity, and emergency infrastructure, while rural and peripheral regions may experience long travel distances, weak road networks, and limited service availability (Ouma et al., 2018; Weiss et al., 2020). These spatial inequalities can create significant barriers to healthcare access even under normal conditions.

From a disaster risk perspective, such inequalities become particularly important because hazard events often disrupt already fragile infrastructure systems. Flooding may damage roads, destroy bridges, isolate settlements, and reduce mobility, thereby limiting the ability of populations to access healthcare services during emergencies. Research increasingly demonstrates that infrastructure disruption is one of the most important mechanisms through which disasters affect healthcare accessibility (Koks et al., 2019; Wu et al., 2024).

This highlights an important distinction between the physical presence of healthcare facilities and their functional accessibility. A healthcare facility may remain operational during a

disaster while still becoming effectively inaccessible if surrounding transport routes are blocked or damaged. Functional healthcare access therefore depends not only on facility availability, but also on the resilience and connectivity of broader infrastructure systems. In hazard-prone environments, transport networks become especially critical because they determine whether populations can maintain mobility during crises.

Koks et al. (2019) show that disruptions to transport connectivity can significantly amplify disaster impacts by isolating communities from essential services and reducing infrastructure redundancy. Similarly, Pozo et al. (2025) demonstrate that infrastructure vulnerability is often concentrated within specific critical transport links, meaning that disruption to relatively small sections of road networks may produce widespread accessibility consequences across larger regions. Such findings are highly relevant in flood-prone areas where transport systems may already be limited and alternative routes scarce.

Spatial vulnerability is therefore closely connected to patterns of infrastructure connectivity and environmental exposure. Populations located in low-lying floodplains, remote rural districts, or poorly connected regions may experience compounded vulnerability because they are simultaneously exposed to hazards and constrained by limited accessibility. During disasters, these conditions may transform already underserved areas into functionally isolated spaces where healthcare access becomes severely restricted.

These dynamics are particularly important in Sofala Province, where dispersed settlement patterns, weak transport connectivity, and extensive flood-prone landscapes shape healthcare accessibility across the region. Many communities rely on a limited number of transport corridors and road connections that may become disrupted during major flood events. Cyclone Idai therefore likely affected healthcare accessibility not only through direct infrastructure damage, but through broader disruptions to mobility and transport connectivity across affected districts.

Recent climate risk research further emphasizes that infrastructure vulnerability is likely to intensify under increasing climate-related hazard exposure (IPCC, 2022; IPCC, 2023). Recurrent flooding and cyclones place additional pressure on already constrained infrastructure systems, particularly in regions characterized by limited investment, uneven development, and low adaptive capacity. In such contexts, healthcare accessibility may

become increasingly unstable as environmental hazards repeatedly disrupt transport systems and essential services.

Infrastructure and spatial vulnerability are central to understanding healthcare accessibility during disasters. Healthcare systems depend not only on the existence of medical facilities, but on the broader infrastructure networks that connect populations to care. When these systems are disrupted, accessibility may decline rapidly and unevenly across space, disproportionately affecting already vulnerable and poorly connected populations. These perspectives are therefore essential for understanding how Cyclone Idai reshaped healthcare accessibility across Sofala Province.

2.3.3. Disaster Impacts on Healthcare Access

Natural hazards can affect healthcare accessibility through both direct and indirect pathways. Direct impacts include physical damage to healthcare facilities, medical equipment, and utilities such as electricity and water supply. However, research increasingly shows that indirect impacts related to infrastructure disruption and reduced mobility are often equally important in shaping healthcare access during disasters (Koks et al., 2019; Dewi et al., 2024).

Flooding and cyclone events may significantly disrupt transport networks by damaging roads, bridges, and communication infrastructure, thereby reducing the ability of populations to reach healthcare services. In many disaster contexts, healthcare facilities may remain operational while surrounding communities become physically isolated due to mobility constraints. This means that disaster impacts on healthcare systems are often mediated through reduced accessibility rather than solely through facility destruction.

Evidence from Cyclone Idai illustrates these dynamics clearly. Widespread flooding across central Mozambique disrupted roads, damaged infrastructure, and reduced mobility across large parts of Sofala Province (World Bank, 2019; Petricola et al., 2022). Similar findings have been documented in other flood-prone regions where transport disruption significantly constrained access to emergency and routine healthcare services during and after disasters (Mroz et al., 2023; Wu et al., 2024).

Importantly, such impacts are rarely distributed evenly across space. Rural and poorly connected areas often experience greater accessibility disruption because populations rely on

limited infrastructure networks and have fewer alternative transport routes. Existing inequalities in healthcare accessibility may therefore intensify during disasters as already underserved populations become increasingly isolated from essential services.

These perspectives are highly relevant for the present study because they highlight how Cyclone Idai likely reshaped healthcare accessibility across Sofala Province through disruptions to mobility and transport connectivity. Understanding disaster impacts on healthcare access therefore requires attention not only to hazard exposure itself, but also to the spatial systems that connect populations to healthcare services.

2.3.4. Accessibility as a Component of Health System Resilience

Accessibility plays a central role in determining the resilience of healthcare systems during disasters. A healthcare system may possess adequate facilities and medical resources, but if populations are unable to physically reach services during crises, effective healthcare delivery becomes significantly constrained. Geographic accessibility therefore represents a critical link between infrastructure availability and healthcare utilization.

Recent research highlights that improving healthcare accessibility can strengthen health system resilience by increasing the ability of populations to obtain timely care during emergencies (Weiss et al., 2020; Ouma et al., 2018). In disaster contexts, resilient healthcare systems depend not only on the operational capacity of healthcare facilities, but also on the functionality of transport networks and mobility systems that connect communities to care.

This perspective is particularly important in flood-prone and infrastructure-constrained regions where accessibility may deteriorate rapidly during extreme events. Flooding can isolate settlements, disrupt transport routes, and reduce connectivity between populations and healthcare facilities, thereby limiting the capacity of healthcare systems to maintain service delivery. Areas characterized by weak infrastructure and limited transport alternatives may therefore experience disproportionately severe accessibility disruptions during disasters.

Twigg (2015) emphasizes that resilient infrastructure systems are essential for maintaining continuity of essential services during hazard events. From this perspective, healthcare accessibility can be understood not only as an outcome of infrastructure systems, but also as a component of adaptive capacity and disaster resilience. Regions with stronger connectivity

and more accessible healthcare systems are generally better positioned to maintain functional service access during crises.

For the present study, this perspective is highly relevant because it highlights how variations in healthcare accessibility may influence disaster vulnerability across Sofala Province. Cyclone Idai likely affected healthcare resilience unevenly by disproportionately disrupting accessibility in already underserved and poorly connected areas. Analysing accessibility spatially therefore provides important insights into how resilience and vulnerability are distributed across the landscape.

2.3.5. Implications for Disaster Risk Reduction

The literature on health system vulnerability highlights the importance of integrating healthcare accessibility into disaster risk reduction (DRR) planning. Traditional DRR approaches have often focused primarily on hazard monitoring, emergency response, and physical infrastructure protection. However, recent research increasingly emphasizes that reducing disaster impacts also requires strengthening the accessibility and resilience of essential service systems, particularly healthcare infrastructure (UNDRR, 2015; IPCC, 2022).

Within this perspective, healthcare accessibility can be understood as both a component of vulnerability and a form of coping capacity. Populations with limited access to healthcare services may experience greater difficulty responding to and recovering from disasters, especially when infrastructure disruption further reduces mobility and connectivity during crises. Improving accessibility may therefore contribute directly to reducing disaster vulnerability and strengthening community resilience.

These issues are particularly important in hazard-prone and infrastructure-constrained regions such as Sofala Province. In areas characterized by dispersed settlements, weak transport networks, and high flood exposure, healthcare accessibility is highly sensitive to environmental disruption. Disaster risk reduction strategies in such contexts must therefore consider not only the location of healthcare facilities, but also the resilience of transport infrastructure and the spatial distribution of vulnerable populations.

Recent DRR frameworks increasingly emphasize the importance of spatially informed planning and infrastructure resilience (UNDRR, 2015; IPCC, 2022). GIS and spatial analyze

can support these efforts by identifying areas where poor healthcare accessibility and hazard exposure overlap, thereby helping decision-makers prioritize vulnerable regions and critical infrastructure systems.

For the present study, these perspectives are important because they frame healthcare accessibility as a key dimension of disaster vulnerability in Sofala Province. Examining how Cyclone Idai affected healthcare accessibility therefore contributes not only to understanding the impacts of a specific disaster event, but also to broader discussions about infrastructure inequality, resilience, and spatially informed disaster risk reduction planning.

2.4. GIS and Spatial Analyze in Disaster and Accessibility Research

Geographic Information Systems (GIS) and spatial analyze have become central tools within both disaster research and healthcare accessibility studies because they allow researchers to examine how hazards, populations, infrastructure systems, and essential services interact across space. Their importance lies not only in visualization, but in their ability to identify spatial inequalities, analyze infrastructure connectivity, and model accessibility under different environmental conditions (Guagliardo, 2004; Koks et al., 2019; Weiss et al., 2020).

Within disaster research, GIS enables hazards, infrastructure, and social vulnerability to be analyzed within a shared spatial framework. Floods, cyclones, and other environmental hazards rarely affect all places equally. Instead, impacts vary depending on settlement distribution, transport connectivity, topography, infrastructure resilience, and the spatial relationship between populations and critical services. Spatial analyze therefore supports a more geographically differentiated understanding of disaster risk by revealing where hazard exposure and vulnerability overlap (Koks et al., 2019; IPCC, 2022).

GIS also plays an important role in healthcare accessibility research. Geographic accessibility is one of the most widely studied dimensions of healthcare access because physical distance and transport constraints strongly influence whether populations can reach medical services, particularly in rural and low-resource settings (Guagliardo, 2004). GIS-based methods allow researchers to model accessibility through distance analyze, transport networks, service areas, and travel-time estimation, thereby making spatial inequalities in service access measurable and comparable across regions.

Several approaches are commonly used to measure spatial accessibility. Euclidean distance measures straight-line distance between populations and healthcare facilities and provides a relatively simple and transparent indicator of spatial proximity. Network-based approaches improve this by modelling accessibility along roads and transport routes, thereby reflecting mobility conditions more realistically. Service area analyze and closest facility analyze further allow researchers to examine how infrastructure connectivity shapes access to services across space (Guagliardo, 2004; Weiss et al., 2020).

Literature increasingly emphasizes that no single accessibility method is universally superior. More advanced travel-time and network models may provide more realistic representations of mobility conditions, but they also depend heavily on high-quality spatial datasets including road conditions, transport speeds, and infrastructure connectivity. In data-constrained environments such as central Mozambique, such information may be incomplete or rapidly altered during disasters (Petricola et al., 2022). Simpler spatial measures may therefore still provide valuable insights into broader accessibility inequalities while offering greater transparency and methodological robustness.

This methodological trade-off is particularly important in disaster contexts where infrastructure conditions may change rapidly during and after hazard events. Flooding may disrupt roads, isolate settlements, and alter mobility patterns in ways that are difficult to model precisely. Accessibility analyze during disasters must therefore account for uncertainty in infrastructure functionality and spatial data quality.

Recent research increasingly combines hazard mapping with accessibility modelling in order to examine compounded vulnerability. Rather than analysing hazard exposure or healthcare access separately, GIS allows researchers to identify areas where populations are simultaneously exposed to environmental hazards and constrained by limited accessibility to essential services (Tellman et al., 2021; Dewi et al., 2024). This type of spatial overlay analyze is particularly important for disaster risk reduction because it reveals where infrastructure disruption and vulnerability may intersect most severely.

Studies of Cyclone Idai illustrate the value of such approaches. Petricola et al. (2022) used GIS-based accessibility modelling to examine how flooding disrupted healthcare accessibility across central Mozambique, demonstrating that infrastructure disruption significantly reduced functional access to care. Their findings also highlighted how methodological choices and

data limitations can strongly influence estimated accessibility outcomes in disaster-affected environments.

Remote sensing technologies further strengthen GIS-based disaster analyze by enabling flood extent and environmental change to be mapped directly from satellite imagery (Hoque, 2017; Tellman et al., 2021). In data-scarce and disaster-affected regions, remotely sensed flood data are especially valuable because they provide spatially explicit information about hazard extent even where ground observations are limited. Integrating such hazard layers with accessibility and infrastructure data allows researchers to analyze how environmental exposure reshapes connectivity and service access across affected landscapes.

For the present study, GIS and spatial analyze provide the methodological foundation for examining how Cyclone Idai reshaped healthcare accessibility across Sofala Province. By combining flood extent data with healthcare facility locations, transport infrastructure, and population distribution, spatial analyze makes it possible to identify areas where flood exposure and limited accessibility overlap spatially. The use of multiple accessibility approaches, including Euclidean distance analyze, service area analyze, and closest facility analyze, further supports a more nuanced understanding of how infrastructure disruption influenced healthcare accessibility during and after the cyclone.

The literature demonstrates that GIS and spatial analyze are essential for understanding how disasters affect healthcare accessibility across space. These approaches make it possible to examine how hazard exposure, infrastructure vulnerability, and accessibility interact geographically, thereby supporting more spatially explicit analyzes of disaster risk and healthcare inequality.

2.5. Empirical Studies on Disaster-related Health Accessibility

Empirical research increasingly demonstrates that disasters affect healthcare accessibility not only through direct infrastructure damage, but also through disruptions to mobility, transport connectivity, and service accessibility. A growing body of literature shows that flood and cyclone impacts are often spatially uneven, disproportionately affecting populations already characterized by limited infrastructure access and geographic isolation.

Several studies have examined how environmental hazards disrupt healthcare systems by reducing functional accessibility to essential services. Koks et al. (2019) demonstrate that transport infrastructure disruptions during disasters can significantly reduce access to healthcare and emergency services, particularly in regions with limited infrastructure redundancy. Their findings highlight the importance of connectivity and mobility systems in shaping disaster vulnerability, emphasizing that accessibility losses often extend far beyond areas experiencing direct physical damage.

Research focusing specifically on flood-related healthcare accessibility similarly shows that disasters may isolate populations even when healthcare facilities remain operational. Mroz et al. (2023) found that flooding events significantly disrupted mobility and healthcare access in vulnerable regions by damaging transport networks and increasing travel constraints. Wu et al. (2024) further demonstrate that flood-related disruptions to road infrastructure can intensify healthcare inequalities by disproportionately affecting populations in rural and poorly connected areas.

Within low- and middle-income contexts, studies consistently show that healthcare accessibility is already uneven prior to disasters due to disparities in infrastructure, transport connectivity, and healthcare distribution (Ouma et al., 2018; Weiss et al., 2020). Hazard events may therefore amplify pre-existing accessibility inequalities rather than creating entirely new patterns of vulnerability. Dewi et al. (2024) argue that climate-related disasters increasingly interact with socio-spatial inequalities, producing compounded vulnerability in areas characterized by weak infrastructure and limited service access.

Research on Cyclone Idai provides particularly relevant insights into the present study. The cyclone caused widespread flooding, transport disruption, and infrastructure damage across central Mozambique, severely affecting mobility and access to essential services (World Bank, 2019). Petricola et al. (2022) used GIS-based accessibility modelling to examine how flooding associated with Cyclone Idai affected healthcare accessibility across affected regions. Their findings showed substantial reductions in functional healthcare access, particularly in rural areas dependent on vulnerable transport infrastructure.

These studies also highlight several methodological challenges within disaster-related accessibility research. Accessibility modelling in disaster contexts is often constrained by limited spatial data, uncertainty regarding infrastructure conditions, and rapidly changing

mobility patterns during and after hazard events (Petricola et al., 2022). As a result, different methodological approaches may produce varying representations of accessibility and vulnerability. This has led researchers to emphasize the importance of methodological transparency and the use of context-appropriate accessibility models, particularly in data-constrained environments.

Recent advances in GIS, remote sensing, and accessibility modelling have nevertheless expanded opportunities for analysing healthcare accessibility under disaster conditions. High-resolution population datasets, satellite-derived flood mapping, and improved transport network analyze increasingly allow researchers to identify areas where hazard exposure and limited healthcare accessibility overlap spatially (Tellman et al., 2021; Hierink et al., 2023). Such approaches contribute to more spatially explicit understandings of disaster vulnerability and infrastructure inequality.

Taken together, the empirical literature demonstrates that disaster-related healthcare accessibility is shaped by the interaction between hazard exposure, infrastructure disruption, and pre-existing spatial inequalities. Flood and cyclone impact often disproportionately affect populations already characterized by weak transport connectivity and limited healthcare access, thereby intensifying existing patterns of vulnerability. These findings provide important support for the present study, which examines how Cyclone Idai reshaped healthcare accessibility across Sofala Province through the disruption of transport infrastructure and mobility systems.

2.6. Research Gap and Relevance of this Study

The literature reviewed in this chapter demonstrates that disaster vulnerability is strongly shaped by the interaction between environmental hazards, infrastructure systems, and uneven patterns of healthcare accessibility. Previous research has shown that floods and cyclones can significantly disrupt mobility, damage transport infrastructure, and reduce access to essential healthcare services, particularly in rural and hazard-prone regions (Koks et al., 2019; Petricola et al., 2022; Dewi et al., 2024). At the same time, healthcare accessibility research consistently demonstrates that access to medical services is already spatially uneven across many low- and middle-income contexts due to disparities in infrastructure distribution, transport connectivity, and service provision (Ouma et al., 2018; Weiss et al., 2020).

Despite these contributions, several important research gaps remain. First, much of the existing disaster literature focuses either on hazard exposure and infrastructure damage or on baseline healthcare accessibility separately. Fewer studies explicitly examine how disasters reshape pre-existing spatial inequalities in healthcare accessibility through disruptions to transport connectivity and mobility systems. As a result, there remains limited understanding of how environmental hazards and healthcare accessibility interact spatially to produce compounded forms of vulnerability.

Second, while GIS and spatial accessibility modelling are increasingly used in both disaster research and health geography, relatively few studies integrate flood extent analyze with multiple healthcare accessibility approaches at subnational scales in disaster-affected low-income regions. Existing research often relies on a single accessibility measure or focuses primarily on urban environments where spatial datasets are more comprehensive. This creates a need for more geographically explicit studies examining how different accessibility methods can reveal varying dimensions of disaster-related healthcare inequality in rural and infrastructure-constrained settings.

Third, although Cyclone Idai has received substantial attention within disaster research, much of the literature has focused on humanitarian impacts, infrastructure damage, or emergency response. Comparatively fewer studies have examined how the cyclone altered functional healthcare accessibility across space, particularly in relation to pre-existing infrastructural inequalities within Sofala Province. Existing studies further highlight persistent challenges related to spatial data quality, transport modelling, and accessibility estimation in disaster-affected regions, underscoring the importance of transparent and context-sensitive methodological approaches (Petricola et al., 2022).

This thesis addresses these gaps by examining how Cyclone Idai reshaped spatial inequalities in healthcare accessibility across Sofala Province, Mozambique. Using GIS and spatial analyze, the study integrates flood extent data, healthcare facility locations, transport infrastructure, and population distribution in order to analyze how accessibility conditions changed following the cyclone. By combining Euclidean distance analyze, service area analyze, and closest facility analyze, the study provides a multi-method assessment of how infrastructure disruption influenced healthcare accessibility under disaster conditions.

The study contributes to existing literature in several ways. Conceptually, it contributes to disaster risk reduction and health geography research by framing healthcare accessibility as both a dimension of disaster vulnerability and a component of coping capacity. Methodologically, it demonstrates how multiple GIS-based accessibility approaches can be combined to examine disaster-related accessibility change in data-constrained environments. Empirically, it contributes new insights into how Cyclone Idai affected healthcare accessibility across Sofala Province and how flood impacts interacted with pre-existing spatial inequalities in infrastructure and service accessibility.

Overall, this study argues that Cyclone Idai did not affect healthcare accessibility uniformly across Sofala Province, but instead intensified pre-existing spatial inequalities by disproportionately disrupting already underserved and hazard-prone areas. By examining how flood exposure, infrastructure disruption, and accessibility intersect spatially, the thesis contributes to broader discussions on disaster vulnerability, infrastructure inequality, and spatially informed disaster risk reduction planning.

3. Study Area

This chapter introduces the geographic, environmental, and socio-economic context of Sofala Province, Mozambique, which forms the empirical setting for this study. Understanding the characteristics of the study area is essential for interpreting patterns of healthcare accessibility and flood exposure, as these are closely shaped by the distribution of population, infrastructure, and environmental conditions.

The chapter outlines the geographic location and administrative context of Sofala Province, followed by a description of its physical environment and flood-prone landscape. It then examines population distribution and infrastructure characteristics, before providing an overview of Cyclone Idai (2019) and its impacts. Finally, the chapter discusses the relevance of Sofala Province as a case study for analysing the spatial interaction between healthcare accessibility and disaster risk.

3.1. Geographic Location and Administrative Context

Sofala Province is in central Mozambique along the country’s eastern coastline facing the Indian Ocean. The province occupies an important position within central Mozambique and includes both coastal and inland areas, linking the interior to the coast through major

transport and settlement corridors. Beira, the provincial capital, is one of the most important urban centers in central Mozambique and serves as a major administrative, economic, and transport hub for the region. The city is situated near the mouths of the Pungwe and Buzi river systems, a location that has contributed both to its regional importance and to its environmental vulnerability (World Bank, 2018; World Bank, 2023).

Figure 1 shows the geographic location of the study area at three spatial scales. Panel (A) shows the location of Mozambique within the African continent, Panel (B) situates Sofala Province within Mozambique using provincial administrative boundaries, and Panel (C) presents Sofala Province itself as the main study area for the healthcare accessibility and flood exposure analyze undertaken in this thesis.

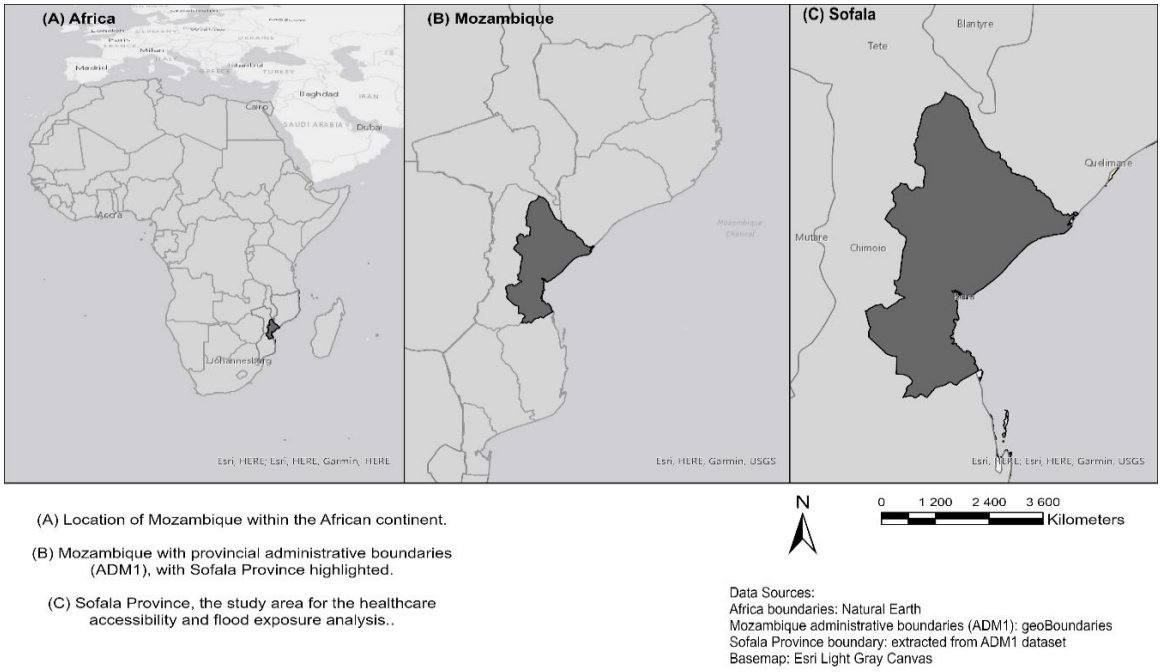


Figure 1. Study area and spatial context in Mozambique.

Sofala was selected as the study area because it provides a highly relevant case for examining the relationship between environmental hazards, infrastructure vulnerability, and healthcare accessibility. The province was among the areas most severely affected by Cyclone Idai in 2019, and the impacts of the disaster were heavily concentrated in central Mozambique, particularly in Sofala Province and the city of Beira (World Bank, 2019a; World Bank, 2019b).

The administrative and geographic characteristics of Sofala Province provide the spatial framework for the analyze conducted in this study. Locating the province within its broader regional setting is important for understanding both the distribution of healthcare services and the environmental conditions that shape flood risk. The following section therefore examines the physical environment and landscape characteristics of Sofala Province in greater detail. This geographic position is particularly important for the present study, as it places Sofala Province at the intersection of coastal and riverine flood risks. The concentration of infrastructure and population in low-lying coastal areas, especially around Beira, increases both exposure to hazards and the potential for disruptions to healthcare accessibility during extreme events (World Bank, 2019; IPCC, 2022). This geographic setting is also central to the analytical approach of this thesis, as it influences how healthcare accessibility is measured using Euclidean distance, service area, and closest facility network analyzes. The combination of coastal exposure, river systems, and infrastructure distribution creates conditions where both spatial proximity and network connectivity play a critical role in determining access to healthcare services.

3.2. Physical Environment and Flood-prone Landscape

The physical environment of Sofala Province is a key factor in understanding why the region is highly exposed to flood hazards. Much of central Mozambique is characterized by low-lying coastal plains, broad floodplains, and major river systems that drain toward the Indian Ocean. In Sofala, these landscape characteristics are particularly evident in the Pungwe and Buzi river basins, which shape both settlement patterns and hazard exposure across the province. Low elevation, relatively flat terrain, and limited drainage capacity make many parts of the province especially susceptible to water accumulation and river overflow during periods of intense rainfall (World Bank, 2010; World Bank, 2025). As illustrated in Figure 2, large parts of Sofala consist of low-lying and waterlogged terrain that is highly exposed to flooding during extreme weather events.



Figure 2. Flood-affected low-lying landscape in Beira, Sofala Province, Mozambique, after Cyclone Idai (2019). The image illustrates the extensive floodplain environment and settlement exposure characteristic of central Mozambique. Source: DFID/Flickr.

The province's environmental setting is closely tied to its exposure to cyclones, heavy rainfall, and flooding. Mozambique is widely recognized as one of the most hazard-prone countries in sub-Saharan Africa, with recurrent floods, cyclones, and storm-related disasters affecting both coastal and riverine areas. In central Mozambique, these hazards are intensified by the interaction between tropical weather systems, river catchments, and low-lying coastal environments. When extreme rainfall occurs upstream or when cyclones make landfall along the coast, floodwater can spread rapidly across extensive plains and inundate settlements, roads, and agricultural land (Intergovernmental Panel on Climate Change [IPCC], 2022; World Bank, 2019b).

Sofala's flood-prone landscape is therefore not only the result of isolated weather events, but also of broader hydrological and geomorphological conditions. River basins such as the Pungwe and Buzi concentrate runoff from inland catchments and carry large water volumes toward the coastal zone. During extreme events, these systems may exceed channel capacity, causing widespread overbank flooding across surrounding floodplains. This helps explain why flood impacts in Sofala often extend over large geographic areas rather than remaining confined to narrow river channels. Such environmental conditions are especially important in the context of this thesis, as flood extent directly affects both settlement exposure and access to healthcare services (World Bank, 2010; World Bank, 2019b).

The coastal location of the province adds an additional layer of environmental vulnerability. Coastal districts and urban areas, including Beira, are exposed not only to river flooding but also to cyclone-related storm surge, intense precipitation, and drainage congestion in low-elevation terrain. This creates a compound hazard environment in which multiple flood-generating processes may occur simultaneously. In practice, this means that both inland floodplains and coastal urban zones can experience severe inundation during major events, particularly when heavy rainfall, overflowing rivers, and coastal surge interact (IPCC, 2022; World Bank, 2023). This has direct implications for healthcare accessibility, as flood-prone areas may experience disruptions to transport networks and reduced mobility during extreme events. In such contexts, the physical landscape plays a key role in shaping not only hazard exposure, but also the ability of populations to access essential services (Koks et al., 2019; Dewi et al., 2024).

These landscape characteristics are highly relevant for the spatial analyze undertaken in this thesis. The distribution of healthcare accessibility cannot be understood independently of the physical environment in which people, settlements, and infrastructure are located. In flood-prone provinces such as Sofala, topography, hydrology, and coastal exposure shape not only where disasters occur, but also how easily populations can reach essential services when transport routes are disrupted. The environmental setting of Sofala therefore provides a crucial foundation for understanding the spatial interaction between flood exposure and healthcare accessibility examined in the following chapters. These environmental characteristics are particularly relevant for network-based accessibility analyzes, as flood-prone landscapes can significantly disrupt transport connectivity. While Euclidean distance provides a generalized measure of proximity, both service area and closest facility analyzes are sensitive to such disruptions, highlighting how physical geography directly influences functional accessibility.

3.3. Population and Infrastructure Characteristics

Population distribution and infrastructure are central to understanding healthcare accessibility in Sofala Province. The province presents a combination of urban centers, peri-urban settlements, and dispersed rural communities, resulting in considerable spatial variation in both service availability and physical access to infrastructure. Beira, as the provincial capital, represents the main concentration of population, economic activity, and public services in the province, while much of the remaining population is distributed across smaller settlements

and rural districts where infrastructure provision is more limited (World Bank, 2021; Sherr et al., 2013). António et al. (2022) similarly highlight considerable spatial differences in demographic distribution and access to services across Sofala Province, particularly between urban areas surrounding Beira and more rural inland districts. This uneven distribution of population and infrastructure contributes to significant spatial variation in healthcare accessibility. Urban areas such as Beira generally benefit from higher service density and better transport connectivity, while rural areas may experience longer travel distances and limited access to healthcare facilities. These disparities are particularly relevant in disaster contexts, where infrastructure disruptions may disproportionately affect already underserved populations (Ouma et al., 2018; Weiss et al., 2020; World Bank, 2021).

This uneven settlement pattern has important implications for healthcare accessibility. In urban areas such as Beira, populations tend to live closer to healthcare facilities and transport infrastructure, which generally improves physical access to services. In contrast, rural populations are often located at greater distances from formal healthcare facilities and may depend on smaller rural health centers, health posts, or limited transport connections. Such spatial variation is particularly important in a province like Sofala, where the distribution of healthcare infrastructure is shaped not only by population density but also by historical inequalities in service provision and broader infrastructural constraints (Sherr et al., 2013; Ouma et al., 2018).

The healthcare system in Sofala has historically been organized around a tiered network of facilities, with Beira functioning as the main referral center and rural districts depending on lower-order facilities. Sherr et al. (2013) note that the health network in Sofala includes a broad but unevenly distributed set of facilities across its districts, with most of the formal outpatient care delivered through the public sector. Although this network provides a crucial foundation for healthcare delivery, geographic proximity to services remains highly uneven, particularly for rural populations living far from district centers or transport corridors.

Transport infrastructure is similarly uneven across the province. This is especially important in the context of this study, as network-based methods such as service area and closest facility analyzes rely on the structure and functionality of transport infrastructure to estimate accessibility. In contrast, Euclidean distance does not account for these infrastructural constraints, making the comparison between methods particularly relevant in regions with uneven and vulnerable transport systems such as Sofala. Roads and bridges are essential for

linking rural communities to markets, urban centers, and healthcare services, yet these networks are highly vulnerable to flood damage and seasonal disruption. In Mozambique more broadly, transport systems are frequently affected by flooding, erosion, and limited maintenance capacity, and these problems are particularly significant in central provinces such as Sofala where large floodplains and river crossings create recurring infrastructure challenges (World Bank, 2018; World Bank, 2022). In practice, this means that the existence of a healthcare facility does not automatically guarantee effective access if roads, bridges, or connecting routes are damaged, seasonally impassable, or poorly maintained.

These infrastructure conditions are especially significant in the context of disaster risk. Research on access to emergency care in sub-Saharan Africa has shown that geographic accessibility is strongly shaped by transport connectivity, with rural populations often facing substantially greater barriers than urban populations in reaching essential health services (Ouma et al., 2018). In flood-prone settings, these barriers can intensify rapidly during extreme weather events, such as road closures, damaged bridges, and inundated routes reduce mobility and isolate settlements. This is particularly relevant in Sofala Province, where flood exposure and transport vulnerability intersect with already uneven patterns of settlement and service provision.

The relationship between population distribution and infrastructure therefore provides an important bridge between the study area context and the analytical focus of this thesis. Healthcare accessibility in Sofala cannot be understood solely in relation to the presence or absence of facilities; it must also be viewed in relation to where people live, how settlements are distributed, and how effectively transport infrastructure connects populations to essential services. These factors help explain why geographic inequalities in healthcare access remain pronounced and why they may become even more severe during flood disasters such as Cyclone Idai.

3.4. Cyclone Idai in Sofala Province

Cyclone Idai was one of the most severe tropical cyclones to affect southern Africa in recent decades and had particularly devastating consequences in central Mozambique. After making landfall near Beira in March 2019, the cyclone brought intense rainfall, strong winds, and widespread flooding across Sofala Province and surrounding areas. The combination of storm surge, river overflow, and prolonged inundation caused extensive damage to settlements,

infrastructure, agricultural land, and public services, making Sofala one of the most severely affected provinces during the disaster (World Bank, 2019a; Charrua et al., 2021).

Sofala's exposure to Cyclone Idai was shaped by both its coastal location and its low-lying flood-prone landscape. Beira, located on the coast near the Pungwe and Buzi river systems, experienced severe impacts due to the interaction of high winds, heavy precipitation, and coastal surge. At the same time, inland areas of the province were heavily affected by river flooding as intense rainfall and rising water levels spread across floodplains and surrounding settlements. This meant that the disaster was not confined to a single urban center but instead affected a broad range of environments across the province, from coastal urban areas to rural inland districts (World Bank, 2019a; Petricola et al., 2022).

Figure 3 illustrates the track of Cyclone Idai and the spatial extent of flooding in central Mozambique, with Sofala Province highlighted as the study area. The figure shows that Sofala was located within one of the main impact zones of the cyclone and that large parts of the province were affected by flooding. This is particularly relevant for the present study, as it provides the environmental context for analysing how flood exposure intersected with healthcare accessibility across the province.

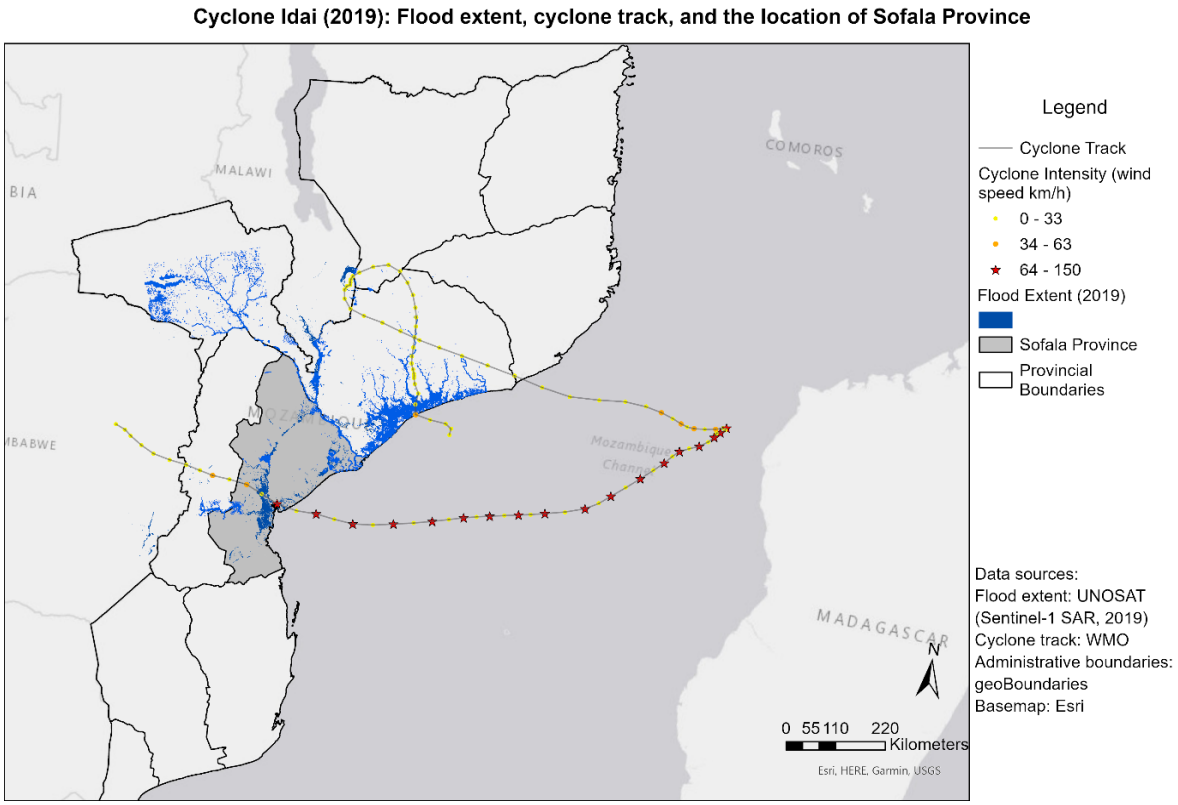


Figure 3. Cyclone Idai (2019): flood extent and cyclone track.

The impacts of Cyclone Idai extended beyond physical destruction to include major disruptions in mobility, service delivery, and public health conditions. Roads, bridges, and other transport infrastructure were damaged or rendered impassable, isolating communities and constraining access to emergency assistance and healthcare services. Health facilities themselves were also affected, while the broader disruption of infrastructure increased the difficulty of reaching available services. In the aftermath of the cyclone, humanitarian reports and post-disaster assessments highlighted severe constraints on access to basic services, particularly in the most flood-affected parts of Sofala Province (World Bank, 2019a; Office for the Coordination of Humanitarian Affairs [OCHA], 2019).

Cyclone Idai is therefore highly relevant to this thesis not only because of the scale of the disaster, but also because it exposed the interaction between environmental hazards and pre-existing spatial inequalities. The event demonstrated how populations already living in flood-prone landscapes and at considerable distance from essential services could experience compounded vulnerability when infrastructure was disrupted. In this sense, Sofala Province provides an important case for examining how flood exposure and healthcare accessibility intersect spatially during major disaster events. From an analytical perspective, these disruptions are critical for understanding differences between accessibility measures. While Euclidean distance remains unchanged by flood conditions, network-based approaches such as service area and closest facility analyze capture how infrastructure damage and inundation reduce connectivity and limit access to healthcare services.

3.5. Relevance of the Study Area

Sofala Province provides a highly relevant empirical setting for examining the relationship between environmental hazards and healthcare accessibility. As demonstrated in the preceding sections, the province combines several characteristics that make it particularly suitable for this analyze. These include a flood-prone physical environment, the presence of major river basins and low-lying coastal landscapes, a mix of urban and rural settlement patterns, and uneven infrastructure distribution across the province. In addition, Sofala was one of the area's most severely affected by Cyclone Idai in 2019, making it an especially important case for analysing how extreme events interact with pre-existing spatial inequalities (World Bank, 2019; Petricola et al., 2022).

The relevance of Sofala lies not only in the scale of hazard exposure, but also in the spatial diversity of the province itself. The province includes densely populated urban areas such as

Beira, where infrastructure and healthcare services are relatively concentrated, as well as extensive rural areas where settlements are more dispersed and access to services is more limited (António et al., 2022). This internal variation makes Sofala analytically valuable because it allows the study to examine how healthcare accessibility differs across contrasting geographic settings within the same administrative unit. In other words, the province contains both well-connected areas and locations characterized by greater physical isolation, making it possible to explore how vulnerability is unevenly distributed across the landscape (Ouma et al., 2018; Weiss et al., 2020).

Sofala is also significant because it illustrates the way disaster impacts are shaped by existing infrastructural and environmental conditions. Flood events do not create vulnerability in isolation; rather, they interact with the spatial organization of settlements, transport systems, and public services. In provinces such as Sofala, where roads, bridges, and healthcare facilities are distributed unevenly and where large areas are environmentally exposed to flooding, the consequences of a major disaster can be particularly severe. This means that healthcare accessibility during and after extreme events cannot be understood solely by examining the hazard itself but must also be analyzed in relation to the underlying geography of infrastructure and population distribution (IPCC, 2022; World Bank, 2019).

From a broader perspective, the choice of Sofala also enhances the relevance of the study beyond the immediate case area. Many regions in sub-Saharan Africa face similar combinations of climate-related hazard exposure, infrastructural inequality, dispersed rural populations, and limited healthcare accessibility. Although the findings of this thesis are context-specific, the case of Sofala reflects wider challenges that are common in hazard-prone and resource-constrained settings. Analysing this province therefore contributes not only to understanding the spatial consequences of Cyclone Idai (2019), but also to broader discussions on disaster vulnerability, health system resilience, and spatial inequality in access to essential services (Kruk et al., 2015; Ouma et al., 2018).

The study area is therefore well aligned with the overall aims of this thesis. By focusing on Sofala Province, the analyze can examine how flood exposure and healthcare accessibility intersect spatially within a context where both environmental risk and infrastructural vulnerability are pronounced. This makes the province an appropriate and analytically meaningful case through which to explore the broader relationship between disaster risk and access to healthcare. The characteristics of Sofala Province make it particularly suitable for

applying multiple accessibility methods. The combination of uneven infrastructure, dispersed population distribution, and exposure to flooding allows for a meaningful comparison between Euclidean distance, service area, and closest facility analyzes. While Euclidean distance captures general spatial inequalities in proximity to healthcare services, network-based approaches provide insight into how these inequalities are shaped by infrastructure and how they are altered during flood events. This makes Sofala an especially relevant case for examining how different methodological approaches capture accessibility under both baseline and disrupted conditions. The following chapter builds on this contextual foundation by outlining the methodological approach used to analyze healthcare facility distribution, population accessibility, and flood exposure across the study area.

4. Method

This chapter outlines the methodological approach used to examine the spatial relationship between flood exposure and healthcare accessibility in Sofala Province, Mozambique. The study adopts a quantitative, GIS-based framework that integrates spatial data on healthcare infrastructure, population distribution, transportation networks, and satellite-derived flood extent (Ouma et al., 2018; Weiss et al., 2020).

The chapter describes the research design, data sources, and preprocessing steps, followed by the methods used for accessibility analyze, flood mapping, and spatial overlay. It then presents the procedures for population estimation and statistical analyze, before concluding with a discussion of methodological limitations and ethical considerations. Together, these methods provide a systematic and reproducible framework for analysing spatial patterns of vulnerability in a disaster-prone context (Dewi et al., 2024). To assess geographic accessibility to healthcare facilities, three complementary spatial methods were applied: a Euclidean distance approach, a network-based service area analyze, and a closest facility analyze (Guagliardo, 2004). These methods capture different dimensions of accessibility (Guagliardo, 2004; Petricola et al., 2022). While Euclidean distance provides a generalized measure of spatial proximity (Guagliardo, 2004), the service area analyze evaluates accessibility based on travel thresholds along the road network (Koks et al., 2019), and the closest facility analyze identifies optimal routes between population locations and healthcare services (Petricola et al., 2022). Together, these approaches provide a more comprehensive understanding of both potential and functional accessibility (Guagliardo, 2004; Dewi et al., 2024).

4.1. Research Design

This study applies a quantitative spatial research design to examine how Cyclone Idai reshaped healthcare accessibility across Sofala Province, Mozambique. The research is grounded in Geographic Information Systems (GIS) and spatial accessibility analyze, combining healthcare infrastructure data, transport networks, population distribution, and flood extent information to analyze how accessibility conditions changed following the cyclone. GIS-based approaches are increasingly used within disaster and health geography research because they allow hazards, infrastructure systems, and accessibility patterns to be analyzed within a shared spatial framework (Guagliardo, 2004; Koks et al., 2019; Weiss et al., 2020). Figure 4 provides an overview of the methodological workflow applied in the study, illustrating how spatial datasets, accessibility analyze, flood exposure analyze, and population-based vulnerability assessment were integrated within the GIS framework.

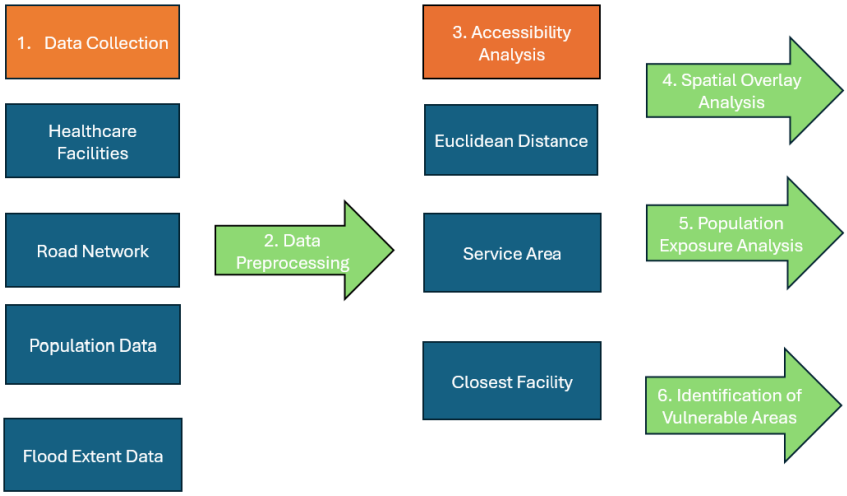


Figure 4. Methodological workflow illustrates the integration of spatial datasets, accessibility analyze, flood exposure analyze, and vulnerability assessment used in this study. Made with Powerpoint.

The research design is guided by the overarching objective of understanding how Cyclone Idai affected spatial inequalities in healthcare accessibility. Rather than treating disaster impacts as geographically uniform, the study assumes that flood-related disruptions affected populations differently depending on their location, transport connectivity, and proximity to healthcare services. Accessibility is therefore conceptualized as both a dimension of vulnerability and a component of coping capacity within disaster contexts (Wisner et al.,2012; UNDRR, 2015; IPCC, 2022).

To address the research questions, the study combines multiple GIS-based accessibility approaches. Euclidean distance analyze is used to examine baseline spatial proximity between populations and healthcare facilities, providing a transparent overview of general accessibility patterns across the province. In addition, network-based methods including service area analyze and closest facility analyze are applied to assess how transport connectivity influences healthcare accessibility under disrupted conditions. Combining multiple accessibility approaches allows the study to capture different dimensions of accessibility and compare how methodological choices influence the representation of spatial inequality (Guagliardo, 2004; Weiss et al., 2020; Dewi et al., 2024).

The study further integrates flood extent data associated with Cyclone Idai in order to examine how environmental exposure interacted with healthcare accessibility and transport infrastructure. Overlay analyze is used to identify areas where flooding coincided with limited healthcare accessibility and vulnerable infrastructure conditions. This approach reflects recent disaster research emphasizing that vulnerability emerges through the spatial interaction between hazard exposure, infrastructure systems, and accessibility constraints (Wisner et al., 2012; Koks et al., 2019; Dewi et al., 2024).

A comparative before-and-after framework is central to the research design. Accessibility conditions are analyzed both prior to and following flood-related infrastructure disruption in order to assess how Cyclone Idai altered functional healthcare accessibility across Sofala Province. This comparative approach supports the identification of areas where pre-existing accessibility inequalities intensified during the disaster (Petricola et al., 2022).

The study is conducted at the provincial scale, with Sofala Province selected as the primary case study due to its severe exposure to Cyclone Idai and its combination of flood-prone landscapes, dispersed settlements, uneven infrastructure distribution, and limited healthcare accessibility. The province therefore provides an appropriate context for examining how disaster impacts interact with pre-existing spatial inequalities in infrastructure and service accessibility.

Methodologically, the study adopts a pragmatic approach to spatial accessibility modelling. While advanced travel-time models may provide highly detailed estimates of mobility conditions, such approaches depend on extensive and reliable transport datasets that are often unavailable or uncertain in disaster-affected and low-resource settings (Guagliardo, 2004;

Petricola et al., 2022; Weiss et al., 2020).The study therefore combines relatively transparent and robust spatial methods with available infrastructure and flood data in order to produce context-appropriate analyzes of healthcare accessibility change.

Finally, the research design recognizes several limitations related to spatial data quality, infrastructure uncertainty, and post-disaster accessibility modelling. Accessibility estimates may not fully capture informal transport systems, seasonal mobility variations, or real-time road conditions during and after flooding. However, by integrating multiple accessibility approaches and combining hazard and infrastructure analyze within a GIS framework, the study aims to provide a spatially grounded understanding of how Cyclone Idai reshaped healthcare accessibility and intensified pre-existing inequalities across Sofala Province (Koks et al., 2019; UNDRR, 2015).

4.2. Data sources and Materials

This study is based on the integration of multiple spatial datasets representing healthcare infrastructure, flood exposure, population distribution, and transportation networks. All data were obtained from publicly available and widely used sources and processed within a Geographic Information Systems (GIS) environment to support spatial analyze. The use of multiple datasets enables a comprehensive assessment of how environmental hazards, infrastructure, and population distribution interact across space (Cutter et al., 2003). These datasets support both proximity-based and network-based accessibility analyzes, allowing for a comparison between generalized and infrastructure-constrained measures of access.

Healthcare facility and road network data were obtained from OpenStreetMap (OSM) through the Geofabrik data extraction service, which provides region-specific extracts of OSM data. These datasets include the geographic locations of healthcare facilities, as well as transportation infrastructure such as roads, which are essential for accessibility analyze. The data form the basis for both Euclidean distance calculations and network-based modelling of access to healthcare services. While OSM provides extensive and openly accessible spatial data, it is important to note that data completeness and accuracy may vary across regions, particularly in rural or less-mapped areas (OpenStreetMap contributors, 2024; Geofabrik, 2024).

Flood exposure data were derived from satellite-based observations of Cyclone Idai (2019). Specifically, flood extent data was obtained from the Humanitarian Data Exchange (HDX), a

platform that provides curated humanitarian datasets from multiple sources. The dataset is based on satellite-derived flood mapping produced by the United Nations Institute for Training and Research Operational Satellite Applications Programme (UNITAR-UNOSAT). It represents areas identified as inundated during the cyclone event and provides a spatially explicit representation of flood extent. These data support the identification of hazard-affected areas and are further used in the network analyze as barriers to simulate disrupted accessibility under flood conditions (UNITAR-UNOSAT, 2019; Humanitarian Data Exchange, 2019). The data sets used in the analyze and their sources are summarized in *Table 1*.

Dataset	Description	Source	Format
Healthcare facilities	Locations of healthcare facilities used to represent healthcare infrastructure in Sofala Province	OpenStreetMap, Geofabrik	Point
Population Distribution	Gridded population dataset used to estimate population exposure	Worldpop (2020)	Raster
Flood Extent	Satellite-derived flood detection of Cyclone Idai (2019)	UNOSAT/HDX	Raster
Administrative Boundaries	Provincial Boundary used to define the study area	GADM	Polygon
Road network	Road network used for spatial reference and contextual mapping	OpenStreetMap, Geofabrik	Line

Table 1. Overview of all spatial datasets used for this thesis.

Note: *All spatial datasets were processed and analyzed in ArcGIS Pro.*

Population data were incorporated to estimate the number of people affected by varying levels of healthcare accessibility and flood exposure. Gridded population datasets from WorldPop were used to represent the spatial distribution of population across Sofala Province. These datasets provide high-resolution estimates of population distribution based on census data and modelling techniques, allowing spatial patterns of accessibility and exposure to be translated into population-based measures of vulnerability (WorldPop, 2020; Tatem, 2017).

Road network data, also derived from OpenStreetMap, were used both as contextual information and as a core input for the network-based accessibility analyze. The road network forms the basis for the closest facility analyze, enabling the modelling of realistic travel paths between population locations and healthcare facilities. Transport infrastructure plays a critical role in shaping access to healthcare services, particularly during disaster events when disruptions to mobility can significantly affect accessibility (Koks et al., 2019; Weiss et al., 2020). The road network data also form the basis for both the closest facility and service area analyzes, enabling the modelling of both route-based accessibility and the spatial extent of healthcare service coverage under different conditions.

All datasets were harmonized prior to analyze to ensure consistency in coordinate reference system (CRS), spatial resolution, and geographic extent. Preprocessing steps included data cleaning, clipping to the study area, and verification of spatial alignment across layers. These steps are essential to ensure the accuracy and reliability of spatial analyze and to minimize errors associated with data integration. The combined use of these datasets enables a comprehensive and spatially explicit assessment of how healthcare accessibility and flood exposure interact within the study area. Several limitations related to data quality and completeness must also be acknowledged. Spatial datasets in low-resource and disaster-affected regions may contain inaccuracies, incomplete infrastructure coverage, or temporal inconsistencies (Petricola et al., 2022). In particular, road conditions and accessibility during and after flooding may not be fully represented within static transport datasets. Similarly, healthcare facility datasets may not capture temporary service disruptions, staffing limitations, or differences in healthcare capacity between facilities. These limitations are important considerations when interpreting the accessibility analyzes presented in this study.

Despite these uncertainties, the combination of healthcare, infrastructure, flood, and population datasets provides an appropriate basis for examining how Cyclone Idai reshaped healthcare accessibility across Sofala Province. Integrating these spatial datasets within a GIS framework allows the study to analyze how hazard exposure, transport disruption, and pre-existing accessibility inequalities interacted geographically during the disaster.

4.3. Data Preprocessing and Preparation

Prior to analyze, all spatial datasets were processed and standardized within a GIS environment to ensure consistency, compatibility, and analytical accuracy. Because the study integrates multiple datasets originating from various sources, preprocessing was necessary to align spatial formats, coordinate systems, and geographic extents before conducting accessibility and flood analyzes (Chang, 2023).

All datasets were projected into a common coordinate reference system to maintain spatial consistency across raster and vector layers. Standardizing projection systems is particularly important in spatial accessibility analyze because distance calculations, network modelling, and overlay operations may otherwise produce inaccurate results (Guagliardo, 2004). Following reprojection, all datasets were clipped to the administrative boundaries of Sofala Province in order to limit analyzes to the defined study area.

Healthcare facility data were reviewed to remove duplicate entries, correct invalid geometries, and verify spatial positioning where necessary. Facilities were categorized according to available dataset attributes and converted into point layers suitable for distance and network analyze. Because healthcare accessibility represents a central variable within the study, ensuring spatial consistency and positional accuracy of facility locations was an important preprocessing step.

Road network data were similarly processed to support network-based accessibility analyze. This included geometry repair, connectivity validation, and the removal of disconnected or invalid network segments where necessary. The road dataset was converted into a routable network structure to enable service area and closest facility analyze (Weiss et al., 2020). While the dataset provides a representation of transport connectivity across Sofala Province, it does not fully capture road quality, seasonal variation, or temporary disruption conditions during the cyclone event.

Flood extent data associated with Cyclone Idai were processed to identify inundated areas and support overlay analyze with healthcare accessibility and infrastructure layers. Flood raster and polygon datasets were aligned spatially with the road and healthcare datasets to ensure compatibility during spatial intersection and exposure analyze. Flood layers were further used to identify potentially disrupted transport corridors and accessibility constraints within affected regions (Koks et al., 2019).

Population datasets were prepared to support spatial comparisons between accessibility conditions and settlement distribution (Tatem, 2017). Gridded population layers were clipped to the study area and aligned with the coordinate system used throughout the analyze. These datasets were later integrated with accessibility outputs in order to identify areas where large population concentrations coincided with flood exposure and limited healthcare access.

Several additional preprocessing steps were undertaken to improve analytical consistency. Raster resolution and spatial extent were standardized where necessary to support overlay analyze, while topology checks and geometry validation were used to reduce spatial processing errors. Attribute tables were also reviewed and cleaned to ensure consistent naming conventions and compatibility between datasets.

Because disaster-related accessibility analyze is highly sensitive to data quality and infrastructure representation, preprocessing also involved consideration of dataset limitations and uncertainty. Static road datasets may not fully represent real-time infrastructure conditions during flooding, while healthcare facility datasets may not capture operational status during the cyclone event (Perticola et al., 2022). These limitations were considered throughout the analyze and informed the interpretation of accessibility results.

Overall, data preparation and preprocessing formed an essential step in ensuring that healthcare infrastructure, transport networks, flood extent, and population data could be analyzed within a consistent GIS framework. Standardizing and validating these datasets enabled the subsequent accessibility and overlay analyzes used to examine how Cyclone Idai reshaped healthcare accessibility across Sofala Province.

4.4. Healthcare Accessibility Analyze

Healthcare accessibility analyze was conducted to examine how spatial access to healthcare services varied across Sofala Province before and after Cyclone Idai. The analyze focused on geographic accessibility, understood as the ability of populations to physically reach healthcare facilities through surrounding transport and infrastructure systems (Levesque et al., 2013). Because accessibility may be represented in different ways depending on methodological approach, the study applied multiple GIS-based accessibility methods in order to capture different dimensions of spatial accessibility and infrastructure connectivity (Koks et al., 2019).

The analyze combined Euclidean distance analyze, service area analyze, and closest facility network analyze within a GIS framework. Using multiple methods allows for a more nuanced understanding of healthcare accessibility by comparing both generalized spatial proximity and transport-based connectivity conditions (Guagliardo, 2004; Weiss et al., 2020).

4.4.1. Euclidean Distance Analyze

Euclidean distance analyze was used to calculate straight-line distance between population locations and healthcare facilities across Sofala Province. This method provides a simplified measure of spatial proximity and is commonly used in healthcare accessibility research due to its transparency and relatively low data requirements (Guagliardo, 2004).

Although Euclidean distance does not account for road conditions, terrain, or transport connectivity, it provides an important baseline representation of general accessibility patterns across the study area. In data-constrained and disaster-affected environments, simpler distance measures may also offer greater methodological robustness because they are less sensitive to incomplete or uncertain transport data (Weiss et al., 2020).

The resulting distance surfaces were used to identify broad spatial inequalities in healthcare accessibility prior to Cyclone Idai and to compare accessibility conditions across different regions of Sofala Province.

4.4.2. Service Area Analyze

Service area analyze was conducted to examine accessibility based on road network connectivity. This approach models the geographic areas that can be reached from healthcare facilities through the transport network within specified travel distances or network ranges. Compared to Euclidean distance analyze, service area modelling provides a more realistic representation of accessibility because it incorporates the structure and connectivity of the road network (Weiss et al., 2020; Hierink et al., 2023).

Service area analyze was used to identify populations located within and outside accessible transport zones surrounding healthcare facilities. The method also supported the examination of how flood-related road disruption may have altered accessibility coverage across affected districts. Areas where transport connectivity was reduced due to flooding were interpreted as experiencing decreased functional healthcare accessibility (Koks et al., 2019).

Because road conditions and travel speeds during and after Cyclone Idai could not be modelled with complete accuracy, the analyze focused primarily on relative accessibility patterns rather than precise travel-time estimation. This approach aligns with previous accessibility research emphasizing the importance of context-appropriate modelling in data-limited environments (Petricola et al., 2022).

4.4.3. Closest Facility Analyze

Closest facility analyze was applied to examine the shortest available network routes between population locations and healthcare facilities within the transport network. Unlike Euclidean distance analyze, this method incorporates road connectivity and network structure to estimate likely access routes under existing infrastructure conditions (Weiss et al., 2020).

The analyze was used to identify how flood-related infrastructure disruption may have altered healthcare accessibility by increasing route distance, reducing connectivity, or isolating settlements from nearby healthcare facilities (Koks et al., 2019). In areas where flooding disrupted major transport corridors or reduced network continuity, populations may have been required to travel substantially longer distances to reach functioning healthcare services.

Closest facility analyze was particularly useful for identifying localized accessibility disruption and spatial variations in transport connectivity across Sofala Province. The method

therefore provided additional insight into how Cyclone Idai reshaped functional healthcare accessibility through infrastructure disruption rather than solely through physical damage to healthcare facilities (Petricola et al., 2022).

4.4.4. Comparative Accessibility Framework

A comparative before-and-after framework was used throughout the accessibility analyze to assess how Cyclone Idai altered spatial access to healthcare services. Baseline accessibility conditions were first analyzed using pre-flood infrastructure and healthcare data. Flood extent layers were then integrated with transport and accessibility datasets in order to examine how inundation and infrastructure disruption may have affected accessibility patterns following the cyclone (Koks et al., 2019).

Comparing accessibility conditions before and after flooding allowed the study to identify areas where pre-existing inequalities intensified during the disaster (Wisner et al., 2012; UNDRR, 2015). Particular attention was given to rural, poorly connected, and flood-prone areas where healthcare accessibility was already limited prior to Cyclone Idai.

The accessibility analyze provided a spatial framework for examining how healthcare access, transport connectivity, and flood exposure interacted across Sofala Province. By combining multiple accessibility approaches, the study was able to analyze both generalized spatial inequalities and more localized patterns of infrastructure disruption associated with Cyclone Idai (Weiss et al., 2020).

4.5. Flood Exposure Mapping and Spatial Overlay Analyze

Flood extent and spatial overlay analyze were conducted to examine how flooding associated with Cyclone Idai interacted with healthcare accessibility, transport connectivity, and population distribution across Sofala Province. The purpose of this analyze was to identify areas where environmental exposure and limited healthcare accessibility overlapped spatially, thereby contributing to compounded patterns of vulnerability.

4.5.1. Flood Extent Data and Flood Exposure Mapping

Flood exposure was assessed using satellite-derived flood extent data associated with Cyclone Idai (2019). Within this study, flood exposure is conceptualized as the spatial

presence of surface water linked to the cyclone event, representing areas potentially affected by inundation and infrastructure disruption (IPCC, 2022).

Flood extent data were obtained from the United Nations Institute for Training and Research Operational Satellite Applications Programme (UNITAR-UNOSAT) and distributed through the Humanitarian Data Exchange (HDX) platform (UNITAR-UNOSAT, 2019; Humanitarian Data Exchange, 2019). These datasets are widely used in humanitarian and disaster response contexts because they provide near-real-time hazard information derived from remote sensing observations.

The dataset represents the maximum observed flood extent associated with Cyclone Idai as of 21 March 2019. Flood mapping was based on a combination of multiple satellite observations collected between 7 and 21 March 2019, corresponding to the primary flood period following the cyclone event. The dataset integrates Copernicus Sentinel-1 synthetic aperture radar (SAR) imagery acquired between 12 and 21 March 2019 together with AFED (ARC Flood Extent Depiction) products representing non-persistent surface water observed between 7–16 March and on 20 March. Combining multiple satellite products and observation periods improves the detection of inundated areas under varying environmental conditions, including cloud-covered regions where optical imagery may be limited (Schumann & Moller, 2015).

Because SAR imagery is capable of detecting surface water independently of cloud cover and daylight conditions, the dataset provides a robust representation of flood extent across Sofala Province during the disaster period. However, the flood layer represents a temporal snapshot of maximum observed inundation rather than a continuous representation of flood dynamics. The dataset therefore does not capture flood duration, water depth, or temporal progression throughout the cyclone event. Flood exposure within this study should consequently be interpreted as an approximation of observed inundation extent rather than a complete representation of flooding processes (Petricola et al., 2022).

Prior to analyze, the flood dataset was preprocessed to ensure compatibility with the other spatial datasets used within the GIS framework. This included clipping the raster data to the spatial extent of Sofala Province and standardizing the coordinate reference system (CRS), spatial extent, and resolution to align with healthcare accessibility, road network, and population datasets. Ensuring spatial consistency between datasets is important for accurate overlay analyze and accessibility modelling.

To facilitate integration with accessibility and infrastructure layers, the flood raster was reclassified into a binary flood exposure layer representing flooded and non-flooded areas. While this approach does not capture variation in flood intensity or severity, it provides a transparent and consistent framework for identifying areas exposed to inundation. The binary flood layer was subsequently incorporated into the network-based accessibility analyze as a spatial constraint representing potential infrastructure disruption and reduced mobility across inundated areas (Koks et al., 2019).

4.5.2. Spatial Overlay and Vulnerability Analyze

Spatial overlay analyze was used to examine how flood exposure, healthcare accessibility, transport connectivity, and population distribution intersected geographically across Sofala Province. Overlay techniques allow multiple spatial variables to be analyzed within a shared geographic framework and are widely applied in disaster risk and vulnerability research to identify areas where hazards and infrastructural inequalities overlap (Koks et al., 2019; IPCC, 2022).

Flood extent layers were combined with healthcare accessibility outputs, road network data, and population distribution in order to identify areas characterized by compounded vulnerability. Attention was given to regions where:

- flood exposure coincided with limited healthcare accessibility,
- transport connectivity was potentially disrupted,
- and vulnerable populations were located within flood-prone and poorly connected areas.

The analyze adopts the assumption that disaster vulnerability emerges through the interaction between hazard exposure and pre-existing socio-spatial inequalities rather than through hazard occurrence alone (Wisner et al., 2012; UNDRR, 2015). Flood-related disruption is therefore particularly significant in areas where healthcare accessibility and infrastructure connectivity were already limited prior to Cyclone Idai.

Spatial intersection techniques were further used to identify road segments and accessibility zones located within inundated areas. Roads intersecting flooded regions were interpreted as potentially vulnerable to reduced functionality or temporary disruption during the cyclone

event. While the analyze does not directly measure real-time road passability, it provides an indication of where mobility and healthcare accessibility were likely affected by flooding.

Overlay analyze also supported the comparative before-and-after accessibility framework by helping identify areas where flood-related infrastructure disruption may have intensified pre-existing inequalities in healthcare accessibility. Areas characterized by both high flood exposure and limited accessibility were interpreted as particularly vulnerable due to the increased likelihood of functional isolation during the disaster.

Several limitations should also be acknowledged. Spatial overlay analyze identifies geographic coincidence between datasets but cannot fully determine the operational status of roads, healthcare facilities, or mobility conditions during the cyclone event. Similarly, the flood layer does not capture temporal changes in inundation conditions or informal mobility strategies used by local populations. Nevertheless, the integration of flood exposure, accessibility, and infrastructure data provides an effective framework for examining how Cyclone Idai reshaped healthcare accessibility across Sofala Province.

The flood extent and spatial overlay analyze formed a central component of the study by linking hazard exposure with healthcare accessibility and infrastructure vulnerability. Integrating flood mapping with accessibility analyze enabled the identification of areas where Cyclone Idai likely intensified pre-existing spatial inequalities through disruptions to transport connectivity, reduced functional accessibility, and unequal access to essential healthcare services during the disaster.

4.6. Population estimation and classification

Population estimation was conducted to quantify the number of people affected by different levels of healthcare accessibility and flood exposure. This step links spatial analyze to population distribution, enabling a more comprehensive assessment of potential vulnerability by translating spatial patterns into population-based measures (Cutter et al., 2003).

Population data were derived from gridded raster datasets provided by WorldPop, where each cell represents an estimated number of people within a defined spatial unit (WorldPop, 2020). These datasets are based on statistical modelling techniques that combine census data with ancillary spatial variables to produce high-resolution population estimates (Tatem, 2017)..

While such data provide detailed spatial coverage, they represent modelled approximations rather than exact population counts and should therefore be interpreted accordingly.

The population raster was integrated with the classified accessibility and flood exposure layers using raster-based spatial analyze in ArcGIS Pro. This integration was achieved through cell-by-cell overlay operations, ensuring that each population grid cell could be associated with corresponding accessibility and flood exposure values. Accessibility classifications was primarily derived from the Euclidean distance analyze, while the service area and closest facility analyzes provided complementary network-based interpretations of accessibility under flood-affected conditions.

The classified accessibility layer and the flood exposure layer were overlaid with the population raster to extract population values corresponding to each spatial category. This process enabled the estimation of the number of people located within areas of good, moderate, and poor healthcare accessibility, as well as those residing in flood-exposed zones. By integrating these datasets, the analyze moves beyond purely spatial representation and enables the quantification of populations potentially exposed to both limited healthcare accessibility and flood hazards

In addition, combined categories were derived to estimate the population exposed to both flooding and varying levels of healthcare accessibility. Particular emphasis was placed on populations located in areas characterized by both flood exposure and poor accessibility, as these represent groups potentially facing the greatest barriers to accessing healthcare services during and after disaster events. These combined categories are central to identifying zones of compounded vulnerability within the study area (Wisner et al., 2012; UNDRR, 2015).

To support interpretation, population values were aggregated for each category and summarized using descriptive statistical methods. This included the calculation of total population counts within each accessibility and exposure class, as well as the generation of tabular summaries. Additional data processing and visualization, including the creation of summary tables and histograms, were conducted using Visual Studio Code to support the presentation and interpretation of results.

It is important to note that the population estimates produced in this analyze are subject to uncertainty due to the modelled nature of the input data and the spatial resolution of the raster datasets. Aggregation and overlay processes may also introduce a degree of generalization, particularly when combining multiple spatial layers with differing resolutions. As such, the

resulting population figures should be interpreted as indicative estimates rather than precise counts (Weiss et al., 2020).

Overall, the population estimation process provides a quantitative basis for assessing the spatial distribution of vulnerability. By linking accessibility, hazard exposure, and population data, the analyze enables a more comprehensive understanding of how disaster risk is distributed across the study area and forms the basis for the results and discussion presented in the following chapter.

4.7. Statistical analyze and data visualization

Descriptive statistical analyze was conducted to summarize the distribution of the population across different categories of healthcare accessibility and flood exposure (Cutter et al., 2003). This included the calculation of total population counts and proportional distributions within each accessibility class (good, moderate, and poor access), as well as within flood-exposed and non-exposed areas.

To support interpretation, tabular summaries were generated to organize the results and provide a clear overview of population distribution across categories. In addition, data visualization techniques were applied to illustrate key patterns in the data. Histograms were used to represent the distribution of population across accessibility classes and to highlight differences between categories (Chang, 2023).

The statistical analyze also supported the comparison between baseline accessibility conditions and flood-affected scenarios, enabling the identification of shifts in population exposure and access. This is particularly relevant for understanding how disruptions to infrastructure influence the distribution of accessibility across the study area (Koks et al., 2019).

Data processing and visualization were carried out using Visual Studio Code, where structured tables and graphical outputs were produced to support the analyze. These descriptive statistical methods complement the GIS-based spatial analyze by providing clear, quantitative summaries of the identified patterns. Together, they enhance the interpretability of results and support a more comprehensive assessment of spatial inequality and vulnerability. In addition, results from the service area analyze were used to quantify changes in the spatial extent of accessible healthcare areas before and after flooding. Comparing these accessibility zones provided a quantitative basis for assessing how Cyclone Idai altered network connectivity and functional healthcare accessibility across Sofala Province.

4.8. Methodological limitations

This study adopts a spatially explicit approach to analyze the relationship between flood exposure and healthcare accessibility. While the methodology provides valuable insights into spatial patterns of vulnerability, several limitations should be acknowledged. These relate to methodological choices, data quality, and the inherent simplifications involved in spatial modelling.

A key limitation concerns the use of straight-line (Euclidean) distance as a proxy for geographic accessibility. Although this approach provides a consistent and transparent measure of spatial proximity, it does not account for real-world travel conditions such as road network structure, terrain, transport availability, or environmental barriers. In flood-prone regions such as Sofala Province, accessibility is highly dependent on infrastructure functionality, meaning that actual travel distances and travel times may differ significantly from Euclidean estimates (Guagliardo, 2004; Weiss et al., 2020). Consequently, the Euclidean analyze should be interpreted as a simplified representation of baseline accessibility rather than a precise measure of actual mobility or healthcare utilization.

To address this limitation, a network-based closest facility analyze was included to provide a more realistic representation of accessibility along the road network. However, this approach is also subject to important constraints. The road network data, derived from OpenStreetMap, lack detailed and locally validated attributes such as travel speeds, road conditions, and transport modes. As a result, the network analyze focuses on route structure and connectivity rather than precise travel-time estimation. This introduces uncertainty in the representation of accessibility, particularly in rural and infrastructure-constrained areas. The use of Euclidean, service area, and network-based closest facility approaches therefore reflects a methodological trade-off, allowing comparison between a simplified baseline measure and a more infrastructure-sensitive, but still imperfect, representation of access.

In addition, the service area analyze, while providing valuable insight into the spatial extent of accessibility, is dependent on the definition of travel thresholds and the completeness of the road network. It does not account for variations in travel conditions within these areas and may therefore oversimplify accessibility by assuming uniform access within defined zones. As with the closest facility analyze, its accuracy is influenced by data limitations related to road quality, travel speeds, and infrastructure disruptions (Weiss et al., 2020; Hierink et al., 2023).

A second limitation concerns the quality and completeness of the input data. Healthcare facility and road network data were derived from OpenStreetMap (OSM), a crowd-sourced database. While OSM provides extensive and openly accessible spatial data, coverage and accuracy can vary across regions, particularly in low-income or rural areas where mapping activity may be limited. Some healthcare facilities or minor roads may be missing, incomplete, or inaccurately represented, which could influence accessibility estimates and lead to either overestimation or underestimation of service availability (OpenStreetMap contributors, 2024).

Similarly, the population data used in this study are based on gridded estimates rather than exact counts. WorldPop datasets are generated through statistical modelling techniques that integrate census data with ancillary spatial variables to produce high-resolution population distributions (Tatem, 2017). While these datasets provide valuable spatial detail, they are subject to uncertainty, particularly in regions with limited or outdated census data (WorldPop, 2020). Consequently, population estimates derived from these data should be interpreted as approximations rather than precise figures.

The flood exposure data also present several important limitations. The dataset used in this study is based on satellite-detected surface water obtained from the Humanitarian Data Exchange (HDX), derived from Sentinel-1 radar imagery and processed as part of the ARC Flood Extent Depiction (AFED) product. While this approach provides valuable observational data, it represents flood extent at a specific point in time rather than a continuous or dynamic representation of the flood event. The dataset captures maximum observed inundation as of 21 March 2019 and does not reflect temporal changes in flood extent, including onset, duration, or recession of floodwaters.

In addition, although the dataset is provided at approximately 90 m spatial resolution, it is derived from coarser-resolution satellite data (~22 km), which may limit its ability to detect smaller-scale or short-lived flooding. As a result, localized inundation, particularly in urban areas or regions with complex land cover, may not be fully captured. Satellite-based detection methods also introduce uncertainty related to observation conditions, including limitations in detecting water beneath vegetation or in areas with mixed land cover. These factors contribute to potential underestimation or misclassification of flooded areas.

Furthermore, the flood dataset represents inundation as a binary classification of water presence, without accounting for flood depth, velocity, or intensity. This simplification

reduces the complexity of flood processes and may obscure important variations in hazard severity and impact. As such, the flood exposure analyze should be interpreted as an approximation of observed inundation patterns rather than a comprehensive representation of flood hazard (UNITAR-UNOSAT, 2019; Humanitarian Data Exchange, 2019).

Another limitation relates to the integration of datasets with differing spatial resolutions and formats (Cutter et al., 2003). The combination of raster and vector data, as well as differences in spatial resolution between population, flood, and accessibility layers, may introduce spatial uncertainty during overlay analyze. Although efforts were made to harmonize datasets in terms of coordinate reference system and resolution, some degree of generalization and loss of spatial detail is unavoidable in multi-layer spatial analyze.

The analyze also assumes static conditions and does not account for temporal dynamics. Accessibility, infrastructure functionality, and population distribution can change significantly during and after disaster events. Roads may become impassable, populations may be displaced, and healthcare facilities may experience disruptions in service delivery. By relying on static datasets, the study provides a snapshot of conditions rather than a dynamic representation of how accessibility and exposure evolve over time (Koks et al., 2019).

Finally, the classification of accessibility into predefined distance thresholds (0–5 km, 5–15 km, and >15 km) introduces an additional level of generalization. While these thresholds are commonly used in accessibility research and provide a useful framework for comparison, they may not fully reflect local perceptions of accessibility or actual healthcare-seeking behaviour. Access to healthcare is influenced by a range of factors beyond distance, including economic constraints, transport availability, cultural practices, and perceived quality of care (Guagliardo, 2004; Levesque et al., 2013; Ouma et al., 2018).

Despite these limitations, the methodology provides a systematic and transparent framework for identifying spatial patterns of vulnerability. By integrating multiple accessibility measures, flood exposure data, and population estimates within a GIS-based approach, the study offers valuable insights into how environmental hazards and service accessibility intersect across space. The results should therefore be interpreted as indicative representations of broader spatial accessibility and vulnerability patterns rather than precise measurements of individual-level healthcare access, mobility, or disaster impact.

4.9. Use of Artificial Intelligence (AI)

Artificial intelligence (AI) tools was used as supportive tools during parts of the writing and data processing process in this thesis. AI was primarily used to assist with language improvements, including sentence structure, grammar, and clarification of academic formulations. The tools were also used to help organize and overview references and literature sources in order to improve structure and efficiency during the writing process.

In addition, AI-assisted support was used in connection with coding and data visualization, particularly for developing and adjusting scripts used to produce diagrams and graphical outputs related to the statistical analyze. The AI tools were therefore used as a technical and linguistic aid rather than for generating independent scientific content, interpretations, or conclusions.

All analyzes, methodological choices, interpretations, and final assessments were carried out independently by the author. All sources, references, results, and academic arguments included in the thesis were reviewed, verified, and critically evaluated by the author in accordance with principles of academic integrity and responsible research practice.

4.10. Ethical considerations

This study is based entirely on secondary data obtained from publicly available sources, including geospatial datasets on healthcare facilities, population distribution, flood extent, and transportation infrastructure. As no primary data collection involving human participants was conducted, the study does not raise direct ethical concerns related to privacy, consent, or personal data protection.

The datasets used in this study are aggregated and anonymized, meaning that no individual-level information can be identified. Population data is represented as gridded estimates rather than personal records, further reducing any potential risk of identifying individuals or specific households (WorldPop, 2020). Similarly, infrastructure and hazard datasets represent spatial features rather than sensitive personal information.

Despite the absence of direct ethical risks, the use and interpretation of spatial data involve important ethical considerations. The results of this study represent generalized patterns of accessibility and flood exposure and should not be interpreted as precise representations of

individual experiences. Care has therefore been taken to present findings in a way that avoids overgeneralization and acknowledges the limitations of the data and methods used.

In addition, spatial analyze of vulnerability may influence how regions and populations are perceived. Mapping areas with poor accessibility or high exposure carries a risk of reinforcing deficit-based or reductionist narratives if not interpreted carefully. To address this, the analyze is framed within a broader understanding of structural vulnerability, emphasizing that observed patterns reflect systemic inequalities in infrastructure, service distribution, and environmental exposure rather than inherent characteristics of the populations themselves.

The study also acknowledges that methodological choices, including the use of simplified accessibility measures and modelled population data, may influence how vulnerability is represented. These choices are therefore explicitly discussed in the methodology and limitations sections to ensure transparency and critical reflection.

All data sources used in this study are properly cited in accordance with academic standards, and their respective licensing conditions have been respected. In particular, datasets obtained from platforms such as Humanitarian Data Exchange and OpenStreetMap are used in compliance with open data licensing agreements.

The study adheres to principles of responsible data use, transparency, and academic integrity. By critically reflecting both data limitations and representational issues, the analyze aims to provide an ethically grounded and methodologically robust assessment of spatial vulnerability.

5. Analyze

This chapter presents the results of the spatial accessibility analyze, examining how Cyclone Idai (2019) reshaped healthcare accessibility in Sofala Province. Building on the methodological framework outlined in Chapter 4, three complementary approaches were applied: Euclidean distance, service area analyze, and closest facility network analyze.

The analyze is structured to first establish baseline accessibility conditions prior to the flood, followed by an assessment of how flood extent disrupted accessibility patterns. Attention is given to the spatial interaction between flood exposure and pre-existing inequalities in healthcare access, in line with disaster risk reduction perspectives emphasizing the

intersection of hazard, exposure, and vulnerability (UNDRR, 2015; IPCC, 2022). By applying these three approaches in parallel, the analyze captures both generalized spatial patterns (Euclidean distance) and infrastructure-dependent accessibility (service area and closest facility), allowing for a more comprehensive assessment of how accessibility is shaped and disrupted in a disaster context.

5.1. Spatial Distribution of Healthcare Facilities

The spatial distribution of healthcare facilities in Sofala Province reveals pronounced spatial inequalities in healthcare infrastructure. As shown in Figure 5, healthcare facilities are strongly concentrated in the central and southern parts of the province, particularly around Beira and the surrounding urban areas, while northern and more remote inland areas exhibit substantially lower healthcare facility density. The figure illustrates a clear contrast between relatively well-served urban and peri-urban areas and large rural regions characterized by sparse healthcare coverage.

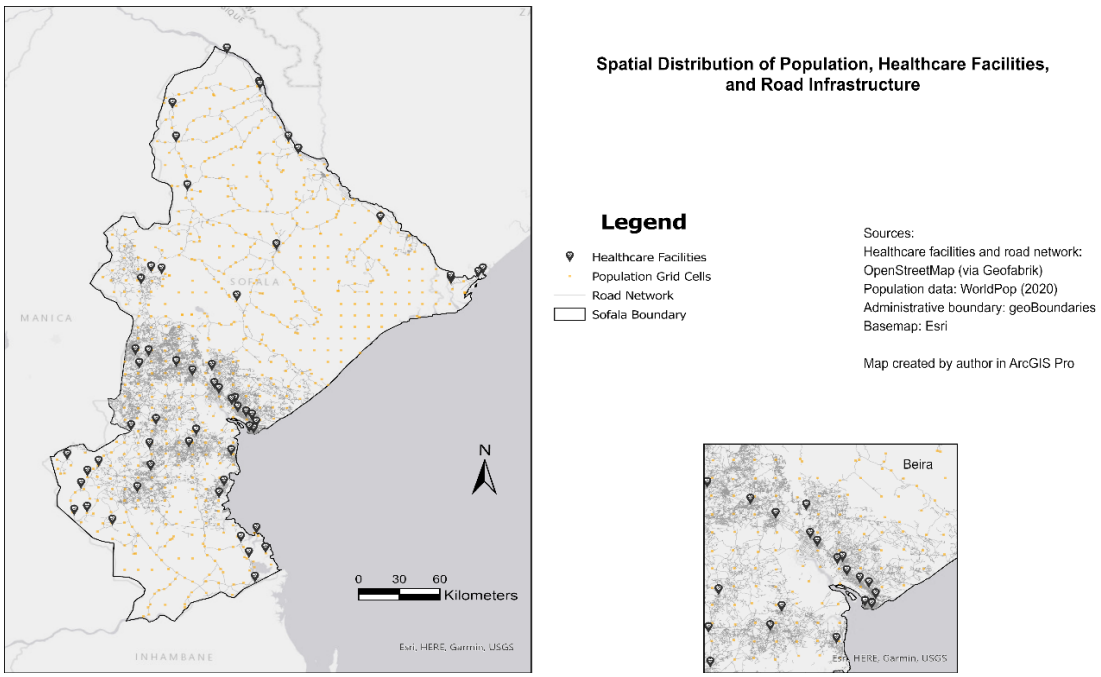


Figure 5. Distribution of healthcare facilities in Sofala Province, Mozambique.

These spatial patterns reflect broader regional inequalities in infrastructure and service provision identified in previous healthcare accessibility research, where healthcare systems tend to cluster around urban centers with higher population density, stronger transport connectivity, and greater infrastructural investment (Ouma et al., 2018; Weiss et al., 2020). In contrast, rural and peripheral regions often experience limited service availability and greater travel distances to essential healthcare facilities.

From a spatial accessibility perspective, the observed distribution suggests that healthcare access was already uneven across Sofala Province prior to Cyclone Idai. Populations located in remote and poorly connected areas were likely more dependent on limited transport infrastructure and fewer available healthcare facilities, increasing the potential for functional isolation during disaster events (Koks et al., 2019; Wisner et al., 2012). Accessibility in these regions is therefore highly sensitive to infrastructure disruption because alternative routes and nearby facilities may be limited (Koks et al., 2019).

The observed spatial inequalities are also important from a disaster risk reduction perspective. Research increasingly demonstrates that hazard impacts are often intensified in areas characterized by weak infrastructure connectivity and limited access to essential services (Koks et al., 2019; Petricola et al., 2022). The concentration of healthcare infrastructure around Beira consequently suggests that rural and inland regions may have experienced disproportionately greater accessibility disruption during Cyclone Idai due to the combination of lower baseline accessibility and increased exposure to transport disruption.

Rather than representing a geographically uniform healthcare system, the spatial distribution of facilities in Sofala Province reflects broader patterns of uneven development and infrastructural inequality (Wisner et al., 2012; IPCC, 2022). These baseline conditions form an important foundation for the subsequent accessibility analyze, which examine how flooding interacted with pre-existing spatial inequalities to reshape healthcare accessibility across the province.

5.2. Overview of Accessibility Patterns Following Cyclone Idai

Healthcare accessibility in Sofala Province exhibits clear spatial variation shaped by the uneven distribution of healthcare infrastructure, transport connectivity, and settlement patterns. Prior to Cyclone Idai, areas with relatively high accessibility were primarily concentrated around Beira and surrounding urban areas, as well as along major transport routes connecting central parts of the province. In contrast, large rural and peripheral regions were characterized by lower accessibility, reflecting greater distances to healthcare facilities and weaker road connectivity (Ouma et al., 2018; Weiss et al., 2020).

Following Cyclone Idai, these accessibility patterns were significantly altered. Flood-affected regions, particularly in central and southern Sofala Province, experienced substantial

reductions in healthcare accessibility as inundation disrupted transport connectivity and mobility (Koks et al., 2019; Petricola et al., 2022). Areas that previously exhibited moderate accessibility shifted into poorer accessibility categories, indicating increased travel constraints and reduced functional access to healthcare services (Dewi et al., 2024).

The spatial relationship between flood exposure and healthcare accessibility further reveals patterns of compounded vulnerability (IPCC, 2022; Wisner et al., 2012). Areas simultaneously affected by flooding and characterized by limited healthcare accessibility were primarily concentrated within flood-prone lowland regions and along major river systems, where exposure to inundation and infrastructure disruption was high. In many of these areas, populations were already dependent on limited transport infrastructure prior to the cyclone, increasing the likelihood of functional isolation during the disaster event (Koks et al., 2019).

The analyze also demonstrates important differences between generalized and infrastructure-dependent accessibility measures. Euclidean distance analyze highlights broader spatial inequalities in healthcare proximity across the province, while service area and closest facility analyze provide insight into how accessibility is mediated through transport infrastructure and network connectivity. These network-based approaches reveal that flood-related disruption can significantly alter accessibility patterns by reducing connectivity and increasing travel distance even where healthcare facilities remain physically present (Guagliardo, 2004; Petricola et al., 2022).

Taken together, the results suggest that Cyclone Idai did not affect healthcare accessibility uniformly across Sofala Province, but instead intensified pre-existing spatial inequalities by disproportionately disrupting already underserved and poorly connected areas (Wisner et al., 2012; UNDRR, 2015). The following sections provide a more detailed analyze of baseline accessibility conditions, flood exposure, and post-flood accessibility changes using spatial maps and quantitative accessibility measures

5.3. Baseline Accessibility (Before Flood)

To establish a reference point for assessing the impact of Cyclone Idai, baseline healthcare accessibility was analyzed under pre-flood conditions using three complementary approaches: Euclidean distance analyze, service area analyze, and closest facility network

analyze. Together, these methods provide a broader understanding of healthcare accessibility across Sofala Province by capturing both generalized spatial proximity and infrastructure-dependent accessibility patterns (Guagliardo, 2004).

The use of multiple accessibility approaches is particularly important in regions where transport connectivity and infrastructure distribution strongly influence access to essential services (Koks et al., 2019; Weiss et al., 2020). While Euclidean distance analyze provides a simplified representation of spatial proximity to healthcare facilities, network-based methods offer a more realistic assessment of functional accessibility by incorporating the structure and connectivity of the transport network (Guagliardo, 2004; Petricola et al., 2022). Comparing these approaches therefore makes it possible to examine not only where healthcare services are located, but also how effectively populations are connected to them through existing infrastructure systems (Dewi et al., 2024).

The following sections present the results of the three accessibility approaches separately before comparing how each method represents healthcare accessibility under pre-flood conditions.

5.3.1. Euclidean Accessibility

The Euclidean accessibility analyze provides a generalized representation of healthcare accessibility based on straight-line distance between population locations and the nearest healthcare facility (Guagliardo, 2004). As shown in Figure 6, areas characterized by relatively high accessibility are concentrated primarily around Beira and other urbanized areas within the central and southern parts of Sofala Province. Higher accessibility is also visible along major settlement and transport corridors, where healthcare facilities and population concentrations are more spatially clustered.

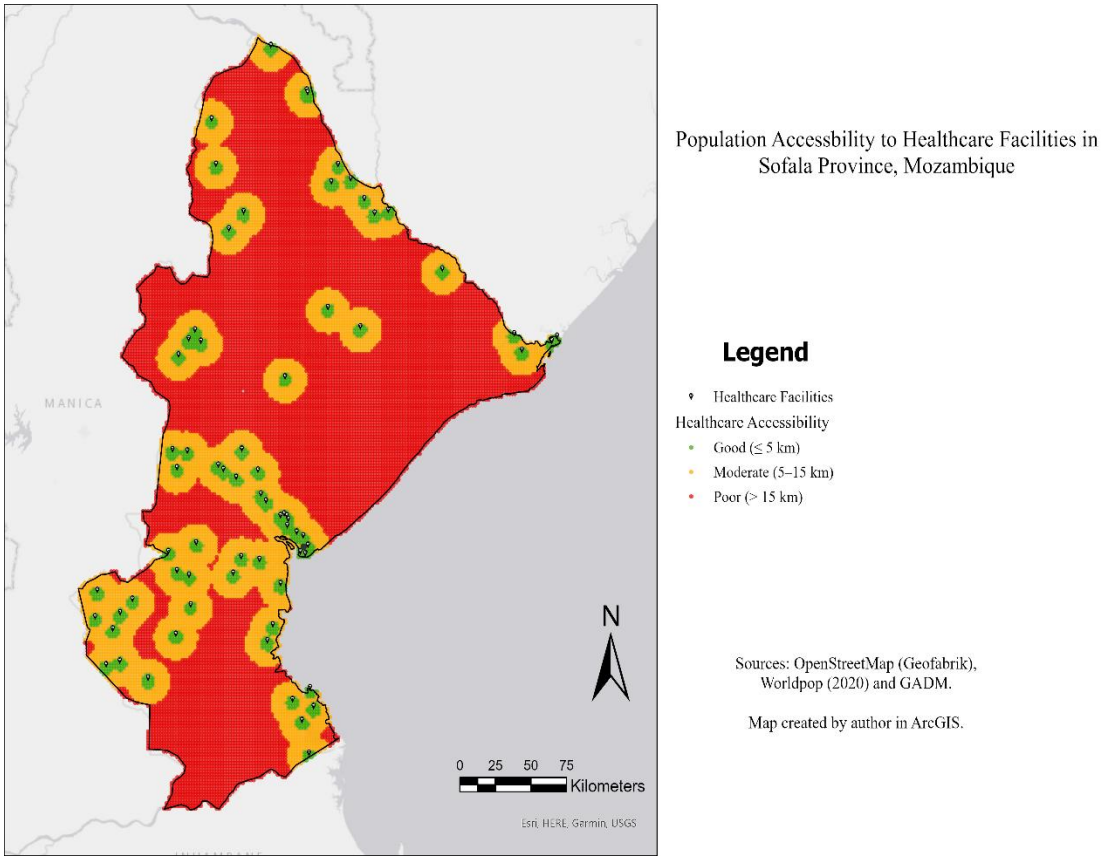


Figure 6.Distribution of healthcare facilities in Sofala Province, Mozambique.

In contrast, large rural and peripheral areas fall within moderate to poor accessibility categories, reflecting greater distances to healthcare facilities and lower spatial concentration of healthcare infrastructure. These spatial patterns demonstrate pronounced urban–rural inequalities in healthcare accessibility, where populations located further from major population centers generally experience reduced geographic access to healthcare services. Similar spatial disparities between urban and rural healthcare accessibility have been identified in previous accessibility research within low- and middle-income regions (Ouma et al., 2018; Weiss et al., 2020).

To further examine the population distribution across accessibility categories, Euclidean accessibility results were combined with WorldPop 2020 population data. The results are presented in *Table 2.*

Accessibility class	Population	Share
Good (<5 km)	782 459	33.3%
Moderate (5-15 km)	751 513	32.0%
Poor (>15 km)	815 140	34.7%

Table 2. Population distribution across Euclidean healthcare accessibility categories in Sofala Province.

Note: Population values represent aggregated estimates derived from the WorldPop 2020 gridded population dataset.

The population-weighted analyze indicates that approximately one-third of the population falls within each accessibility category. However, the largest proportion of the population is located within the poor accessibility category (>15 km), suggesting that substantial segments of the population experience relatively limited geographic proximity to healthcare facilities. These findings reinforce the broader spatial inequality patterns observed in Figure 7, where rural and remote populations are generally characterized by lower levels of healthcare accessibility (Ouma et al., 2018). This pattern is particularly evident in northern and inland parts of Sofala Province, where lower healthcare facility density and weaker transport connectivity contribute to longer travel distances and reduced accessibility compared to urban areas surrounding Beira.

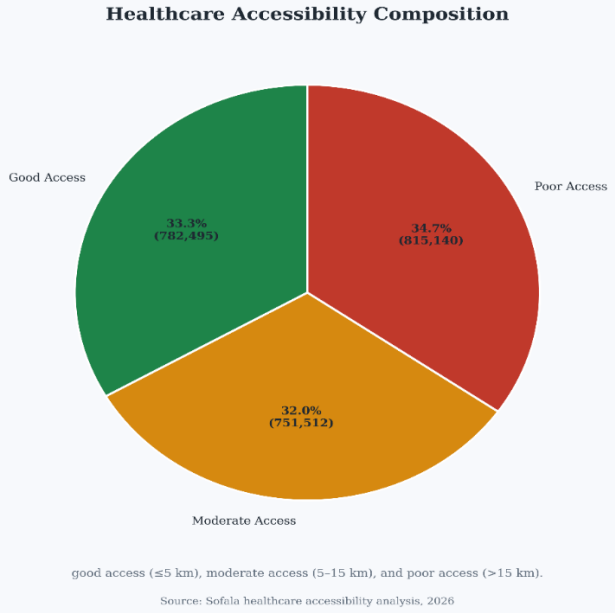


Figure 7. Accessibility distribution (pie chart).

While the Euclidean approach provides a useful overview of generalized spatial accessibility patterns, it also contains important methodological limitations. The analyze simplifies real-world accessibility conditions by measuring straight-line distance and does not account for transport networks, terrain, rivers, floodplains, infrastructure quality, or other physical barriers that may influence mobility and travel conditions. As a result, accessibility is likely overestimated, particularly within rural and infrastructure-constrained regions where actual travel routes may differ substantially from direct geographic distance (Guagliardo, 2004; Weiss et al., 2020).

This limitation is widely recognized within accessibility research, where Euclidean distance analyze is generally considered effective for identifying broader spatial accessibility patterns but less suitable for representing functional accessibility and real-world travel conditions (Guagliardo, 2004; Weiss et al., 2020). Nevertheless, the Euclidean analyze provides an important baseline for comparison with the network-based accessibility approaches. Comparing Euclidean and network-based accessibility results helps identify areas where healthcare accessibility is constrained not only by geographic distance, but also by transport connectivity and infrastructural limitations (Koks et al., 2019; Petricola et al., 2022).

5.3.2. Service Area Accesibility (Before Flood)

The service area analyze provides a more realistic representation of healthcare accessibility by incorporating the structure and connectivity of the road network together with estimated travel time (Guagliardo, 2004). Unlike the Euclidean approach, which measures straight-line distance, the service area analyze reflects how accessibility is shaped by transport infrastructure and mobility conditions across space (Weiss et al., 2020; Dewi et al., 2024).

As illustrated in Figure 8, areas characterized by relatively high accessibility (≤30 minutes) are concentrated primarily around healthcare facilities, urban centers, and major transport corridors within the central and southern parts of Sofala Province. These areas benefit from stronger road connectivity and shorter estimated travel times to healthcare services (Ouma et al., 2018).

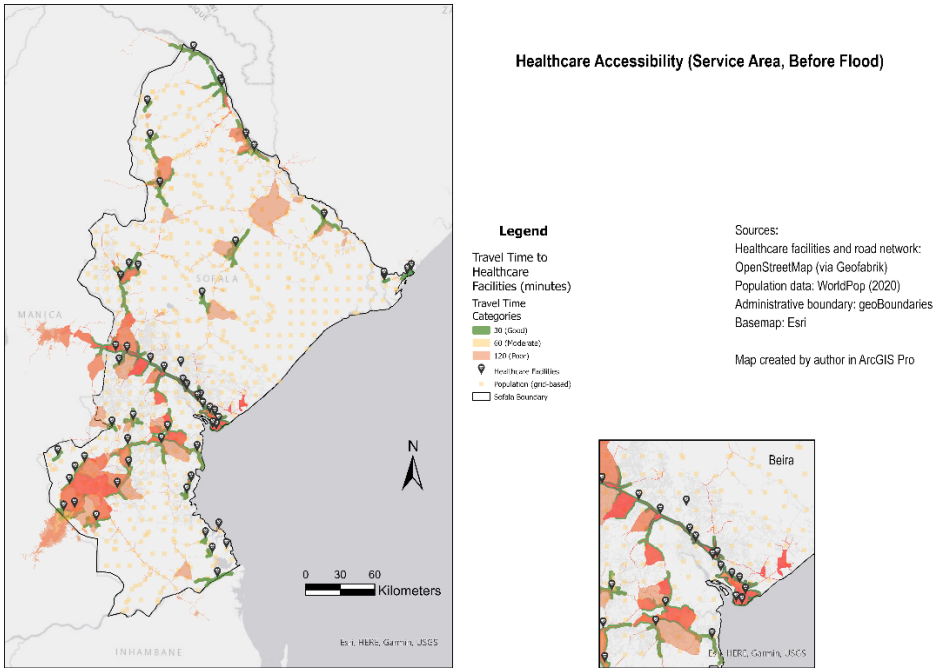


Figure 8. Service area accessibility to healthcare facilities before Cyclone Idai.

Moderate accessibility zones generally extend outward from these central transport corridors and healthcare clusters, while large rural and peripheral regions remain within poor accessibility categories (>60 minutes). These patterns demonstrate that healthcare accessibility in Sofala Province is strongly influenced by the spatial structure and connectivity of the transport network (Koks et al., 2019; Hierink et al., 2023). Populations located within well-connected regions are able to access healthcare services more efficiently, whereas populations in remote and weakly connected areas face substantially longer travel times and reduced mobility options (Weiss et al., 2020).

Compared to the Euclidean accessibility analyze, the service area results reveal a more spatially constrained accessibility pattern. Several areas that appeared relatively accessible under straight-line distance analyze exhibit substantially lower accessibility once movement is constrained by the actual road network. This difference highlights the importance of incorporating transport infrastructure into accessibility analyze, particularly in regions where mobility depends heavily on limited road connectivity and where geographic barriers may significantly influence travel conditions (Guagliardo, 2004; Petricola et al., 2022).

The findings reinforce previous research emphasizing that transport infrastructure plays a critical role in shaping healthcare accessibility, especially within rural and resource-constrained regions where limited network connectivity may significantly restrict physical access to essential services (Ouma et al., 2018; Hierink et al., 2023). From a spatial

perspective, the results further suggest that baseline healthcare accessibility in Sofala Province was already uneven prior to Cyclone Idai, with rural and peripheral populations experiencing comparatively lower levels of functional accessibility due to infrastructural constraints and limited transport connectivity (Koks et al., 2019).

The service area analyze therefore provides an important foundation for understanding how flood-related disruption may subsequently alter healthcare accessibility across the province. Because accessibility is strongly dependent on transport network connectivity, areas already characterized by weak infrastructure and long travel times before the flood were likely more vulnerable to accessibility disruption during Cyclone Idai (Wisner et al., 2012; UNDRR, 2015).

5.3.3. Closest Facility Accessibility (Before Flood)

The closest facility analyze provides a more detailed assessment of healthcare accessibility by identifying the shortest available travel routes between population locations and healthcare facilities through the existing road network. Unlike Euclidean distance analyze, which measures straight-line proximity, the closest facility approach reflects how accessibility is shaped by actual transport connectivity and route availability (Guagliardo, 2004; Petricola et al., 2022).

Under pre-flood conditions, the transport network in central and southern Sofala Province appears relatively well connected, with multiple routes linking populated areas to nearby healthcare facilities. As illustrated in Figure 9, the network-based accessibility pattern reveals stronger connectivity around Beira and surrounding urban and peri-urban regions, where road density and infrastructure availability are comparatively higher.

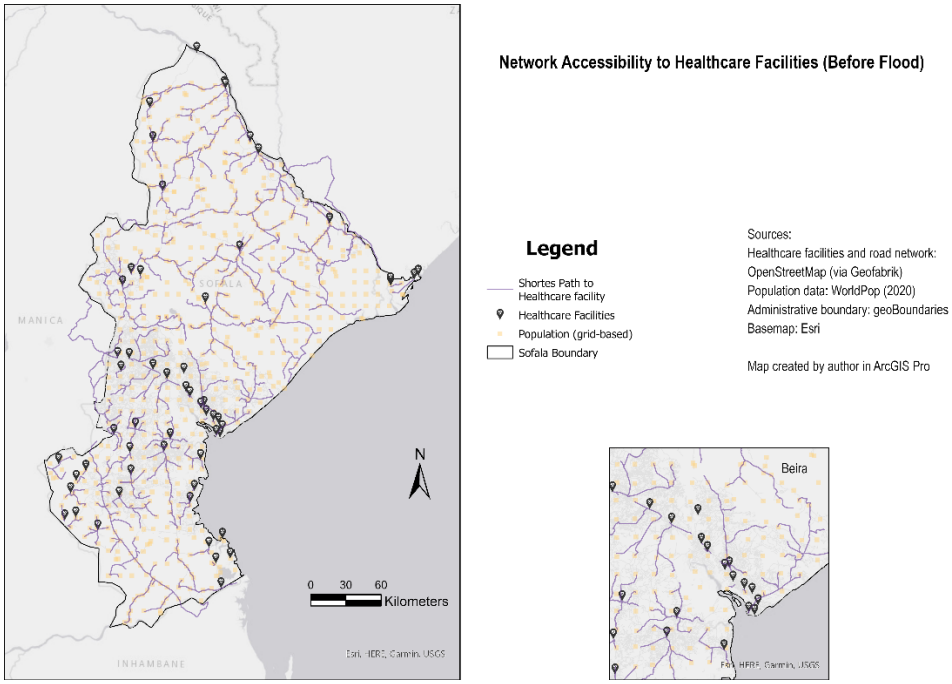


Figure 9. Network-based shortest paths to healthcare facilities before flooding.

In contrast, accessibility patterns within more remote and peripheral regions appear substantially more constrained. In these areas, routes become longer, less direct, and increasingly dependent on limited road connections, indicating weaker network connectivity and greater travel burden for surrounding populations. These findings demonstrate that healthcare accessibility is strongly influenced not only by the spatial location of healthcare facilities, but also by the structure, density, and redundancy of the surrounding transport network (Koks et al., 2019; Weiss et al., 2020).

The analyze further highlights the importance of alternative routes and network redundancy in shaping accessibility conditions. Areas characterized by denser and more interconnected transport networks generally exhibit shorter and more efficient travel routes, whereas areas dependent on limited road infrastructure appear more vulnerable to mobility constraints and potential disruption. This distinction is particularly important in disaster-prone environments where accessibility may rapidly deteriorate if key transport routes become disrupted.

Overall, the closest facility analyze confirms that healthcare accessibility is not solely determined by geographic distance, but also by network connectivity and transport infrastructure functionality. Even where healthcare facilities are geographically nearby, indirect or poorly connected road networks may substantially increase travel time and reduce effective accessibility. Similar findings have been identified in previous accessibility research

emphasizing that infrastructure connectivity is a critical determinant of access to essential services, particularly within rural and infrastructure-constrained regions (Koks et al., 2019; Hierink et al., 2023).

Together with the service area analyze, the closest facility results demonstrate that healthcare accessibility in Sofala Province is fundamentally network-dependent. The efficiency, connectivity, and redundancy of transport routes therefore play a central role in shaping functional access to healthcare services across the province. These baseline conditions also provide an important foundation for understanding how flood-related infrastructure disruption may subsequently reshape accessibility patterns during Cyclone Idai.

5.4. Flood Extent of Cyclone Idai (2019)

The spatial extent of flooding associated with Cyclone Idai reveals widespread inundation across central and southern parts of Sofala Province. As shown in Figure 10, the most severely affected areas are concentrated along major river systems and low-lying floodplains, particularly surrounding the Pungwe and Buzi river basins. These regions exhibit extensive flood coverage due to their low elevation, hydrological connectivity, and susceptibility to water accumulation during extreme rainfall and river overflow events (Charrua et al ., 2021).

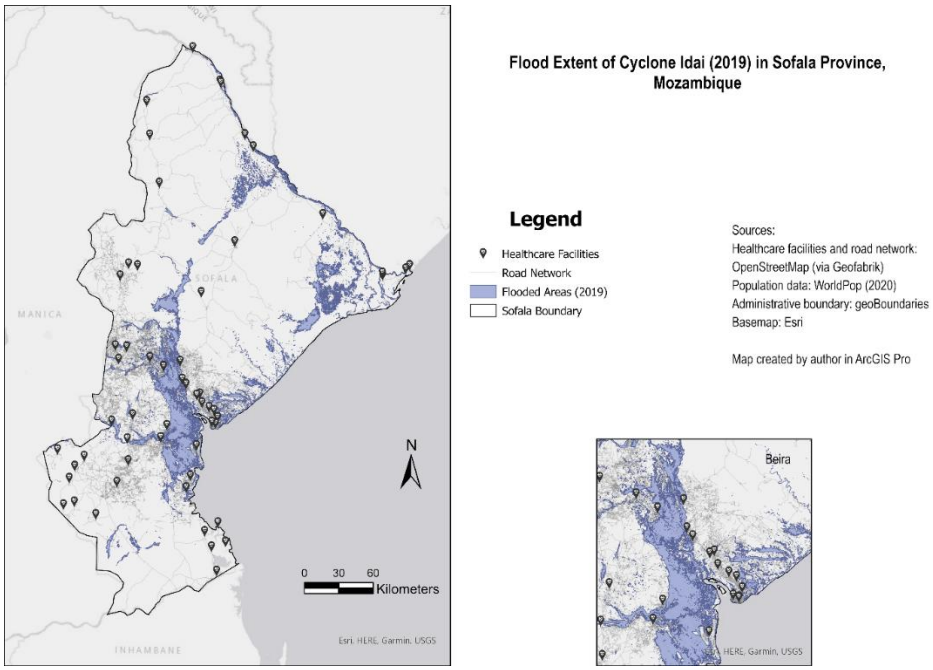


Figure 10. Flood extent of Cyclone Idai in Sofala Province (2019).

The observed flood patterns are not evenly distributed across the province but instead follow distinct hydrological and topographical structures. Flooding is concentrated primarily within

central floodplain regions and coastal lowlands, including areas surrounding Beira, where the combined effects of intense rainfall, river overflow, and coastal flooding contributed to extensive inundation (World Bank, 2019; Charrua et al ., 2021). In contrast, higher inland areas experienced comparatively lower levels of flood exposure.

Importantly, several densely populated areas and major transport corridors fall within the mapped flood extent. This spatial overlap suggests a high potential for disruption to settlements, mobility systems, and critical infrastructure during the cyclone event (Koks et al., 2019). Because transport connectivity plays a central role in healthcare accessibility across Sofala Province, widespread flooding likely had significant implications for the ability of populations to physically reach healthcare services (Guagliardo, 2004; Weiss et al., 2020).

The flood extent also highlights the uneven spatial nature of disaster exposure across the province (IPCC, 2022). Areas located within flood-prone river basins and lowland environments were disproportionately affected, indicating that environmental exposure itself was spatially differentiated. However, exposure alone does not fully explain vulnerability (Wisner et al., 2012; UNDRR, 2015). The implications of flooding become particularly significant in areas already characterized by weak infrastructure connectivity and limited healthcare accessibility, where flood-related disruption may intensify pre-existing inequalities (Koks et al., 2019; Dewi et al., 2024).

The spatial concentration of flooding along the Pungwe and Buzi river systems further illustrates the importance of hydrological and topographical conditions in shaping disaster exposure across Sofala Province. Large parts of the affected areas are characterized by low elevation and broad floodplains, increasing susceptibility to prolonged inundation during extreme rainfall and cyclone events. These flood-prone landscapes are also important settlement and agricultural areas, meaning that significant population concentrations and transport infrastructure are located within environmentally exposed zones (IPCC, 2022; World Bank, 2019). As a result, flood impacts were not limited to direct inundation of settlements, but also included widespread disruption to mobility, transport connectivity, and access to essential services such as healthcare.

These findings are consistent with previous research on Cyclone Idai, which emphasizes the extensive spatial footprint of the disaster and its concentration within low-lying and flood-prone regions of central Mozambique (World Bank, 2019; Charrua et al ., 2021). From an

accessibility perspective, widespread inundation is particularly important because it directly affects the transport infrastructure underpinning network-based accessibility. Flooded roads and disrupted connectivity may significantly affect functional healthcare accessibility even where healthcare facilities themselves remain operational (Petricola et al., 2022; Koks et al., 2019).

The flood extent analyze demonstrates that Cyclone Idai created highly uneven patterns of environmental exposure across Sofala Province. Integrating these flood patterns with accessibility analyze provides an important basis for understanding how hazard exposure interacted with infrastructure systems and pre-existing spatial inequalities to reshape healthcare accessibility during the disaster (IPCC, 2022; Wisner et al., 2012).

5.5. Accessibility After Flooding

Following the flooding associated with Cyclone Idai (2019), healthcare accessibility in Sofala Province was reassessed in order to examine how flood-related disruption altered spatial accessibility patterns across the province. The analyze focuses particularly on how inundation affected transport connectivity and the ability of populations to physically access healthcare services under disrupted conditions (Koks et al., 2019; Petricola et al., 2022).

Comparing pre- and post-flood accessibility conditions reveals the dynamic nature of healthcare accessibility within disaster contexts (Dewi et al., 2024). While the spatial distribution of healthcare facilities remained largely unchanged during the cyclone event, functional accessibility changed substantially due to disruptions affecting roads, mobility systems, and network connectivity. This distinction highlights the importance of differentiating between the physical presence of healthcare infrastructure and the ability of populations to reach services in practice during environmental crises (Guagliardo, 2004; Weiss et al., 2020).

The post-flood accessibility analyze demonstrates that flood-related disruptions did not affect all areas equally. Accessibility reductions were most pronounced in flood-prone and poorly connected regions where populations were already dependent on limited transport infrastructure prior to the disaster (Koks et al., 2019). In these areas, inundation contributed to increased travel constraints, reduced connectivity, and greater potential for functional isolation from healthcare services (Petricola et al., 2022).

From a spatial perspective, the results suggest that Cyclone Idai intensified pre-existing inequalities in healthcare accessibility rather than creating entirely new patterns of vulnerability (Wisner et al., 2012; UNDRR, 2015). Areas characterized by lower baseline accessibility before the flood generally experienced greater accessibility disruption after flooding occurred. This indicates that the impacts of the cyclone were mediated through existing infrastructural inequalities and uneven transport connectivity across Sofala Province (IPCC, 2022).

The comparison between pre- and post-flood conditions further demonstrates the importance of network-based accessibility analyze within disaster research (Guagliardo, 2004; Petricola et al., 2022). While generalized proximity to healthcare facilities may remain relatively stable, disruptions to transport infrastructure can substantially alter functional accessibility by reducing route availability and increasing travel distance. Accessibility during disasters therefore depends not only on where healthcare facilities are located, but also on the resilience and connectivity of the surrounding infrastructure network (Koks et al., 2019; Dewi et al., 2024).

The following sections examine post-flood accessibility patterns in greater detail using Euclidean distance, service area analyze, and closest facility analyze in order to assess how different accessibility approaches capture the spatial impacts of Cyclone Idai on healthcare access across Sofala Province.

5.5.1. Service Area Accessibility (After Flood)

The service area analyze reveals a substantial reduction in healthcare accessibility following the flooding associated with Cyclone Idai. As shown in Figure 11, areas characterized by relatively high accessibility (≤30 minutes) decreased considerably after the flood event, particularly within central and southern parts of Sofala Province where inundation was most extensive.

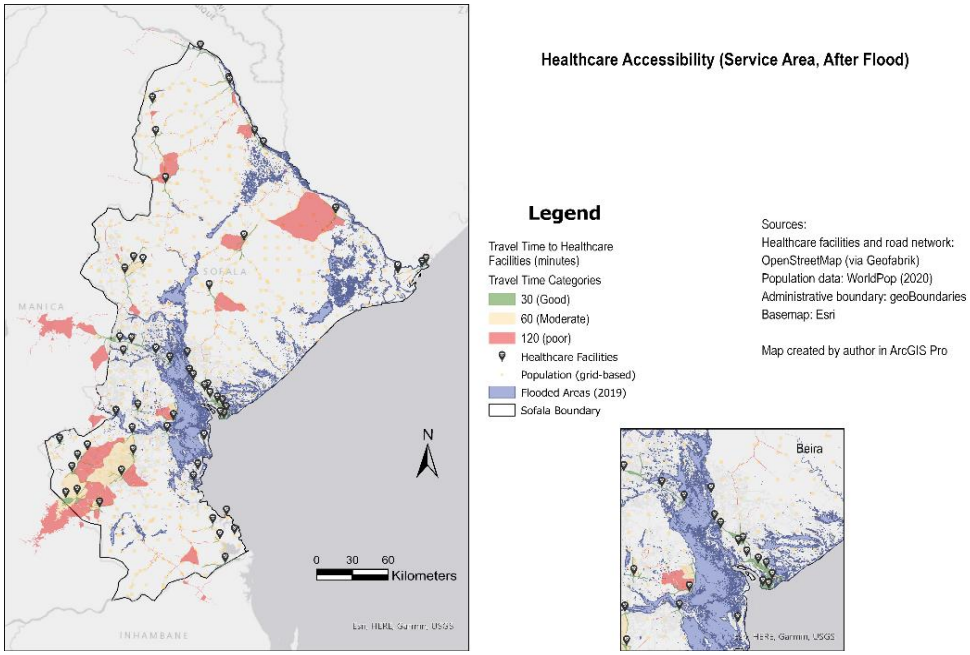


Figure 11. Service area accessibility to healthcare facilities after Cyclone Idai flooding.

In contrast, areas classified as having moderate and poor accessibility expanded noticeably, indicating increased travel constraints and reduced connectivity to healthcare facilities (Koks et al., 2019; Petricola et al., 2022). These changes reflect the disruption of the transport network, where flooded roads and inundated areas functioned as barriers that restricted movement and reduced the efficiency of existing travel routes (Koks et al., 2019).

The post-flood accessibility pattern also became significantly more fragmented (Dewi et al., 2024). Service areas that were previously relatively continuous under pre-flood conditions were divided into smaller and more isolated accessibility zones following inundation. This fragmentation is particularly visible in central and southern Sofala Province, where flood extent overlapped with major transport corridors and low-lying floodplain regions.

Importantly, the results suggest that the reduction in healthcare accessibility was driven primarily by disrupted network connectivity rather than by changes in the spatial distribution of healthcare facilities themselves (Guagliardo, 2004; Petricola et al., 2022). Although many healthcare facilities remained physically present, flooding reduced the ability of surrounding populations to reach them through existing road networks. This pattern was particularly visible in central and southern parts of Sofala Province, especially within flood-prone areas surrounding the Pungwe and Buzi river systems, where inundation disrupted major transport corridors and reduced connectivity between rural settlements and healthcare facilities. In these areas, accessibility was often maintained only through alternative routes that were

substantially longer and less efficient, contributing to increased travel distance and reduced functional accessibility (Weiss et al., 2020).

From a disaster vulnerability perspective, these findings highlight the importance of transport infrastructure resilience in shaping healthcare accessibility during hazard events (Koks et al., 2019; UNDRR, 2015). Areas already characterized by weak connectivity and limited transport redundancy before the flood appear particularly vulnerable to accessibility disruption because relatively small interruptions to the road network can produce disproportionately large reductions in functional access to healthcare services (Koks et al., 2019).

The observed contraction and fragmentation of service areas therefore demonstrate how flood events can reshape accessibility patterns across space by disrupting mobility and limiting network connectivity. Rather than affecting healthcare accessibility uniformly across the province, Cyclone Idai appears to have intensified pre-existing spatial inequalities by disproportionately reducing accessibility in already vulnerable and poorly connected regions (Wisner et al., 2012; IPCC, 2022).

5.5.2. Closest Facility Accessibility (After Flood)

The closest facility analyze further demonstrates how flooding associated with Cyclone Idai altered transport connectivity and healthcare accessibility across Sofala Province (Koks et al., 2019; Petricola et al., 2022). As illustrated in Figure 12, many routes connecting population locations to healthcare facilities became longer, less direct, or partially disrupted following the flood event.

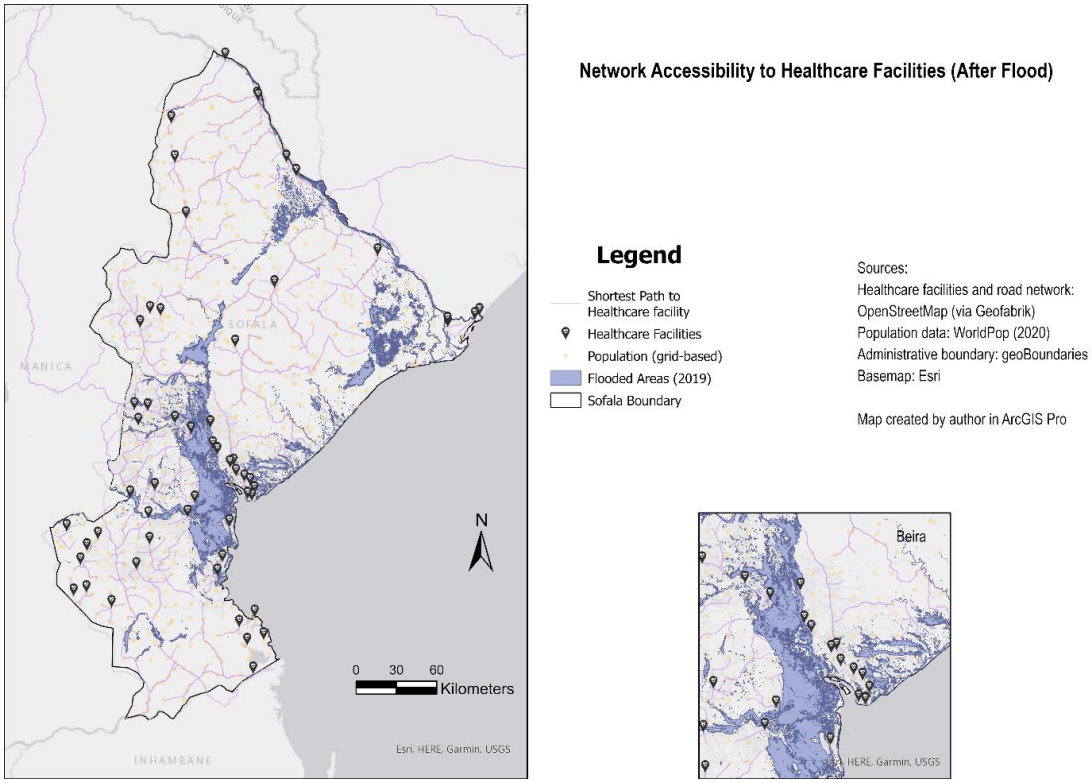


Figure 12. Network-based routes to healthcare facilities after flooding.

In several areas, particularly those located within or adjacent to major flood zones, routes were rerouted around inundated regions, resulting in increased travel distances and reduced route efficiency (Koks et al., 2019). In more severely affected areas, connectivity was substantially reduced, and some settlements appear partially isolated due to the disruption of direct road access (Petricola et al., 2022). These patterns are especially visible within central floodplain regions where flooding intersected with key transport corridors and road networks.

The analyze highlights the critical role of transport infrastructure in shaping functional healthcare accessibility during disasters (Guagliardo, 2004; Koks et al., 2019). Although many healthcare facilities remained operational following Cyclone Idai, accessibility was nevertheless reduced because surrounding infrastructure systems were disrupted. This demonstrates that healthcare accessibility depends not only on the spatial location of facilities, but also on the resilience and connectivity of the transport network linking populations to essential services (Weiss et al., 2020; Dewi et al., 2024).

The results further indicate that Cyclone Idai did not uniformly eliminate healthcare access across the province, but instead reshaped accessibility unevenly by increasing travel distances, reducing route efficiency, and fragmenting network connectivity (Wisner et al.,

2012; IPCC, 2022). Areas already characterized by limited transport redundancy and weak baseline accessibility experienced particularly severe disruption because the loss of relatively few road connections substantially reduced available travel options (Koks et al., 2019).

From a disaster risk reduction perspective, these findings reinforce the importance of network resilience and infrastructure redundancy in maintaining healthcare accessibility during hazard events (UNDRR, 2015; Koks et al., 2019). The disruption of key transport routes can significantly increase travel burdens and contribute to functional isolation, even where alternative paths remain technically available (Petricola et al., 2022). In this sense, the flood impacts associated with Cyclone Idai appears to have intensified pre-existing spatial inequalities by disproportionately affecting already vulnerable and poorly connected regions (Wisner et al., 2012; IPCC, 2022).

The closest facility analyze provides further evidence that flood-related infrastructure disruption played a central role in reshaping healthcare accessibility across Sofala Province. The results demonstrate how disasters may alter not only physical access routes, but also the broader spatial relationships between populations, infrastructure systems, and essential healthcare services (Dewi et al., 2024).

5.6. Population Accessibility and Spatial Inequality

The accessibility analyze reveal substantial spatial inequalities in healthcare access across Sofala Province, with clear differences between urban, peri-urban, and rural areas. These inequalities are closely linked to the uneven distribution of healthcare facilities and transport infrastructure, which are concentrated primarily within central and southern parts of the province, particularly around Beira. As a result, populations located in rural and remote regions generally experience lower levels of healthcare accessibility characterized by longer travel distances, weaker transport connectivity, and fewer available healthcare facilities (Ouma et al., 2018). These findings are consistent with previous accessibility research showing that healthcare services in low- and middle-income regions are often concentrated around urban centers with stronger infrastructure and higher population density (Ouma et al., 2018; Weiss et al., 2020).

In contrast, populations located within urban and peri-urban areas benefit from greater proximity to healthcare services and more developed transport networks, resulting in shorter

travel times and stronger network connectivity (Weiss et al., 2020). These patterns suggest that healthcare accessibility in Sofala Province is strongly shaped by broader patterns of infrastructural inequality and uneven regional development rather than by geographic distance alone (Wisner et al., 2012; IPCC, 2022).

To further examine the human dimension of accessibility, a population-weighted accessibility analyze was conducted using WorldPop 2020 population data combined with network-based travel-time service areas. The results are presented in *Table 3.*

Travel time category	Estimated population (after flood)
0–30 min	334,848
30–60 min	77,013
60–120 min	118,379

Table 3. Population-weighted healthcare accessibility after Cyclone Idai flooding in Sofala Province.

Note: Population estimates were derived from WorldPop 2020 raster data using zonal statistics within healthcare travel-time service areas.

The population-weighted accessibility analyze indicates that approximately 334,848 people remained within 0–30 minutes of a healthcare facility following the flood event, while 77,013 people were located within 30–60 minutes travel time and 118,379 people were within 60–120 minutes travel time. Although a substantial proportion of the population retained relatively high accessibility after Cyclone Idai, significant populations remained within areas characterized by moderate to poor accessibility conditions.

The observed population accessibility patterns also reflect broader structural inequalities in infrastructure and service distribution across Sofala Province particularly between urban and rural districts (António et al., 2022). Populations located within rural and peripheral districts are more dependent on limited transport infrastructure and fewer healthcare facilities, making them particularly vulnerable to accessibility disruption during flood events. In contrast, urban populations surrounding Beira generally benefit from denser road networks, shorter travel distances, and higher healthcare facility concentration. These differences demonstrate how pre-existing spatial inequalities can influence the severity of disaster impacts, as communities already experiencing reduced accessibility are more likely to become isolated when transport networks are disrupted (Wisner et al., 2012; Ouma et al., 2018).

The results further suggest that flood-related accessibility disruption was unevenly distributed across the province. Populations located in already underserved and peripheral areas appear to have experienced greater reductions in connectivity following the flood event because these regions relied more heavily on limited transport infrastructure and had fewer alternative access routes available. Similar patterns have been identified in previous disaster accessibility studies, which demonstrate that hazard events often disproportionately affect populations characterized by weak infrastructure connectivity and limited service accessibility (Koks et al., 2019; Petricola et al., 2022).

The combined use of Euclidean distance analyze, service area analyze, and closest facility network analyze further demonstrates that healthcare accessibility in Sofala Province is shaped not only by physical proximity to healthcare facilities, but also by the structure, resilience, and connectivity of transport infrastructure systems (Koks et al., 2019). While Euclidean distance analyze highlights generalized spatial inequalities in healthcare proximity, the network-based analyzes reveal how accessibility conditions may change substantially when mobility systems are disrupted by environmental hazards (Petricola et al., 2022). This distinction between nominal and functional accessibility is increasingly emphasized within disaster and health geography research (Guagliardo, 2004; Dewi et al., 2024).

From a disaster risk reduction perspective, these findings emphasize the importance of infrastructure resilience and transport connectivity in maintaining access to essential healthcare services during hazard events (UNDRR, 2015; IPCC, 2022). Areas characterized by weak baseline accessibility and limited network redundancy appear particularly vulnerable to flood-related disruption because even relatively localized infrastructure failure may significantly reduce functional healthcare accessibility (Wisner et al., 2012).

The population accessibility analyze demonstrates that Cyclone Idai did not affect healthcare accessibility uniformly across Sofala Province. Instead, the disaster disproportionately affected already vulnerable and poorly connected populations, reinforcing broader patterns of spatial inequality and infrastructural vulnerability across the province (IPCC, 2022; Wisner et al., 2012).

5.7. Combined Impact: Flood Exposure and Accessibility Constraints

The combined analyze of flood extent and healthcare accessibility reveals clear patterns of compounded vulnerability across Sofala Province (IPCC, 2022; Wisner et al., 2012). Several regions, particularly within central and southern parts of the province, were simultaneously affected by extensive flooding and reduced accessibility to healthcare facilities following Cyclone Idai. These areas represent critical zones where populations were both exposed to environmental hazards and faced increased barriers in accessing essential healthcare services (Petricola et al., 2022).

The spatial overlap between flood exposure and accessibility constraints is most evident along major floodplains and low-lying river basins, particularly surrounding the Pungwe and Buzi river systems. In these regions, high population concentration coincided with extensive infrastructure disruption and reduced transport connectivity, increasing the likelihood of functional isolation during the disaster event (Koks et al., 2019). These findings demonstrate that the impacts of Cyclone Idai were not spatially uniform, but instead concentrated within areas already characterized by infrastructural vulnerability and limited accessibility (Wisner et al., 2012; IPCC, 2022).

To further quantify these accessibility changes, Figure 13 presents the distribution of accessibility categories before and after Cyclone Idai based on the service area analyze.

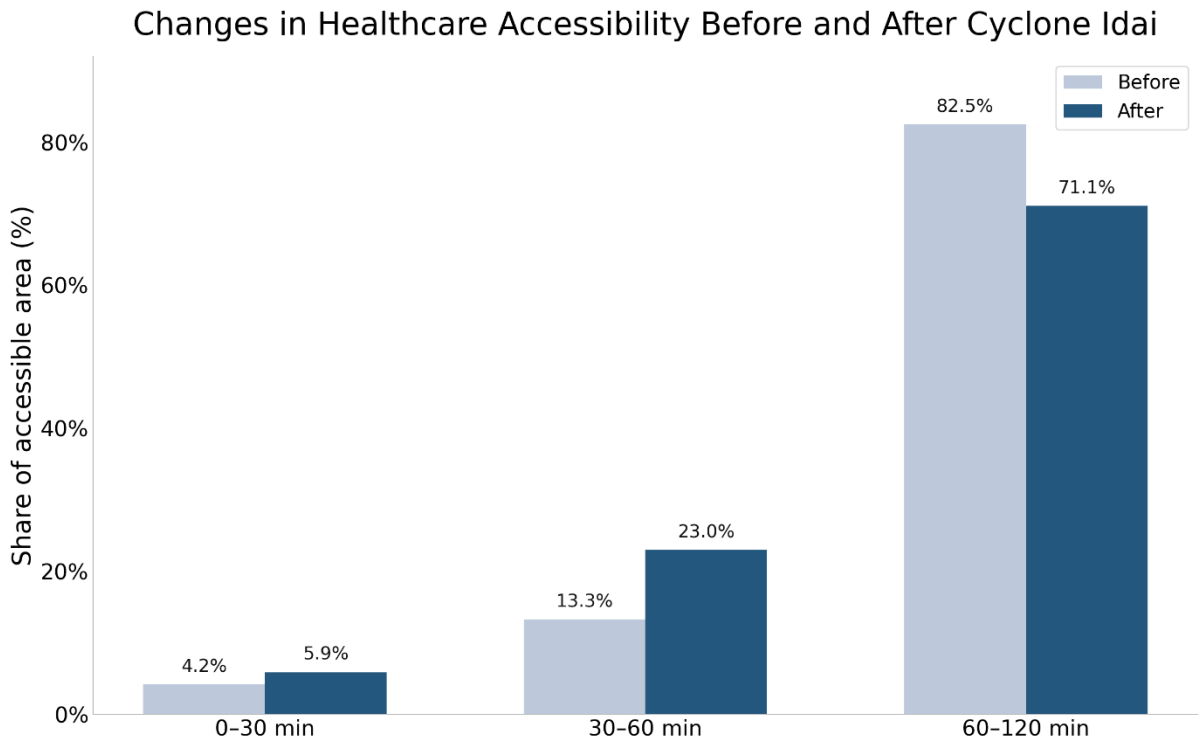


Figure 13. Comparison of healthcare accessibility categories before and after Cyclone Idai based on service area analyze. Made in Visual Studio.

As shown in Figure 13, the proportion of areas within the 60–120 minute accessibility category decreased from 82.5% to 71.1% following the flood event, while the proportion of areas within the 30–60 minute category increased from 13.3% to 23.0%. Similarly, areas classified within the 0–30 minute category increased from 4.2% to 5.9%.

However, these proportional changes should not be interpreted as indicating improved accessibility. Instead, they reflect a substantial contraction of the accessible transport network following flood-related infrastructure disruption (Koks et al., 2019). The total accessible area decreased markedly after Cyclone Idai, indicating that many locations previously connected to healthcare services were no longer reachable within the network analyze. Consequently, the apparent increase in shorter travel-time categories reflects the exclusion of disconnected and inaccessible areas rather than improved access conditions (Guagliardo, 2004).

The results therefore suggest that flooding disproportionately affected longer-distance and more peripheral accessibility routes, particularly in rural and poorly connected areas (Petricola et al., 2022). Large sections of the transport network appear to have become fragmented or inaccessible following inundation, reducing overall network connectivity across the province (Dewi et al., 2024). Accessibility after the flood thus became more

spatially constrained and fragmented, with many populations effectively losing functional access to healthcare services altogether (Koks et al., 2019).

This interpretation is further supported by the closest facility analyze, which demonstrates that routes became longer, less direct, and increasingly dependent on alternative pathways following the flood event. While Euclidean distance analyze identifies generalized spatial accessibility patterns, the network-based analyzes provide a more realistic representation of healthcare accessibility under disrupted disaster conditions because they account for changes in transport connectivity and route availability (Guagliardo, 2004; Petricola et al., 2022).

From a disaster risk reduction perspective, these findings can be understood through the interaction between hazard, exposure, and vulnerability (UNDRR, 2015; IPCC, 2022). In this study, flooding associated with Cyclone Idai represents the hazard, population distribution reflects exposure, and limited healthcare accessibility and transport connectivity represent important dimensions of vulnerability. The spatial overlap of these factors produces zones of compounded risk where populations are simultaneously exposed to environmental hazards and constrained by reduced access to essential healthcare services.

The results further demonstrate that Cyclone Idai significantly reduced functional healthcare accessibility by disrupting transport infrastructure and fragmenting network connectivity across Sofala Province (Koks et al., 2019). Importantly, the impacts were most severe in areas where flood exposure coincided with pre-existing accessibility constraints, reinforcing broader patterns of spatial inequality and infrastructural vulnerability among already underserved populations (Wisner et al., 2012; IPCC, 2022).

5.8. Synthesis of Accessibility Changes Across Methods

This section synthesizes the findings from the three applied accessibility approaches, Euclidean distance analyze, service area analyze, and closest facility network analyze, in order to provide a comprehensive understanding of how Cyclone Idai (2019) affected healthcare accessibility across Sofala Province.

Across all analytical approaches, the results consistently demonstrate that Cyclone Idai led to substantial reductions in healthcare accessibility throughout the province. Although the magnitude and spatial expression of accessibility change vary between methods, all analyzes

indicate that flooding significantly disrupted mobility, transport connectivity, and functional access to healthcare services (Koks et al., 2019; Petricola et al., 2022).

The Euclidean distance analyze provides a generalized representation of baseline spatial accessibility patterns by measuring straight-line proximity between populations and healthcare facilities. The results demonstrate that large parts of Sofala Province already experienced moderate to poor accessibility prior to the cyclone event, particularly within rural and peripheral regions. Following Cyclone Idai, areas classified as having poor accessibility expanded, especially within central and southern regions where flood exposure was most extensive. While this approach effectively highlights broader spatial inequalities in healthcare proximity, it does not account for transport infrastructure, road connectivity, or physical barriers, and therefore provides only a simplified representation of accessibility conditions (Guagliardo, 2004).

The service area analyze provides a more infrastructure-dependent representation of healthcare accessibility by incorporating movement through the road network. The results reveal a substantial contraction of accessible areas across all travel-time categories following Cyclone Idai. In particular, large reductions occurred within the 60–120 minute accessibility category, suggesting that many peripheral and rural regions became increasingly disconnected from healthcare services after flooding disrupted transport connectivity (Koks et al., 2019). Although proportional representations indicate an apparent increase in shorter travel-time categories, the analyze demonstrates that this pattern reflects a reduction in overall network extent rather than actual improvements in accessibility (Guagliardo, 2004).

The closest facility analyze further reinforces these findings by illustrating how flood-related disruption altered travel routes and network connectivity across the province. Routes between population locations and healthcare facilities became longer, less direct, and increasingly fragmented following inundation. In several flood-affected regions, reduced road connectivity limited available travel options and increased the likelihood of functional isolation (Petricola et al., 2022). This method therefore highlights the importance of transport network integrity in maintaining healthcare accessibility during disaster events, particularly within regions characterized by limited infrastructure redundancy and high environmental exposure (Koks et al., 2019).

Comparing the three accessibility approaches highlights important methodological differences in how healthcare accessibility is represented and interpreted. The Euclidean distance analyze provides the broadest representation of accessibility by focusing on straight-line proximity between populations and healthcare facilities. This approach is useful for identifying general spatial inequalities but tends to simplify real-world movement conditions because it does not account for transport infrastructure or environmental barriers (Guagliardo, 2004; Weiss et al., 2020). In contrast, the service area analyze incorporates road network connectivity and therefore provides a more infrastructure-sensitive representation of accessibility coverage. The closest facility analyze extends this further by examining how route structure and network continuity influence access between specific population locations and healthcare facilities. As a result, the network-based methods reveal a greater degree of accessibility disruption following Cyclone Idai than the Euclidean approach alone. This demonstrates how methodological choice influences the interpretation of accessibility and highlights the importance of incorporating transport connectivity when analysing disaster-related accessibility conditions (Koks et al., 2019; Dewi et al., 2024).

Taken together, the three methods provide complementary insights into the spatial dynamics of healthcare accessibility during and after Cyclone Idai. The Euclidean distance analyze captures generalized spatial inequality, the service area analyze quantifies reductions in reachable areas, and the closest facility analyze reveals network-level disruption and changing route connectivity. Despite methodological differences, all approaches converge on the same overall pattern: Cyclone Idai significantly reduced healthcare accessibility across Sofala Province, with the most severe impacts concentrated in already vulnerable rural and flood-prone regions (Wisner et al., 2012; IPCC, 2022).

The synthesis further demonstrates that healthcare accessibility is shaped not only by geographic proximity to healthcare facilities, but also by the resilience, connectivity, and functionality of surrounding infrastructure systems. Flood-related disruption therefore affected accessibility unevenly because populations already dependent on limited transport infrastructure experienced disproportionately greater reductions in mobility and healthcare access (Koks et al., 2019). These findings align with disaster risk reduction perspectives emphasizing that vulnerability emerges through the interaction between hazard exposure, infrastructure conditions, and pre-existing socio-spatial inequalities (UNDRR, 2015; IPCC, 2022).

The convergence of findings across all three methods strengthens the overall validity of the analyze and suggests that the observed accessibility reductions represent robust spatial patterns rather than methodological artefacts. At the same time, the differences between methods demonstrate the importance of methodological choice in accessibility research, as each approach captures different dimensions of accessibility and vulnerability (Guagliardo, 2004). This reinforces the value of multi-method accessibility analyze within disaster-related research, particularly in data-constrained and infrastructure-vulnerable environments (Dewi et al., 2024).

5.9. Limitations of the Analyze

While the analyze provides important insights into the spatial dynamics of healthcare accessibility following Cyclone Idai, several limitations and sources of uncertainty should be acknowledged when interpreting the findings.

First, the analyze depends on the quality and completeness of the spatial datasets used. Healthcare facility locations and road network data were derived from OpenStreetMap (Geofabrik), which, although widely used within GIS and accessibility research, may contain omissions, positional inaccuracies, or incomplete infrastructure representation, particularly within rural and remote areas (Haklay, 2010). Similarly, the WorldPop population dataset represents modelled population estimates rather than exact population counts, introducing uncertainty in the spatial representation of population distribution (Weiss et al., 2020).

Second, each accessibility method applied within the study introduces specific methodological limitations. The Euclidean distance analyze simplifies accessibility by measuring straight-line distance between population locations and healthcare facilities. While useful for identifying broader spatial inequalities, this approach does not account for terrain, transport infrastructure, physical barriers, or mobility constraints and may therefore underestimate actual travel distance and accessibility challenges (Guagliardo, 2004).

The service area and closest facility analyze provide more realistic representations of functional accessibility by incorporating the transport network, but these approaches also involve simplifying assumptions regarding infrastructure functionality and travel conditions (Petricola et al., 2022). The analyze assume relatively stable movement conditions across the road network and do not fully capture variability in road quality, transport availability,

seasonal conditions, or informal mobility patterns (Dewi et al., 2024). Importantly, the analyze do not directly model real-time infrastructure disruption caused by flooding, including road damage, debris, bridge collapse, or temporary impassability during the cyclone event (Koks et al., 2019). Consequently, post-flood accessibility conditions may still be somewhat overestimated compared to actual on-the-ground conditions experienced during Cyclone Idai.

Third, the flood extent dataset represents a spatial snapshot of maximum observed inundation derived from satellite observations rather than a continuous representation of flood dynamics. While the dataset effectively captures the spatial footprint of flooding, it does not include information regarding flood duration, water depth, flood velocity, or temporal progression throughout the disaster period. These dynamic flood characteristics may significantly influence mobility and accessibility conditions but are difficult to incorporate within static GIS-based accessibility modelling (Guagliardo, 2004).

The study is also limited by its primary focus on physical accessibility measured through distance, travel time, and transport connectivity. Other important dimensions of healthcare access, including healthcare quality, facility capacity, staffing levels, affordability, and socioeconomic barriers, are not included within the analyze. The findings should therefore be interpreted specifically as an assessment of geographic and infrastructural accessibility rather than healthcare access in its broader social and institutional sense (Guagliardo, 2004).

At the same time, the use of multiple accessibility approaches represents an important methodological strength of the study. While each individual method contains limitations, combining Euclidean distance analyze, service area analyze, and closest facility analyze allows for cross-method comparison and validation of broader accessibility patterns (Dewi et al., 2024). The consistency of findings across all three approaches increases confidence in the overall conclusions and suggests that the observed reductions in healthcare accessibility represent robust spatial trends rather than methodological artefacts.

Despite these limitations, the analyze provides a spatially explicit and methodologically transparent assessment of how Cyclone Idai affected healthcare accessibility across Sofala Province. Integrating flood extent data, transport infrastructure, healthcare facilities, and population distribution within a GIS framework enables the identification of broader patterns

of spatial inequality and infrastructural vulnerability associated with the disaster (Wisner et al., 2012; IPCC, 2022).

Future research could further improve disaster-related accessibility analyze by incorporating dynamic flood modelling, real-time infrastructure conditions, travel-speed variability, and additional dimensions of healthcare access (Koks et al., 2019; Dewi et al., 2024). Integrating such approaches may provide a more detailed representation of how environmental hazards affect mobility and healthcare accessibility under rapidly changing disaster conditions.

6. Discussion

This chapter interprets the findings of the spatial analyzes in relation to the research questions and broader perspectives within health geography, disaster risk reduction (DRR), and spatial vulnerability research. Building on the results presented in Chapter 5, the discussion examines how Cyclone Idai (2019) interacted with pre-existing spatial inequalities in healthcare accessibility across Sofala Province and how flood-related infrastructure disruption reshaped functional access to healthcare services.

The findings suggest that Cyclone Idai did not affect healthcare accessibility uniformly across the province, but instead intensified existing inequalities by disproportionately disrupting already underserved and poorly connected regions. The discussion therefore focuses on how environmental exposure, transport connectivity, healthcare infrastructure, and settlement patterns interacted to produce uneven patterns of vulnerability during and after the flood event. In doing so, the chapter situates the findings within broader theoretical discussions concerning hazard exposure, infrastructural inequality, and compounded vulnerability (Wisner et al., 2012; UNDRR, 2015; IPCC, 2022).

The chapter first summarizes the key findings before relating them to existing literature on healthcare accessibility, infrastructure resilience, and disaster vulnerability. It then examines the structural and spatial drivers underlying the observed inequalities, including rural–urban disparities, uneven infrastructure distribution, and floodplain exposure. Finally, the discussion considers the implications of the findings for disaster risk reduction, healthcare planning, and infrastructure resilience, before reflecting on methodological limitations and directions for future research.

6.1. Key Findings

This study examined how flood exposure associated with Cyclone Idai intersected with geographic accessibility to healthcare services in Sofala Province, Mozambique. By integrating spatial accessibility analyze, satellite-derived flood extent data, and population distribution within a GIS framework, the study provides insight into how disaster risk is spatially differentiated and how pre-existing infrastructural inequalities shape vulnerability patterns across the province.

The findings demonstrate that healthcare accessibility in Sofala Province was already highly uneven prior to Cyclone Idai. Baseline accessibility patterns revealed substantial differences between urban, peri-urban, and rural areas, with populations located in remote and peripheral regions generally experiencing lower levels of accessibility to healthcare services. These findings reinforce broader accessibility research showing that healthcare systems in many low- and middle-income regions remain spatially concentrated around urban centers and major transport corridors, while rural populations experience greater travel constraints and weaker infrastructure connectivity (Ouma et al., 2018; Weiss et al., 2020; Hierink et al., 2023). The results therefore suggest that barriers to healthcare access in Sofala Province were not created by the disaster itself, but reflected broader patterns of uneven infrastructural development and service distribution that existed prior to the cyclone event.

The flood exposure analyze further demonstrates that Cyclone Idai produced extensive inundation across central and southern Sofala Province, particularly within low-lying floodplains and river basin environments surrounding the Pungwe and Buzi river systems. These findings are consistent with previous studies documenting the large spatial footprint of Cyclone Idai and the concentration of flood impacts within environmentally exposed regions of central Mozambique (World Bank, 2019; Charrua et al ., 2021). The results further highlight how environmental factors such as topography, hydrological structure, and coastal exposure play a central role in shaping spatial hazard patterns and disaster exposure (IPCC, 2022; IPCC, 2023).

One of the most important findings of the study is the clear spatial overlap between flood exposure and limited healthcare accessibility. The overlay analyze demonstrates that many populations were simultaneously located within flood-affected areas and characterized by moderate to poor accessibility to healthcare services. These regions can therefore be

understood as zones of compounded vulnerability, where environmental exposure intersects with infrastructural and spatial disadvantage. This finding strongly supports disaster risk reduction perspectives emphasizing that disaster impacts emerge through the interaction between hazard exposure, infrastructure conditions, and pre-existing vulnerabilities rather than through hazards alone (Wisner et al., 2012; UNDRR, 2015; Koks et al., 2019).

The findings further indicate that Cyclone Idai did not affect healthcare accessibility uniformly across Sofala Province. Instead, flood-related disruption disproportionately affected populations already characterized by limited connectivity and weak baseline accessibility. Communities dependent on sparse transport infrastructure and limited road redundancy experienced greater reductions in functional accessibility following inundation because relatively localized infrastructure disruption substantially reduced available travel routes. This suggests that the cyclone primarily intensified existing spatial inequalities rather than creating entirely new patterns of vulnerability. Similar dynamics have been identified in previous disaster accessibility research, which demonstrates that infrastructure disruption often amplifies pre-existing patterns of marginalization and uneven service accessibility (Wisner et al., 2012; Petricola et al., 2022; Dewi et al., 2024).

The population-weighted accessibility analyze further highlights the scale and social significance of these spatial inequalities. Although substantial parts of the population remained within relatively shorter travel-time categories following Cyclone Idai, large population groups continued to experience moderate to poor healthcare accessibility after flooding occurred. Importantly, many of these populations were concentrated within flood-prone and infrastructure-constrained regions, indicating that hazard exposure and accessibility disadvantage were closely interconnected across space. These findings reinforce broader accessibility literature emphasizing that geographic accessibility remains a critical determinant of vulnerability and healthcare inequality, particularly in hazard-prone and infrastructure-limited environments (Ouma et al., 2018; Weiss et al., 2020).

The use of multiple accessibility approaches further strengthens the interpretation of these findings. While Euclidean distance analyze identified broader spatial inequalities in healthcare proximity, the service area and closest facility analyzes demonstrated how transport connectivity and network structure strongly influence functional accessibility under disaster conditions. The network-based analyzes reveal that accessibility is highly sensitive to infrastructure disruption, as flooding altered route availability, fragmented connectivity, and

increased travel constraints across large parts of the province. These findings support recent research emphasizing that healthcare accessibility during disasters depends not only on the spatial distribution of facilities, but also on the resilience and functionality of surrounding infrastructure systems (Koks et al., 2019; Pozo et al., 2025).

Overall, the findings demonstrate that disaster risk in Sofala Province cannot be understood solely through the physical characteristics of flooding itself. Rather, the impacts of Cyclone Idai were shaped by the interaction between environmental exposure, transport infrastructure, and pre-existing spatial inequalities in healthcare accessibility. Healthcare accessibility therefore emerges as a critical dimension of vulnerability and coping capacity, influencing the ability of populations to respond to and recover from disaster events (UNDRR, 2015; IPCC, 2022). By identifying where flood exposure and limited healthcare accessibility overlap, this study provides a spatially explicit understanding of compounded vulnerability that may support more targeted disaster risk reduction planning, infrastructure resilience strategies, and health system preparedness within flood-prone regions.

The findings are also relevant beyond Sofala Province, as many regions across sub-Saharan Africa face similar combinations of climate-related hazard exposure, uneven infrastructure development, and limited healthcare accessibility. The study therefore contributes to broader discussions on how environmental hazards interact with spatial inequality and infrastructure vulnerability in disaster-prone regions. As climate change is expected to increase the frequency and intensity of extreme weather events in many parts of southern Africa, understanding how healthcare accessibility is affected by infrastructure disruption becomes increasingly important for disaster preparedness and long-term resilience planning (IPCC, 2022; IPCC, 2023).

6.2. Explaining Spatial Inequalities

The spatial patterns identified in this study are not random, but instead reflect broader structural, environmental, and infrastructural processes that shape both healthcare accessibility and disaster vulnerability across Sofala Province. Interpreting these patterns requires situating the findings within wider geographic and socio-economic dynamics that influence how healthcare services, transport infrastructure, and populations are distributed across space. The network-based analyze particularly illustrate these dynamics, as the service area analyze demonstrates a contraction of reachable areas following flooding, while the

closest facility analyze reveals how travel routes became longer, more fragmented, and increasingly dependent on limited transport connections after Cyclone Idai. These findings suggest that disaster impacts were mediated through existing infrastructural conditions rather than being evenly distributed across the province (Koks et al., 2019; Petricola et al., 2022). Figure 14 illustrates the conceptual relationship between flood exposure, transport connectivity, healthcare accessibility, and compounded vulnerability identified in this study.

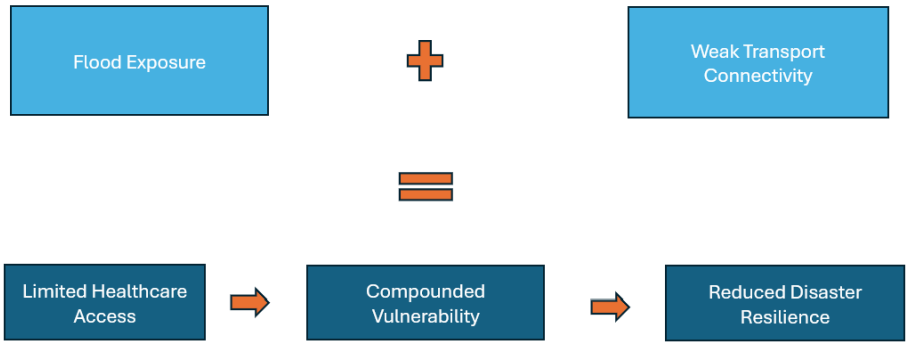


Figure 14. Conceptual framework illustrating how flood exposure and weak transport connectivity, interact to produce compounded limited healthcare access, vulnerability and reduced disaster resilience. Made with PowerPoint.

One of the primary factors explaining the observed inequalities in healthcare accessibility is the uneven spatial distribution of healthcare infrastructure and transport networks. Healthcare facilities are concentrated mainly around urban centers and major transport corridors, whereas rural and peripheral regions remain comparatively underserved. Similar spatial inequalities have been widely documented across low- and middle-income regions, where historical investment priorities, limited financial resources, and infrastructural constraints have contributed to uneven healthcare provision and accessibility (Ouma et al., 2018; Weiss et al., 2020; Hierink et al., 2023). In Sofala Province, these broader development patterns contribute to a landscape in which access to healthcare services is strongly shaped by geographic location, with rural populations generally experiencing substantially longer travel distances and weaker infrastructure connectivity.

However, the findings demonstrate that healthcare accessibility cannot be understood solely in terms of geographic distance. Accessibility is also strongly dependent on the structure,

quality, and resilience of the transport network connecting populations to healthcare facilities. The network-based analyzes reveal that many areas with relatively moderate Euclidean proximity nevertheless experienced poor functional accessibility because road connectivity was limited or indirect. This reinforces broader accessibility research emphasizing that transport infrastructure plays a central role in determining effective access to essential services (Guagliardo, 2004; Dewi et al., 2024).

In many parts of Mozambique, transport infrastructure remains sparse, unevenly maintained, and highly vulnerable to environmental disruption (World Bank, 2019). Even under normal conditions, limited road connectivity constrains mobility, particularly in rural areas where populations often depend on tertiary roads, informal pathways, or limited transport options. During extreme flood events such as Cyclone Idai, these infrastructural limitations become significantly more pronounced because inundation may render roads impassable, isolate settlements, and fragment already fragile transport systems. The findings therefore suggest that accessibility in Sofala Province is shaped not only by the spatial distribution of healthcare facilities, but also by the resilience and redundancy of surrounding infrastructure systems (Koks et al., 2019; Pozo et al., 2025).

Environmental conditions further contribute to the uneven spatial distribution of disaster risk across the province. The concentration of flood exposure within low-lying floodplains and deltaic environments reflects the broader physical geography of central Mozambique, where flat terrain, river systems, and coastal processes create conditions conducive to widespread inundation (Charrua et al ., 2021; IPCC, 2022). At the same time, these regions often support relatively high population densities because of their agricultural productivity and access to water resources. Consequently, populations become concentrated within environments that are simultaneously economically important and environmentally hazardous. Hazard exposure is therefore shaped not only by physical geography, but also by settlement patterns, land-use dynamics, and socio-economic dependence on environmentally exposed regions (IPCC, 2022; Koks et al., 2019).

The comparison between the three accessibility methods used in this study further highlights how spatial inequalities are shaped by both geographic proximity and infrastructure connectivity. The Euclidean distance analyze identifies broad spatial patterns of accessibility and demonstrates that many rural populations are already located far from healthcare facilities under baseline conditions. However, the network-based service area and closest

facility analyzes reveal that actual accessibility constraints become significantly more severe when transport infrastructure and flood-related disruption are considered. This is particularly evident in central and southern Sofala Province, where flooding along the Pungwe and Buzi floodplains disrupted major transport corridors and reduced connectivity between rural settlements and healthcare facilities. In these areas, populations often remained geographically close to healthcare facilities but experienced reduced functional accessibility because roads and transport routes became disconnected or substantially longer. This demonstrates that healthcare accessibility during disaster events is influenced not only by the spatial distribution of facilities themselves, but also by the resilience and connectivity of surrounding infrastructure systems (Koks et al., 2019; Dewi et al., 2024).

The differences between methods also illustrate how methodological choices influence the interpretation of vulnerability. While Euclidean distance provides an important overview of generalized spatial inequality, the network-based approaches provide a more realistic representation of how accessibility is experienced during infrastructure disruption. The closest facility analyze in particular demonstrates how flooding reshaped movement patterns across the province by fragmenting transport networks and reducing route efficiency. These findings reinforce the importance of applying multiple accessibility methods when analysing healthcare access in hazard-prone and infrastructure-constrained environments, as different approaches capture different dimensions of vulnerability and mobility (Guagliardo, 2004; Weiss et al., 2020).

The overlap between flood exposure and poor healthcare accessibility can therefore be understood as the outcome of interacting spatial processes. On the one hand, populations are concentrated within flood-prone environments because of environmental and economic opportunities; on the other hand, healthcare infrastructure and transport systems remain unevenly distributed and often insufficiently developed within these same areas. The interaction between environmental exposure and infrastructural inequality consequently produces zones of compounded vulnerability, where populations experience both elevated hazard exposure and reduced access to essential healthcare services. These findings strongly align with disaster risk reduction frameworks conceptualizing disaster risk as the interaction between hazard, exposure, and vulnerability rather than as the product of environmental hazards alone (UNDRR, 2015; Wisner et al., 2012; IPCC, 2022).

Importantly, the inequalities identified in this study are not solely spatial, but also structural in nature. The observed accessibility patterns reflect broader socio-economic and political processes that shape access to infrastructure, resources, and public services. As argued by Wisner et al. (2012), vulnerability is produced through root causes such as economic inequality, marginalization, governance limitations, and uneven development, which subsequently manifest as unsafe conditions and unequal coping capacity at the local scale. Within Sofala Province, limited healthcare accessibility and high flood exposure may therefore be understood as manifestations of these broader structural inequalities.

The findings also emphasize the importance of infrastructure resilience in shaping disaster outcomes and healthcare accessibility during hazard events. The presence of healthcare facilities alone does not guarantee effective access to healthcare services. Rather, accessibility depends on the functionality and connectivity of the wider infrastructure systems linking populations to healthcare facilities. Flood-related disruption to transport infrastructure can therefore substantially reduce healthcare accessibility even where healthcare facilities themselves remain operational. Similar patterns have been identified in previous disaster accessibility research demonstrating that indirect impacts such as infrastructure disruption, mobility reduction, and connectivity loss may significantly amplify the overall consequences of disaster events (Koks et al., 2019; Petricola et al., 2022).

6.3. Rural-urban and Infrastructure Inequalities in Floodplain Areas

The spatial inequalities identified in this study are closely linked to differences between rural and urban areas, as well as to broader patterns of infrastructure distribution and environmental exposure across Sofala Province. These interacting factors shape both healthcare accessibility and flood vulnerability, contributing to uneven patterns of risk and resilience throughout the province. The findings therefore suggest that accessibility inequalities are not simply geographic, but are embedded within wider socio-economic, infrastructural, and environmental processes that influence how populations experience disaster impacts (Wisner et al., 2012; IPCC, 2022).

A clear distinction emerges between urban and rural areas in relation to healthcare accessibility. Urban centers such as Beira generally contain a higher concentration of healthcare facilities, more developed transport infrastructure, and stronger network connectivity compared to rural and peripheral regions. Populations located within these urban

and peri-urban environments therefore benefit from shorter travel distances, greater route availability, and more reliable accessibility to healthcare services under baseline conditions. In contrast, rural areas are characterized by dispersed settlements, fewer healthcare facilities, weaker transport connectivity, and greater dependence on limited road infrastructure. These findings reinforce broader accessibility research across sub-Saharan Africa demonstrating that rural populations consistently experience greater barriers to healthcare access due to infrastructural limitations, longer travel distances, and uneven service distribution (Ouma et al., 2018; Weiss et al., 2020; Hierink et al., 2023).

The findings further demonstrate that infrastructure inequalities play a central role in reinforcing these spatial disparities. Transport networks within Sofala Province are unevenly distributed, with primary and secondary roads concentrated mainly around major urban centers and economic corridors, while rural regions frequently depend on tertiary roads, informal pathways, or limited transport infrastructure. This uneven connectivity affects not only everyday accessibility to healthcare services, but also the ability of populations to respond to, cope with, and recover from disaster events. Limited infrastructure redundancy increases the likelihood that relatively localized disruption may substantially reduce mobility and isolate already vulnerable communities. Similar patterns have been identified in previous disaster accessibility studies showing that infrastructure disruption and transport fragmentation can significantly reduce functional accessibility during hazard events (World Bank, 2019; Koks et al., 2019; Petricola et al., 2022).

The findings also highlight the importance of strengthening healthcare preparedness and emergency response capacity within hazard-prone regions. In disaster contexts such as Cyclone Idai, healthcare accessibility is influenced not only by the physical location of healthcare facilities, but also by the ability of health systems to continue functioning under disrupted conditions. This includes maintaining transport access, ensuring continuity of medical supplies, and supporting emergency response coordination across affected districts. In rural and flood-prone areas where transport connectivity is limited, disruptions to roads and bridges may significantly delay access to healthcare, emergency assistance, and evacuation services. Strengthening preparedness therefore requires not only investment in healthcare infrastructure itself, but also improvements in supporting systems such as transport, communication, and emergency logistics (Kruk et al., 2015; Koks et al., 2019).

The results further emphasize the need for risk-informed spatial planning and infrastructure development. In many parts of Sofala Province, settlements, transport corridors, and healthcare services are concentrated within low-lying and environmentally exposed areas. While these locations are often economically and socially important, they are also highly vulnerable to flood disruption. Integrating flood risk considerations into infrastructure planning could therefore help reduce future accessibility disruptions and improve long-term resilience. This may include locating critical infrastructure outside high-risk flood zones where possible, improving drainage systems, strengthening bridge and road design, and developing alternative transport routes to reduce network fragmentation during disasters (IPCC, 2022; World Bank, 2019).

The study demonstrates the broader value of GIS-based accessibility analyze for disaster risk reduction and healthcare planning. Spatial accessibility models can support decision-making by identifying areas where healthcare access is already limited and where disaster impacts are likely to be most severe. In resource-constrained settings, such analyzes can help prioritize investments, emergency preparedness measures, and infrastructure improvements in areas characterized by both high hazard exposure and limited service accessibility. GIS-based approaches may therefore contribute to more targeted and evidence-based planning for both disaster preparedness and long-term health system resilience (UNDRR, 2015; Weiss et al., 2020).

Floodplain geography further intensifies these vulnerability patterns across the province. Many of the area’s most severely affected by flooding are located within low-lying riverine and coastal floodplains surrounding the Pungwe and Buzi river systems. The physical geography of these regions, including flat terrain, hydrological connectivity, and coastal exposure, makes them particularly susceptible to widespread inundation during extreme rainfall and cyclone events (Charrua et al ., 2021; IPCC, 2022). At the same time, floodplain regions often support relatively dense populations because of their agricultural productivity, water access, and economic importance. Consequently, large population groups become concentrated within environments characterized by both high environmental exposure and limited infrastructural resilience.

Importantly, the findings indicate that many of these flood-prone areas also experience comparatively poor healthcare accessibility and weaker transport connectivity. The overlap between environmental exposure and infrastructural limitation therefore produces spatially

concentrated vulnerability, where populations are simultaneously exposed to flooding and constrained by reduced access to essential healthcare services. This interaction demonstrates that vulnerability within Sofala Province is shaped not only by the physical characteristics of flooding itself, but also by the uneven spatial distribution of infrastructure, healthcare services, and transport connectivity (UNDRR, 2015; Wisner et al., 2012).

The interaction between rural marginalization, infrastructure inequality, and floodplain geography is particularly important for understanding the broader implications of Cyclone Idai. Populations located within rural flood-prone environments were not only more exposed to environmental hazards, but also faced greater barriers to healthcare accessibility both before and after flooding occurred. Flood-related disruption therefore intensified pre-existing accessibility inequalities by disproportionately affecting populations already characterized by weak baseline connectivity and limited infrastructure redundancy. These findings strongly support the broader argument emerging throughout this study: that Cyclone Idai did not create vulnerability in isolation, but instead interacted with and amplified existing spatial inequalities in healthcare accessibility and infrastructure conditions across Sofala Province (Wisner et al., 2012; IPCC, 2022).

The results further demonstrate that healthcare accessibility should be understood as a dynamic and infrastructure-dependent process rather than a static measure of geographic distance alone. Accessibility conditions are continuously shaped by the interaction between transport connectivity, environmental exposure, infrastructure resilience, and mobility constraints. The network-based analyzes particularly illustrate how rapidly accessibility may change during disaster events when critical transport infrastructure becomes disrupted. These findings therefore reinforce the importance of integrating infrastructure resilience and spatial accessibility considerations into disaster risk reduction and healthcare planning within flood-prone and infrastructure-constrained regions (Koks et al., 2019; UNDRR, 2015).

6.4. Implications for DRR and Healthcare Systems

The findings of this study have important implications for both disaster risk reduction (DRR) and healthcare system planning, particularly within hazard-prone and infrastructure-constrained regions such as Sofala Province. The analyze demonstrates how flood exposure and healthcare accessibility intersect spatially. This highlights the need for more integrated and spatially informed approaches to disaster risk management and public service provision.

The study further demonstrates that accessibility outcomes are strongly influenced by methodological approach, as Euclidean distance analyze captures generalized spatial inequalities while network-based analyzes reveal how infrastructure disruption alters functional accessibility during disaster events. This reinforces the importance of combining multiple accessibility approaches in order to capture both broader spatial patterns and infrastructure-dependent accessibility dynamics (Guagliardo, 2004; Petricola et al., 2022).

One of the most important implications emerging from the findings is that disaster risk reduction strategies must move beyond a narrow focus on hazard mitigation alone, and instead address the broader structural conditions that produce vulnerability. The results indicate that populations most severely affected by flood-related accessibility disruption were often those already characterized by weak baseline accessibility, limited infrastructure connectivity, and greater dependence on fragile transport networks. Disaster impacts were therefore shaped not only by the physical characteristics of flooding, but also by pre-existing infrastructural inequalities and uneven development patterns across the province. These findings strongly support disaster risk reduction frameworks emphasizing that vulnerability reduction requires integration between infrastructure planning, development policy, social inequality reduction, and risk management rather than treating disasters solely as emergency events (UNDRR, 2015; Wisner et al., 2012; IPCC, 2022).

From a healthcare systems perspective, the findings highlight the need for improved spatial planning and more equitable distribution of healthcare infrastructure. The concentration of healthcare facilities around urban centers and major transport corridors suggests that current healthcare provision does not fully reflect the spatial distribution of populations or patterns of environmental exposure. Rural and flood-prone regions consequently remain characterized by comparatively poor baseline accessibility and reduced service connectivity. Strategic placement of healthcare facilities within underserved and environmentally exposed regions could therefore contribute to improving baseline healthcare accessibility and strengthening disaster resilience. These findings align with broader accessibility research emphasizing the importance of spatially equitable healthcare provision in reducing healthcare inequality and improving resilience within vulnerable populations (Ouma et al., 2018; Weiss et al., 2020).

The findings also demonstrate that healthcare accessibility depends not only on the physical presence of healthcare facilities, but also on the resilience and functionality of supporting infrastructure systems. Transport connectivity emerged as a particularly critical factor

shaping accessibility during and after Cyclone Idai. Flood-related disruption to roads and transport corridors significantly reduced functional healthcare accessibility by fragmenting connectivity and increasing travel constraints across large parts of the province. Investments in transport infrastructure, maintenance, and climate-resilient design are therefore essential for maintaining healthcare accessibility during extreme events. In flood-prone environments, such measures may include elevated road infrastructure, improved drainage systems, strengthened bridge connections, and increased transport network redundancy to reduce the likelihood of community isolation during disasters (Koks et al., 2019; World Bank, 2019).

The study further highlights the value of spatial data and GIS-based accessibility analyze for supporting disaster risk reduction and healthcare planning. Integrating flood extent data, healthcare accessibility, transport infrastructure, and population distribution within a spatial analytical framework enables the identification of areas characterized by compounded vulnerability. Such analyzes may support more targeted allocation of resources, prioritization of infrastructure investment, and identification of populations facing the greatest accessibility constraints during hazard events. This is particularly important within resource-constrained contexts where effective prioritization is necessary to maximize the impact of interventions and strengthen resilience capacity (UNDRR, 2015; Dewi et al., 2024).

At a broader level, the findings also emphasize the growing importance of integrating climate change adaptation (CCA) and disaster risk reduction strategies. Climate change is expected to increase the frequency and intensity of extreme weather events, including floods and tropical cyclones, particularly within environmentally vulnerable regions such as southern Africa (IPCC, 2022; IPCC, 2023). In this context, strengthening healthcare accessibility and infrastructure resilience becomes essential not only for managing present-day disaster risks, but also for supporting long-term adaptation to changing environmental conditions. The findings therefore suggest that healthcare accessibility should be understood as an important component of climate resilience and adaptive capacity within disaster-prone regions.

Finally, the study demonstrates that healthcare accessibility is fundamentally a spatial and infrastructural issue shaped by the interaction between environmental exposure, transport connectivity, and uneven development. Effective disaster risk reduction and healthcare planning therefore require integrated approaches that recognize the interdependence between infrastructure systems, spatial inequality, and environmental risk. Strengthening healthcare accessibility within vulnerable regions may consequently contribute not only to improved

public health outcomes, but also to broader resilience and disaster preparedness across hazard-prone environments.

6.5. Limitations and Future Research

While this study provides a spatially explicit analyze of the relationship between flood exposure and healthcare accessibility in Sofala Province, several methodological limitations and sources of uncertainty should be acknowledged. Reflecting on these limitations is important both for contextualizing the findings and for identifying opportunities to further strengthen disaster-related accessibility research.

One important limitation relates to the use of multiple accessibility approaches, each of which captures different dimensions of accessibility while also introducing specific methodological constraints. The Euclidean distance method provides a simplified and transparent representation of accessibility by measuring straight-line distance between populations and healthcare facilities. Although this approach is useful for identifying broader spatial accessibility patterns, it does not account for transport networks, terrain, physical barriers, or mobility constraints and may therefore underestimate actual travel burdens and overestimate accessibility, particularly within rural and infrastructure-constrained environments (Guagliardo, 2004; Weiss et al., 2020).

In contrast, the service area and closest facility analyzes provide more realistic representations of functional accessibility because they incorporate movement through the road network. However, these approaches are highly dependent on the quality, completeness, and accuracy of the underlying infrastructure data. Road network data derived from OpenStreetMap may contain omissions, inconsistencies, or incomplete mapping coverage, particularly within remote and rural regions where volunteered geographic information remains limited (Haklay, 2010). Consequently, the analyze may not fully capture actual connectivity conditions across all parts of Sofala Province.

Furthermore, the network-based analyze assume relatively stable travel conditions across the transport network. In practice, accessibility is strongly influenced by variations in road quality, transport availability, seasonal conditions, and infrastructure functionality. The analyze does not directly incorporate dynamic infrastructure disruption caused by flooding, including bridge failure, road damage, debris, temporary closures, or changing travel speeds

during the cyclone event. As a result, post-flood accessibility conditions may still be somewhat overestimated compared to actual mobility conditions experienced during Cyclone Idai (Koks et al., 2019; Petricola et al., 2022). The network analyzes does not fully account for dynamic disaster conditions such as damaged bridges, debris, temporary road closures, transport shortages, or delays caused by floodwater and infrastructure damage. Consequently, actual travel conditions during and immediately after the cyclone were likely more constrained than represented in the model.

Another important limitation concerns the static nature of the analyze itself. Both flood exposure and healthcare accessibility are represented as fixed spatial conditions, whereas in reality they are highly dynamic processes. Flood events evolve temporally, and their effects on infrastructure, mobility, and accessibility may change rapidly throughout a disaster period. The flood dataset used in this study represents maximum observed inundation derived from satellite observations rather than continuous flood dynamics and therefore does not capture flood duration, temporal progression, water depth, or recession patterns. Similarly, population distribution is treated as static despite the likelihood of displacement, migration, and temporary relocation during and after the cyclone event. These limitations reflect broader challenges associated with static GIS-based disaster accessibility modelling (Guagliardo, 2004; Dewi et al., 2024).

Data quality and spatial resolution also introduce uncertainty into the analyze. The study relies on multiple secondary datasets, including OpenStreetMap road data, WorldPop population estimates, and satellite-derived flood mapping products, each of which contains inherent limitations. OpenStreetMap data may be incomplete in less mapped regions, while WorldPop data represents modelled population estimates rather than exact population counts (Weiss et al., 2020). Similarly, satellite-derived flood extent data may not capture all localized flooding events because of spatial resolution limitations, detection uncertainty, and varying observation conditions during the disaster period (Charrua et al., 2021).

Additionally, the analyze focuses primarily on physical accessibility measured through distance, travel time, and transport connectivity. Other important dimensions of healthcare access, including healthcare quality, staffing levels, service capacity, affordability, and socio-cultural barriers, are not incorporated into the analyze. The findings should therefore be interpreted specifically as an assessment of geographic and infrastructural accessibility rather than healthcare access in its broader social and institutional sense (Guagliardo, 2004).

Despite these limitations, the use of multiple complementary accessibility approaches represents a significant methodological strength of the study. Combining Euclidean distance analyze, service area analyze, and closest facility analyze enables a more comprehensive understanding of accessibility patterns by capturing both generalized spatial inequalities and network-dependent accessibility dynamics. The consistency of findings across the three approaches strengthens confidence in the broader conclusions and suggests that the observed reductions in healthcare accessibility represent robust spatial patterns rather than methodological artefacts (Dewi et al., 2024).

Future research could build on this work by incorporating more detailed and dynamic datasets and modelling approaches. This may include travel-time modelling based on empirical mobility data, integration of time-series flood observations, dynamic infrastructure conditions, and analyze of road recovery processes following disasters. Incorporating field-based data collection, participatory mapping, or qualitative community perspectives could also provide important insight into how accessibility disruptions are experienced in practice and how local populations adapt to changing mobility conditions during disaster events.

While the study is subject to methodological constraints, it nevertheless provides a robust and spatially explicit analyze of how flood exposure and healthcare accessibility interact across Sofala Province. By acknowledging these limitations, the study contributes to a more nuanced understanding of disaster vulnerability while also identifying opportunities for improving future accessibility analyze, disaster risk reduction planning, and infrastructure resilience research within hazard-prone regions.

6.6. Linking to Research Question

This thesis examined how Cyclone Idai (2019) interacted with and reshaped pre-existing spatial inequalities in healthcare accessibility across Sofala Province, Mozambique. Building on perspectives from health geography, disaster risk reduction, and spatial vulnerability research, the study explored how flood exposure, transport infrastructure, and healthcare accessibility intersected spatially to produce uneven patterns of vulnerability during the disaster event. Through the combined use of Euclidean distance analyze, service area analyze, and closest facility network analyze, the study provides a multi-dimensional understanding of accessibility conditions before and after Cyclone Idai and demonstrates how environmental hazards may intensify existing infrastructural inequalities across space.

The main research question guiding this thesis asked: *How did Cyclone Idai reshape spatial inequalities in healthcare accessibility in Sofala Province, Mozambique?* The findings demonstrate that Cyclone Idai reshaped healthcare accessibility primarily by intensifying pre-existing spatial inequalities rather than creating entirely new patterns of vulnerability. Flood-related disruption disproportionately affected areas already characterized by weak transport connectivity, limited healthcare accessibility, and infrastructural marginalization. As a result, populations located in rural, peripheral, and flood-prone regions experienced the greatest reductions in functional healthcare accessibility following the cyclone event. The findings therefore suggest that disaster impacts were mediated through existing spatial structures of infrastructure inequality and uneven service provision across the province (Wisner et al., 2012; UNDRR, 2015; IPCC, 2022).

The first research question asked: *What were the spatial patterns of healthcare accessibility in Sofala Province before Cyclone Idai?* The findings demonstrate that healthcare accessibility in Sofala Province was already highly uneven under baseline conditions. Healthcare facilities were concentrated primarily within urban and peri-urban regions, particularly around Beira and along major transport corridors, while rural and peripheral areas experienced substantially lower accessibility levels. The Euclidean accessibility analyze revealed that large parts of the province fell within moderate to poor accessibility categories prior to the flood event, indicating that many populations already faced considerable geographic barriers to healthcare access. The service area and closest facility analyzes further demonstrated that accessibility was strongly shaped by transport connectivity and infrastructure distribution rather than by geographic proximity alone. These findings are consistent with previous research emphasizing that healthcare accessibility across many parts of sub-Saharan Africa remains heavily influenced by uneven infrastructure development, weak transport connectivity, and spatial disparities in service provision (Ouma et al., 2018; Weiss et al., 2020; Hierink et al., 2023).

The second research question examined: *How did flooding associated with Cyclone Idai affect geographic accessibility to healthcare services?* The findings demonstrate that flooding substantially altered accessibility conditions across Sofala Province by disrupting transport connectivity and fragmenting the road network. The service area analyze revealed a contraction of reachable healthcare areas following inundation, while the closest facility analyze demonstrated that travel routes became longer, less direct, and increasingly

disconnected after flooding affected key transport corridors. These changes indicate that the impact of Cyclone Idai extended beyond physical flood exposure itself and significantly reduced functional healthcare accessibility through infrastructure disruption. The network-based analyze particularly demonstrate that healthcare accessibility during disaster events depends not only on the spatial distribution of healthcare facilities, but also on the resilience and functionality of transport infrastructure systems connecting populations to essential services (Koks et al., 2019; Petricola et al., 2022).

The third research question asked: *Which populations and areas experienced the greatest overlap between flood exposure and limited healthcare accessibility?* The overlay analyze demonstrated a strong spatial overlap between flood-prone regions and areas characterized by moderate to poor healthcare accessibility. These patterns were especially visible within low-lying floodplain regions and rural environments where infrastructure connectivity was already limited before the disaster occurred. Populations located within these areas experienced both elevated hazard exposure and reduced healthcare accessibility, creating zones of compounded vulnerability. The population-weighted accessibility analyze further demonstrated that substantial population groups remained within moderate and poor accessibility categories following the flood event, particularly in rural and infrastructure-constrained areas. These findings indicate that populations already characterized by limited accessibility before Cyclone Idai were also among the most vulnerable to flood-related disruption. Similar patterns have been identified within disaster vulnerability research emphasizing that environmental hazards often disproportionately affect populations characterized by weak infrastructure connectivity and limited access to essential services (Wisner et al., 2012; Koks et al., 2019; IPCC, 2022).

The fourth research question explored: *What do these spatial patterns reveal about disaster vulnerability and infrastructure inequality in Sofala Province?* The findings demonstrate that disaster vulnerability within Sofala Province is strongly shaped by the interaction between environmental exposure, transport connectivity, and pre-existing infrastructural inequalities. Cyclone Idai did not create healthcare accessibility inequalities independently, but instead amplified spatial disparities that already existed across the province prior to the flood event. Areas characterized by weak baseline accessibility, limited transport redundancy, and sparse infrastructure experienced the greatest reductions in functional healthcare accessibility following inundation. These findings therefore support broader disaster risk reduction

perspectives emphasizing that vulnerability emerges through the interaction between hazards, exposure, infrastructure conditions, and socio-spatial inequality rather than through environmental hazards alone (UNDRR, 2015; Wisner et al., 2012; IPCC, 2022).

The study also provides important methodological insights regarding accessibility analyze within disaster contexts. The Euclidean accessibility approach proved useful for identifying generalized spatial inequalities in healthcare proximity, but it simplified real-world accessibility conditions by excluding transport connectivity and infrastructure constraints. In contrast, the service area and closest facility analyzes provided more realistic representations of functional accessibility because they incorporated road network structure and route availability. Combining these approaches therefore made it possible to distinguish between nominal geographic accessibility and infrastructure-dependent accessibility under disrupted conditions. The consistency of findings across all three methods strengthens confidence in the broader conclusions while simultaneously demonstrating the value of multi-method accessibility analyze within disaster-related research (Guagliardo, 2004; Dewi et al., 2024).

The findings directly support the central argument presented in the introduction of this thesis: that Cyclone Idai did not affect healthcare accessibility uniformly across Sofala Province, but instead intensified pre-existing spatial inequalities by disproportionately disrupting already underserved and hazard-prone regions. The study therefore demonstrates that disaster impacts are not solely determined by the magnitude or physical characteristics of environmental hazards themselves, but are fundamentally shaped by existing patterns of infrastructure distribution, transport connectivity, and healthcare accessibility (Wisner et al., 2012; UNDRR, 2015; IPCC, 2022).

The findings further reinforce the importance of integrating spatial accessibility into disaster risk reduction and healthcare planning within hazard-prone environments. The results demonstrate that reductions in healthcare accessibility following Cyclone Idai were driven primarily by disrupted transport connectivity rather than by the physical absence of healthcare facilities alone. In many flood-affected areas, healthcare facilities remained geographically present but became substantially more difficult to reach because surrounding roads and transport corridors were inundated or disconnected. This highlights the importance of viewing healthcare accessibility as an infrastructure-dependent and dynamic process shaped by mobility conditions and network resilience during disaster events (Koks et al., 2019; Petricola et al., 2022).

The study also demonstrates the broader value of GIS-based accessibility analyze for identifying areas characterized by compounded vulnerability. Integrating flood exposure, healthcare accessibility, transport infrastructure, and population distribution within a shared analytical framework makes it possible to identify where environmental hazards and accessibility constraints intersect spatially. Such analyzes may support more targeted approaches to infrastructure investment, healthcare planning, emergency preparedness, and resilience building, particularly within rural and flood-prone regions where populations are already characterized by limited accessibility under normal conditions (Dewi et al., 2024; Weiss et al., 2020).

Within the context of increasing climate-related extreme weather events, strengthening healthcare accessibility and transport resilience becomes increasingly important for reducing vulnerability and improving adaptive capacity across disaster-prone regions (IPCC, 2022; UNDRR, 2015). Understanding how environmental hazards interact with infrastructure systems and pre-existing spatial inequalities will therefore remain essential for improving disaster preparedness and healthcare resilience across vulnerable regions such as Sofala Province.

7. Conclusion

This thesis examined how Cyclone Idai (2019) reshaped spatial inequalities in healthcare accessibility across Sofala Province, Mozambique. By integrating Geographic Information Systems (GIS), spatial accessibility analyze, flood extent data, transport infrastructure, and population distribution, the study explored how environmental hazards interacted with pre-existing infrastructural inequalities to produce uneven patterns of vulnerability during and after the cyclone event.

The findings demonstrate that healthcare accessibility in Sofala Province was already highly uneven prior to Cyclone Idai. Healthcare facilities and transport infrastructure were concentrated primarily around Beira and major transport corridors, while rural and peripheral regions experienced substantially lower levels of accessibility and weaker connectivity. These baseline inequalities meant that many populations were already characterized by limited functional access to healthcare services before the disaster occurred.

The study further demonstrates that flooding associated with Cyclone Idai significantly disrupted transport connectivity and reduced healthcare accessibility across large parts of the province. Flood-related infrastructure disruption altered accessibility patterns by fragmenting the road network, increasing travel constraints, and reducing the ability of populations to physically reach healthcare facilities. The network-based analyzes particularly illustrate how accessibility depends not only on the spatial location of healthcare services, but also on the resilience and connectivity of the surrounding transport infrastructure.

One of the most important findings emerging from the study is the strong spatial overlap between flood exposure and limited healthcare accessibility. Areas most severely affected by flooding were often the same areas already characterized by weak transport connectivity, limited healthcare provision, and infrastructural marginalization. As a result, Cyclone Idai did not affect healthcare accessibility uniformly across Sofala Province, but instead intensified pre-existing spatial inequalities by disproportionately disrupting already underserved and hazard-prone regions. The findings therefore support broader disaster risk reduction perspectives emphasizing that disaster impacts are shaped through the interaction between hazard exposure, infrastructural conditions, and underlying vulnerability rather than through environmental hazards alone (UNDRR, 2015; Wisner et al., 2012; IPCC, 2022).

The study also demonstrates the importance of combining multiple accessibility approaches in disaster-related spatial analyze. The Euclidean distance analyze provided insight into generalized spatial inequalities in healthcare proximity, while the service area and closest facility analyzes captured the infrastructure-dependent and network-based dimensions of accessibility under disrupted conditions. Together, these approaches provided a more comprehensive understanding of how Cyclone Idai altered both nominal and functional healthcare accessibility across the province. The consistency of findings across the different methods strengthens confidence in the broader conclusions and highlights the value of multi-method GIS approaches within disaster and health geography research.

Beyond its empirical findings, the thesis contributes to broader discussions concerning spatial vulnerability, infrastructure resilience, and disaster risk reduction within hazard-prone and infrastructure-constrained regions. The findings suggest that improving healthcare accessibility requires more than increasing the number of healthcare facilities alone. Accessibility is fundamentally shaped by transport connectivity, infrastructure resilience, and the spatial distribution of services across the landscape. Disaster risk reduction and healthcare

planning therefore need to address underlying infrastructural inequalities and strengthen connectivity within vulnerable and underserved regions in order to reduce the impacts of future hazard events.

The study further highlights the value of GIS-based spatial analyze for identifying areas characterized by compounded vulnerability. Integrating flood exposure, healthcare accessibility, transport infrastructure, and population distribution within a shared analytical framework makes it possible to identify where environmental hazards and accessibility constraints intersect spatially. Such analyzes may support more targeted disaster preparedness, infrastructure planning, and resilience-building efforts, particularly within resource-constrained environments where prioritization of interventions is necessary.

At a broader level, the findings are increasingly relevant within the context of climate change and growing disaster risk. Extreme weather events such as floods and tropical cyclones are expected to increase in frequency and intensity across many vulnerable regions, including southern Africa (IPCC, 2022). Understanding how these hazards interact with existing infrastructural inequalities and accessibility constraints therefore becomes critical for strengthening adaptive capacity and reducing vulnerability in the future.

The study also highlights the importance of integrating accessibility analyze into disaster preparedness and spatial planning processes. In hazard-prone regions such as Sofala Province, improving healthcare accessibility is not solely a matter of expanding healthcare infrastructure, but also of strengthening the resilience and connectivity of surrounding transport systems. Investments in roads, bridges, and alternative transport corridors may therefore play a critical role in reducing functional isolation during future flood events. The findings further suggest that disaster preparedness strategies should pay particular attention to rural and peripheral areas where populations are already characterized by limited accessibility under normal conditions. These areas are more likely to experience severe accessibility disruption during extreme events because they often depend on a limited number of transport routes and healthcare facilities.

The thesis also demonstrates the broader potential of GIS-based accessibility modelling for supporting disaster risk reduction and health system planning within vulnerable regions. Spatial accessibility analyze can help identify areas where infrastructure vulnerability, hazard exposure, and population concentration intersect, thereby supporting more targeted and

evidence-based planning decisions. In this way, GIS-based approaches may contribute not only to post-disaster assessment, but also to proactive planning aimed at strengthening resilience before future hazard events occur.

While the study is subject to limitations related to data quality, accessibility modelling, and the static representation of flood dynamics, it nevertheless provides a spatially grounded and methodologically transparent assessment of how Cyclone Idai reshaped healthcare accessibility across Sofala Province. The findings demonstrate that healthcare accessibility is not a fixed spatial condition, but a dynamic process shaped by the interaction between environmental exposure, infrastructure systems, and mobility conditions during disaster events.

To conclude this thesis argues that disaster vulnerability in Sofala Province cannot be understood solely through the physical characteristics of flooding itself. Rather, vulnerability emerges through the interaction between environmental hazards and pre-existing spatial inequalities in infrastructure and healthcare accessibility. Cyclone Idai therefore acted not only as an environmental disaster, but also as a process that exposed and intensified uneven patterns of infrastructural vulnerability across the province.

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9. Appendix

The appendices provide supplementary methodological details, supporting tables, and additional map outputs referenced throughout the thesis. These materials are included to enhance methodological transparency and support interpretation of the main analyze.

9.1. Appendix A: ArcGIS Workflow

This appendix provides a detailed description of the GIS-based workflow used to analyze healthcare accessibility and flood exposure in Sofala Province, Mozambique. All spatial data processing and analyzes were conducted in **ArcGIS Pro**, using standard geoprocessing tools and the Network Analyst extension.

The workflow consists of five main stages:

1. Data preparation and preprocessing
2. Euclidean distance analyze
3. Network-based analyze (service area and closest facility)
4. Flood integration and barrier modelling
5. Spatial overlay and population estimation

All datasets were imported into ArcGIS Pro and projected into a common coordinate reference system (CRS) to ensure spatial consistency.

The following preprocessing steps were performed:

- **Clipping datasets**
  All spatial layers (healthcare facilities, road network, population raster, and flood extent) were clipped to the boundary of Sofala Province using the *Clip* tool.
- **Selection of relevant features**
  From the OpenStreetMap dataset, only relevant features were extracted:
  - Healthcare facilities (hospitals and clinics)
  - Road network (primary, secondary, and tertiary roads)
- **Data cleaning**
  - Removal of duplicate features
  - Verification of geometry
  - Attribute consistency checks

- **Raster alignment**

  Population and flood raster datasets were aligned in terms of:

  - Cell size
  - Extent
  - Projection

The Euclidean accessibility analyze was conducted using the **Near tool** in ArcGIS Pro.

Steps:

1. Population raster was converted to point features using cell centroids
2. The *Near* tool was applied to calculate:
   - Distance from each population point
   - To the nearest healthcare facility
3. The resulting distance values were stored in the attribute table

The output was classified into three accessibility categories:

- Good access: < 5 km
- Moderate access: 5–15 km
- Poor access: > 15 km

The classified output was converted into a raster layer for visualization and further analyze.

To enable network-based analyzes, a network dataset was created from the road network.

Steps:

1. Road network feature class was prepared for network analyze
2. Topology was validated to ensure connectivity
3. A network dataset was created using:
   - Road segments as edges
   - Default connectivity rules
4. The network dataset was built and validated

No travel speed attributes were used; analyze was based on distance and connectivity.

The closest facility analyze was performed using the **Network Analyst extension**.

Steps:

1. Population points were used as *Incidents*
2. Healthcare facilities were used as *Facilities*
3. The closest facility solver was configured to:
    - Find the nearest facility for each population point
    - Generate shortest paths along the road network

The analyze was conducted under two conditions:

- **Baseline scenario (before flood)**
- **Flood scenario (with barriers applied)**

Outputs included:

- Route lines
- Distance-based accessibility patterns

Service area analyze was conducted to determine areas reachable within specified travel distances.

Steps:

1. Healthcare facilities were used as input locations
2. Service area solver was configured with break values:
    - 30 minutes
    - 60 minutes
    - 120 minutes
3. Service areas were generated based on the road network

The analyze was performed under two conditions:

- **Baseline conditions**
- **Flood-affected conditions**

Outputs included:

- Polygons representing accessible areas
- Classification of accessibility based on travel thresholds

Flood extent data were incorporated into the network analyze to simulate disrupted accessibility.

Steps:

1. Flood raster was converted into a binary layer:
    - Flooded
    - Non-flooded
2. Flooded areas were converted into polygon features
3. These polygons were used as **barriers** in the network dataset:
    - Preventing travel through flooded areas

This allowed simulation of reduced connectivity in both:

- Service area analyze
- Closest facility analyze

Spatial overlay was used to identify areas of combined flood exposure and limited accessibility.

Steps:

1. Euclidean accessibility raster was combined with flood raster using raster calculator
2. Categories were generated:
    - Accessible & not flooded
    - Flooded & accessible
    - Flooded & poor accessibility
3. Network-based results were used to interpret connectivity changes

Population exposure was calculated by overlaying accessibility and flood layers with population data. Population estimates within travel-time service areas were calculated using

the Zonal Statistics as Table tool in ArcGIS Pro, where WorldPop (2020) raster values were aggregated within each accessibility zone.

Steps:

1. Population raster was combined with:
    - Accessibility classifications
    - Flood extent
2. Population values were extracted for each category
3. Results were aggregated into:
    - Tables
    - Statistical summaries

Final outputs included:

- Accessibility maps (Euclidean, service area, closest facility)
- Flood extent maps
- Combined vulnerability maps
- Statistical tables and charts

Data visualization and chart production were conducted using:

- ArcGIS Pro
- Visual Studio Code

9.2. Appendix B: Accessibility Tables

This appendix presents detailed tables supporting the accessibility and population analyzes conducted in this study. The tables provide full numerical results underlying the summarized findings presented in Chapter 5, including population distribution across accessibility categories and changes in service area coverage before and after Cyclone Idai.

Population values are derived from the **WorldPop (2020)** gridded population dataset and represent aggregated estimates rather than exact counts.

Table B1. Service area coverage before Cyclone Idai

Accessibility Class	Travel Time	Area Coverage (relative units)	Share (%)
Very Good	≤ 30 min	0.103450	4.2%
Moderate	30–60 min	0.330077	13.3%
Poor	60–120 min	2.046076	82.5%
Total	---	2.479603	100%

Note: Area values represent relative polygon area derived from the projected service area outputs and are used for comparative purposes rather than absolute area measurement.

Table B2. Service area coverage after Cyclone Idai

Accessibility Class	Travel Time	Area (units)	Share (%)
Very Good	≤ 30 min	0.041607	5.9%
Moderate	30–60 min	0.160997	23.0%
Poor	60–120 min	0.497584	71.1%
Total	---	0.700188	100%

Note: Area values represent relative polygon area derived from the projected service area outputs and are used for comparative purposes rather than absolute area measurement.

Table B3. Absolute and relative changes in service area accessibility

Accessibility Class	Before	After	Absolute Change	Relative Change (%)
≤ 30 min	0.103450	0.041607	−0.061843	−59.8%
30–60 min	0.330077	0.160997	−0.169080	−51.3%
60–120 min	2.046076	0.497584	−1.548492	−75.7%
Total	2.479603	0.700188	−1.779415	−71.8%

Interpretation Note

The results in Tables B2–B4 demonstrate a substantial reduction in the total accessible area following Cyclone Idai. While the proportional share of shorter travel-time categories appears to increase, this reflects a contraction of the overall network rather than an improvement in accessibility. Large areas previously reachable within longer travel times are no longer accessible due to flood-induced disruptions to the transport network.

Table B4. Summary of closest facility accessibility patterns

Condition	Network Connectivity	Route Efficiency	Accessibility Pattern
Before Flood	High in central areas	Direct routes	Relatively connected network
After Flood	Reduced connectivity	Indirect routes	Fragmented network, increased travel distances

Table B5. Population accessibility estimates before flooding

Interpretation Note

The table below presents estimated population accessibility within pre-flood travel-time service areas derived from WorldPop 2020 raster data. These results are included as supporting material for comparison with post-flood accessibility patterns presented in the main analyze.

Travel-Time Category (Before Flood)	Estimated Population
0–30 minutes	370,435
30–60 minutes	477,884
60–120 minutes	755,817

Note: Pre-flood service areas were generated using overlapping network-based travel-time zones. Population estimates should therefore be interpreted as indicative rather than strictly

discrete category totals. Population estimates were derived from WorldPop 2020 raster data using zonal statistics within healthcare travel-time service areas.

9.3. Appendix C: Classification Thresholds

This appendix presents the classification thresholds and analytical criteria used to define healthcare accessibility and flood exposure in this study. These classifications provide a consistent framework for interpreting spatial accessibility patterns across the three applied methods: Euclidean distance, service area analyze, and closest facility network analyze.

The thresholds are based on commonly used standards in healthcare accessibility research and are intended to provide a generalized but comparable representation of access across the study area.

Healthcare accessibility based on Euclidean distance was classified into three categories according to straight-line distance between population locations and the nearest healthcare facility.

Table C1. Euclidean accessibility classification

Accessibility Class	Distance Range	Interpretation
Good	< 5 km	High proximity to healthcare services
Moderate	5–15 km	Intermediate access, moderate travel burden
Poor	> 15 km	Low accessibility, significant travel distance

These thresholds are widely used in studies of healthcare access in low- and middle-income countries and provide a standardized framework for assessing spatial proximity (Guagliardo, 2004; Ouma et al., 2018).

Service area accessibility was classified based on travel time thresholds derived from the road network. These categories represent the estimated time required to reach the nearest healthcare facility under network-based conditions.

Table C2. Service area accessibility classification

Accessibility Class	Travel Time	Interpretation
Very Good	≤ 30 minutes	High accessibility within short travel time
Moderate	30–60 minutes	Acceptable access with moderate travel effort
Poor	60–120 minutes	Limited access, long travel time required

These thresholds are consistent with accessibility studies that use travel-time-based measures to evaluate access to healthcare services, particularly in rural and infrastructure-constrained environments (Weiss et al., 2020; Hierink et al., 2023).

The closest facility analyze identifies the shortest path between population locations and healthcare facilities along the road network.

Unlike Euclidean and service area approaches, this method does not rely on predefined classification thresholds. Instead, accessibility is assessed based on:

- Route length (distance along the network)
- Route structure (direct vs indirect paths)
- Network connectivity (availability of viable routes)

Accessibility interpretation is therefore based on:

- **Short, direct routes → higher accessibility**
- **Long, indirect routes → reduced accessibility**
- **Disconnected or missing routes → severely limited accessibility**

This method provides a detailed representation of functional accessibility, particularly in contexts where infrastructure plays a key role.

Flood exposure was represented using a binary classification derived from satellite-based flood extent data.

Table C3. Flood exposure classification

Class	Description
Flooded	Areas identified as inundated during Cyclone Idai
Not Flooded	Areas not identified as flooded

This binary classification simplifies flood representation but enables clear integration with accessibility data for overlay analyze.

To identify areas of compounded vulnerability, accessibility classifications were combined with flood exposure data.

Table C4. Combined classification framework

Flood Status	Accessibility Level	Interpretation
Not Flooded	Good	Low vulnerability
Not Flooded	Moderate	Moderate baseline vulnerability
Not Flooded	Poor	High baseline vulnerability
Flooded	Good	Temporary disruption risk
Flooded	Moderate	Elevated vulnerability
Flooded	Poor	**Highest vulnerability (compounded risk)**

This combined classification reflects the conceptual understanding of disaster risk as the interaction between hazard exposure and vulnerability (UNDRR, 2015; IPCC, 2022).

It is important to note that these classifications represent generalized thresholds and do not capture all aspects of accessibility. Actual access to healthcare services may also be influenced by:

- Transport availability
- Road conditions
- Socio-economic factors
- Healthcare facility capacity

The classification framework should therefore be interpreted as an analytical tool for identifying spatial patterns rather than a precise representation of individual access conditions.

Figure C1: Flood impact statistics for Sofala Province, Mozambique. From the Euclidean analyze.

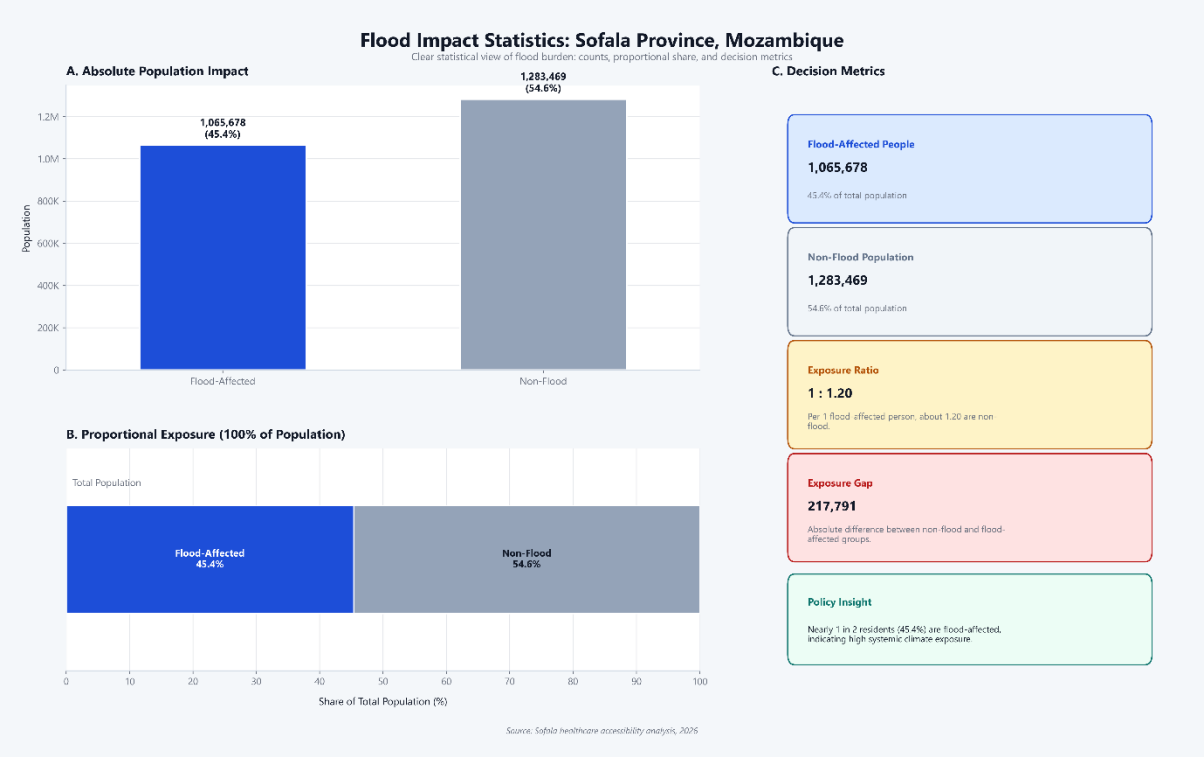


Figure C1. The figure presents a statistical summary of population exposure to flooding associated with Cyclone Idai in Sofala Province. Panel A illustrates the absolute number of people located within flood-affected and non-flooded areas based on the WorldPop 2020 population dataset and satellite-derived flood extent data. Approximately 1,065,678 people (45.4%) were estimated to be located within flood-affected areas, while 1,283,469 people (54.6%) were located outside the mapped flood extent. Panel B presents the proportional distribution of the population between flooded and non-flooded areas, illustrating the substantial share of the provincial population exposed to flooding. Panel C summarizes key exposure metrics, including the exposure ratio and population gap between flood-affected and non-flooded groups. The figure highlights the large-scale spatial exposure associated with Cyclone Idai and provides additional statistical context supporting the flood exposure analysis presented in Chapter 5.

9.4. Appendix D: Additional Maps

Appendix D presents additional maps generated during the methodological development of this study. Initial analyze used an Origin-Destination (OD) cost matrix approach to estimate travel time to the nearest healthcare facility under both non-flood and flood conditions. However, limitations in model performance and interpretability led to the adoption of a network-based accessibility approach presented in the main results. The maps below are included to demonstrate this methodological progression.

Figure D1. Travel time to the nearest healthcare facility under non-flood conditions using an Origin-Destination (OD) cost matrix approach. This method was later refined due to limitations in representing accessibility at the population level.

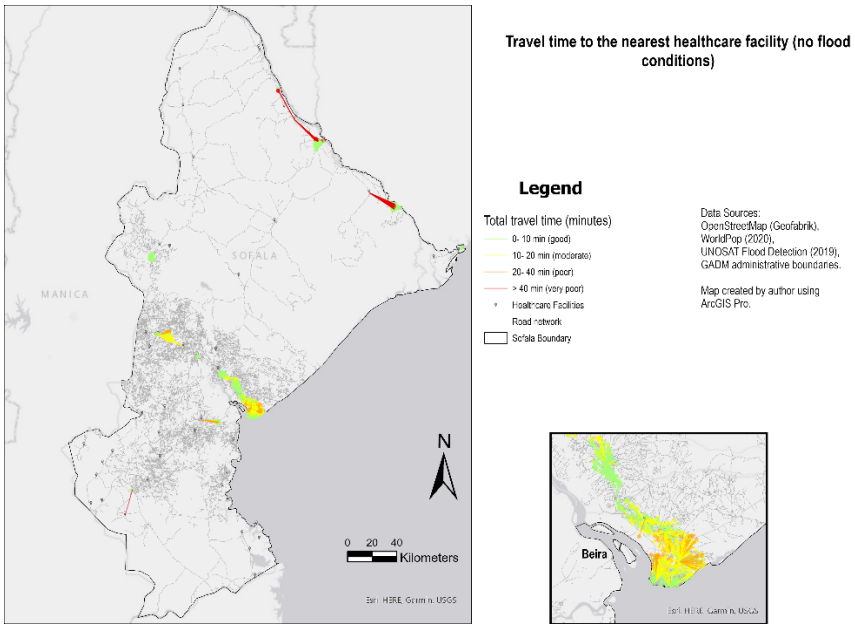


Figure D2. Travel time to the nearest healthcare facility under flood conditions using an Origin-Destination (OD) cost matrix approach. Flooded areas were incorporated as barriers; however, the approach proved less effective for capturing spatial accessibility patterns compared to the final network-based method.

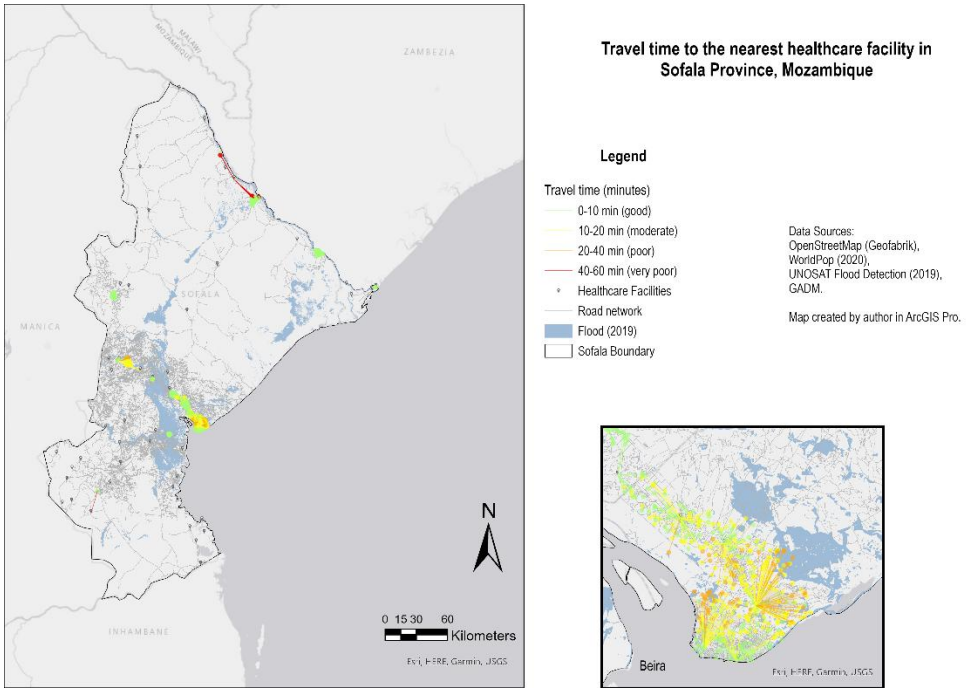


Figure D3. Accessibility to healthcare facilities before flooding based on shortest-path network analyze from population grid cells.

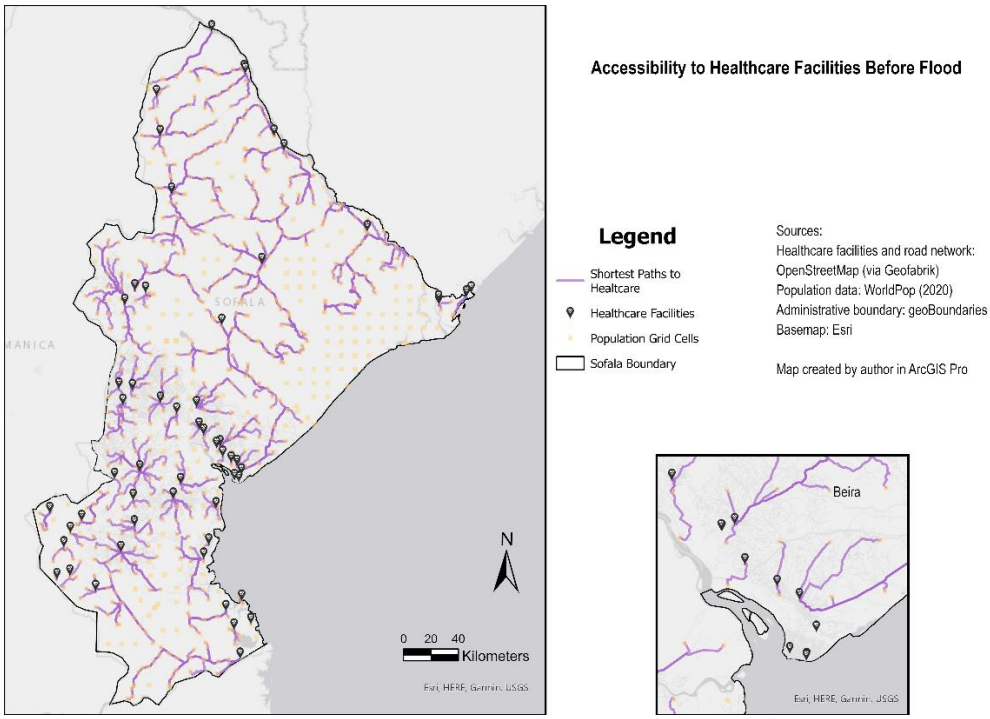
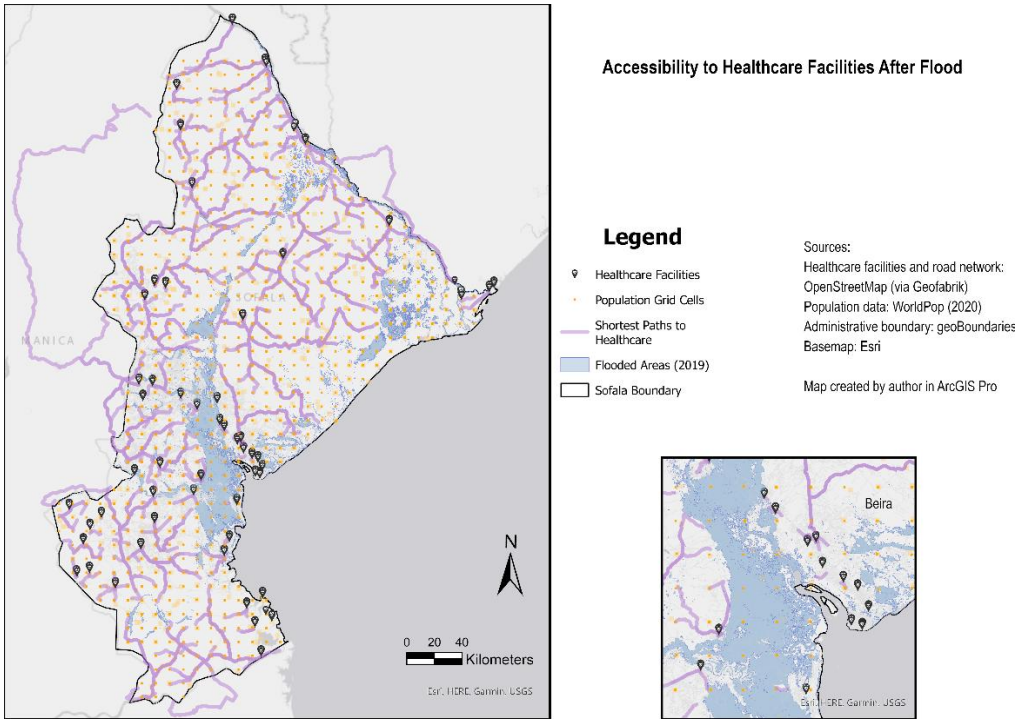
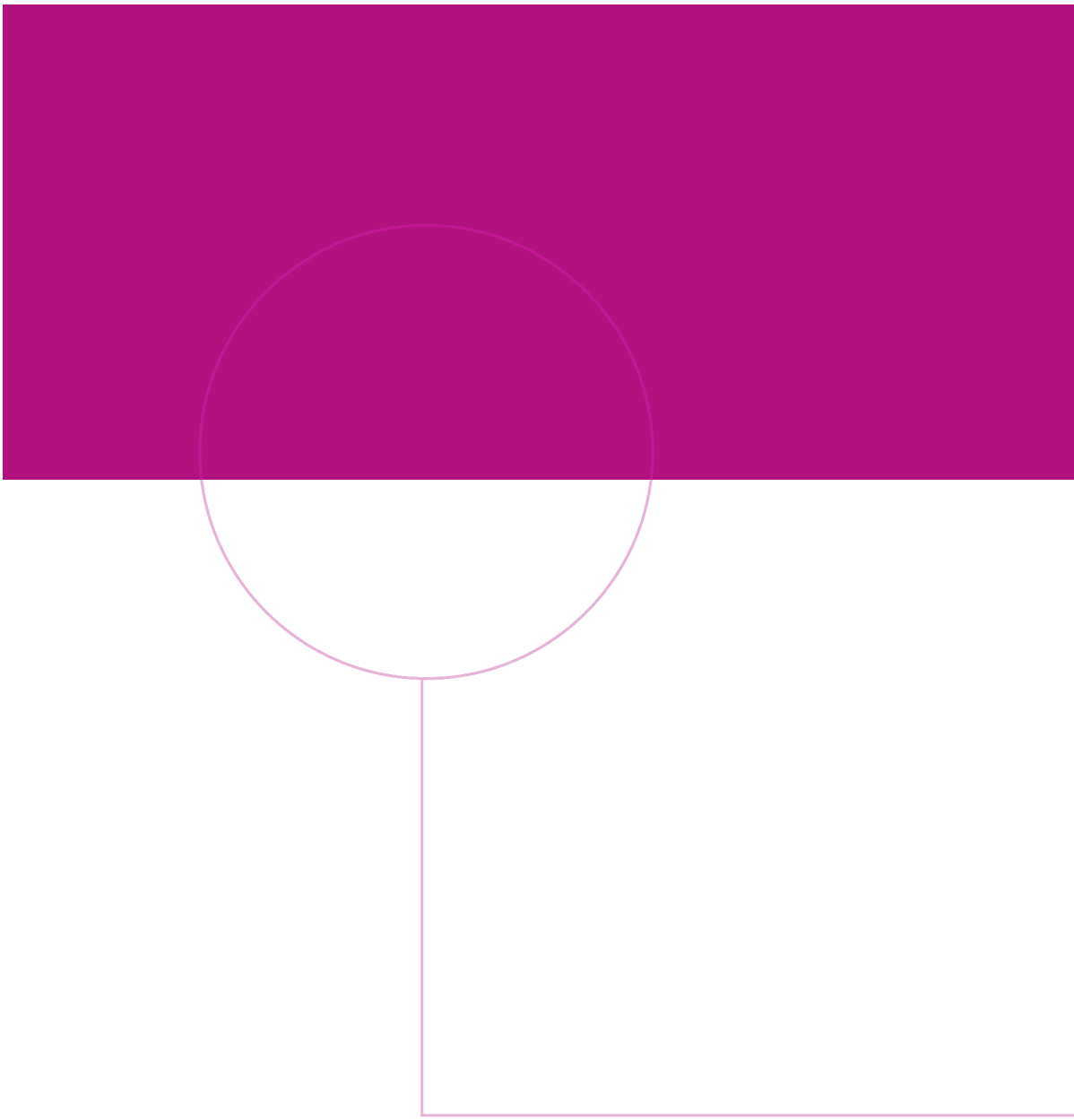


Figure D4. Accessibility to healthcare facilities after flooding, showing disrupted routes and reduced connectivity due to inundated areas.



The initial analyze employed an Origin–Destination (OD) cost matrix to estimate travel time between population locations and the nearest healthcare facilities under both non-flood and flood conditions. While this approach provided general estimates of travel time, it proved limited in effectively representing spatial accessibility across the study area. In particular, the OD matrix outputs were less intuitive to interpret at a population level and did not clearly capture the network-wide impacts of flooding on connectivity. As a result, a network-based shortest path approach was adopted, allowing accessibility to be modelled more explicitly from population grid cells to healthcare facilities. This method provided a more detailed and spatially coherent representation of how flooding disrupted routes and increased travel constraints and was therefore used for the final analyze presented in the main results.



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