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Modelling geographical accessibility to support disaster response and rehabilitation of a health care system:

An impact analysis of Cyclones Idai and Kenneth in Mozambique

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ABSTRACT

Objectives

Modelling and assessing the loss of geographical accessibility is key to support disaster response and rehabilitation of the health care system. The aim of this study was therefore to assess post-disaster travel times to functional health facilities and analyze population coverage losses after Cyclones Idai and Kenneth that affected Mozambique in 2019.

Setting

We modeled travel time of the population to the nearest functional health facility in two cyclone-affected regions in Mozambique. Modelling was done using AccessMod 5, where roads, rivers, lakes, flood extent, topography, and landcover datasets were overlaid with health facility coordinates and high resolution population data to obtain population coverage statistics under different travel scenarios.

Outcome measures

Travel time to functional health facilities and population coverage statistics were used to identify spatial differences between pre-disaster and post-disaster geographical accessibility.

Results

We found that population coverage significantly decreased in the flood affected districts, as a result of reduced travel speeds, road constraints and non-functional health facilities ($p<0.05$). In Idai affected districts, population coverage decreased from 78.8% to 52.5%, implying that 136,941 children under 5, were no longer able to reach the nearest facility within 2 hours travel time. In Kenneth affected districts, population coverage decreased from 82.2% to 71.5%, corresponding to 14,330 children under 5 having to travel more than 2 hours to reach the nearest facility. Damage to transport networks and reduced travel speeds resulted in the most substantial population coverage losses in both Idai and Kenneth affected districts.

Conclusion

Post-disaster accessibility modelling can increase understanding of spatial differences in geographic access to care in the direct aftermath of a disaster and can inform targeting and prioritization of limited resources. Our results reflect opportunities for integrating accessibility modelling in early disaster response, and to inform discussions on health system recovery, mitigation and preparedness.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- This is the first study presenting the applicability of post-disaster geographical accessibility modelling.
- The approach enables quantification of disaster impacts on geographical health care accessibility to prioritize post-disaster interventions and to build resilience for future disasters.
- To account for uncertainty of the assumed travel speeds, we considered multiple possible scenarios.
- Data from various sources were combined to represent the post-cyclone situation as realistically as possible, but since data gathering was ongoing, it was expected that some data were incomplete or not fully processed at the time of usage.
- Our accessibility modelling assumes that patients always travel to the nearest health facility. However, literature has shown that patients sometimes bypass health facilities in search of higher quality care in Mozambique

1. INTRODUCTION

Geographical proximity to health facilities is a crucial aspect of accessibility, utilization and the provision of health services to populations in need [1]. Road networks and natural barriers (such as rivers, water bodies, and flooded areas) are important factors that determine the geographical (i.e. physical) accessibility of a population to the network of functional health facilities. During natural disasters, roads and health facilities are often damaged, yet health care demand rises substantially at the same time due to injuries and increased communicable disease risks [2,3]. The interplay between the disruption of health infrastructure, transport network, and the rise in health care demand, is expected to disable a large portion of the population's access to care they need in the aftermath of a disaster [3,4]. This is especially the case in already medically underserved regions, where the event can lead to new health disparities or exacerbate existing ones [2].

In March and April 2019, two cyclones made landfall in Mozambique. This was the first time in history that two strong cyclones hit Mozambique consecutively in the same season [5]. On 14 March 2019 Tropical Cyclone Idai made landfall in Beira, followed by a week of heavy rains and winds, the storm ended on 21 March 2019 [6]. In the middle of the humanitarian emergency response for Cyclone Idai, a second cyclone hit Northern Mozambique. Cyclone Kenneth, a category 4 cyclone and the strongest recorded cyclone on the African continent, made landfall in Pemba, Cabo Delgado on 25 April 2019 [7,8]. The two cyclones combined had a death toll of 648 (603 fatalities due to Idai and 45 deaths caused by Kenneth) and left over 2.2 million people in need of humanitarian assistance [5]. The cyclone's destruction left entire communities isolated for weeks due to flood waters, destroyed telecommunication networks, and extensive road damage [9,10]. In addition, stagnant waters, inaccessibility to safe water and sanitation, and overcrowding in temporary accommodation led to a cholera outbreak and a significant increase in malaria cases [5,8,11,12]. Major damage to 113 health facilities were reported after both cyclones, causing severe disruption in health service provision and restricting the population's to access the adequate health care [13,14].

Cyclones impact entire populations, however the burden disproportionately affects children and women [15]. It is estimated that for cyclones Idai and Kenneth more than 50% of the affected population were children, and with flood waters rising above 6 meters, their movements to safety and health care were particularly limited [5]. Geographic inaccessibility to health facilities can interrupt childhood immunization, or prevent receipt of treatment for injuries [16,17].

Although many humanitarian actors have estimated substantial losses in health care accessibility and availability [5,9,10,13,18], the quantitative impact of Cyclone Idai and Kenneth on geographical accessibility to health care for children under the age of 5 across the most affected districts in Mozambique remains unknown. Modelling physical accessibility and population coverage by means of travel time to health facilities, can give important insights for targeting humanitarian action and preparing for future disasters in a coordinated manner [19]. International efforts to support humanitarian responses on the ground have accelerated data gathering in the country, enabling post-disaster accessibility modelling by means of health facility damages, loss of road access, and barriers to movement such as flood waters [20].

Currently, quantitative post-disaster accessibility assessments are not a part of standardized response guidelines, preventing coordinated and centralized decision making on temporary facility location to serve beneficiaries in the most optimal way [19]. Since humanitarian actors often have to deal with limited resources, informed decision making on temporary facility locations and prioritization of health facility rehabilitation can prevent duplicated action and therefore enhances both financial and operational efficiency [21,22].

This study presents a data processing and spatial accessibility modelling method to assess post-disaster accessibility to health facilities and analyze population coverage losses as a result of the disaster. The approach enables quantification of disaster impacts on geographical health care accessibility to prioritize post-disaster interventions and to build resilience for future disasters. This is the first study presenting the applicability of post-disaster geographical accessibility modelling.

2. METHODS

2.1 Overall methodology

In this study, accessibility is measured as the travel time to health facilities and coverage is defined as the number or percentage of people covered or located within a travel time catchment area [23]. To model accessibility to health facilities, we consider topography, road networks, constraints to movement (e.g. rivers, lakes and flood extent), target population distribution, and the locations of functional health facilities. We accessed and prepared multiple data layers (Table 1) assembled in the aftermath of Cyclone Idai and Kenneth, between April 2019 and September 2019. A total of three scenarios were prepared, representing 1) pre-Idai and pre-Kenneth, 2) post-Idai, and 3) post-Kenneth situations. We modeled population travel time to the nearest health facility and population coverage, for two cyclone-affected regions.

Table 1 – Overview of data layers and data sources

Layer name	Source[a]	Source date[b]	Download date	Type	Original resolution
Administrative boundaries	INE & UN-OCHA ROSEA (HDX)	02.04.19	31.07.19	Polygon	-
Land cover	Copernicus	15.11.18	31.07.19	Raster	100 meters
Elevation	SRTM CGIAR	25.11.18	20.09.19	Raster	30 meters
Rivers and lakes	DNGRH	12.8.19	19.9.19	Polygon	-
Flood extent Idai	Sentinel 1 (HDX)	19.03.19	31.07.19	Polygon	-
Flood extent Kenneth	Copernicus EMSR354 (INGC Geonode)	02.05.19	31.07.19	Polygon	-
Roads	OpenStreetMap (INGC Geonode)	25.11.18	07.08.19	Lines	-
Road damages (Idai/Kenneth)	LOG-WFP	19.03.19/ 03.05.19	23.09.19	PDF file	-
Health facilities	SIS-MA (HDX)	31.12.17	08.08.19	Points	-
Health facilities damages	Provided by WHO-Mozambique	48h – 1 week post cyclone	17.09.19	Points	-
Population density	Facebook/CIESIN population density	01.10.18	06.08.19	Raster	30 meters

[a] Abbreviations: CIESN = Center for International Earth Science Information Network, HDX = Humanitarian Data Exchange, INE = National Institute for Statistics Mozambique, INGC = National Institute for Disaster Management Mozambique, SIS-MA = Ministry of Health Mozambique, SRTM = Shuttle Radar Topography Mission, UN-OCHA ROSEA = United Nations Office for the Coordination of Humanitarian Affairs Southern and Eastern Africa, LOG-WFP = Logistics Cluster World Food Program

[b] Source date represents the imagery acquisition date for the flood extents and the release date for all other data

2.2 Data sources and preparation

The projection, resolution and alignment of geospatial data was processed using Quantum Geographical Information System (QGIS) (version 3.4) [24] and, to a limited extent, R (version 3.5.2) [25]. As indicated in Table 1, most data layers were retrieved from open data platforms. All raster- and shapefiles were saved in the projection system of Mozambique, i.e. UTM-37S [EPSG:32737]. The data preparation process is briefly described below, and fully detailed in Supplementary 1.

Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) in tiles at a resolution of 30 meters [26]. Slopes were derived from it and accounted for when modelling walking movements.

Land cover data was downloaded for the whole African continent at 100 meter resolution from Copernicus Global Land Service [27] and was clipped to the extent of Mozambique. As analyses were carried out at 30-meter resolution the land cover raster was resampled at a resolution of 30 meters, using nearest neighbor interpolation.

The pre-cyclone road network dataset was retrieved from Open Street Map (OSM) through the Geonode Platform of the National Institute for Disaster Management Mozambique (INGC), and linked to the road damage information as indicated by the Logistics Cluster of the World Food Program (LOG-WFP) [28,29]. Historical post-cyclone status of roads and road segments were manually digitized from pdf maps provided by LOG-WFP. The maps were cross-referenced with the OSM road network layer, to include post-cyclone road damage status, i.e. 1) open 2) restricted 3) closed. Road damages as a consequence of cyclones Idai and Kenneth were taken from maps dated March 19 and May 3 2019, respectively (Table 1) [28,29]. Information on road type and damage were combined in order to obtain unique road type-damage combinations.

Information on rivers and lake layout were obtained as shapefiles from the National Directorate for Water Resource Management (DNGRH). Only primary rivers and lakes were considered as barriers to movement, under the assumption that smaller rivers and streams were passable by the population. Flood extents for Idai (on 19 March 2019) and Kenneth (on

2 May 2019) were sourced as shapefiles from Sentinel-1 and Copernicus EMSR354, respectively. The flood extents were visually inspected and found to be largest on those two dates, and thus represent the biggest constraints for health care access. All flooded areas were treated under two scenarios: 1) as being impassable, under the assumption that people avoid traversing flood water to prevent further injury, 2) as being passable by foot at an average walking speed of 1.5 km/h. In the first scenario, health facilities located on flood extents were always treated as inaccessible since they are located on barriers.

High-resolution population density estimates for children under five were obtained from the Facebook Connectivity Lab and Center for International Earth Science Information network[30] with a 30-meter resolution.

Additionally, geographic coordinates of all villages (i.e. communities) in Idai-affected districts were obtained from UNICEF Mozambique, which had gathered this information through a community mapping initiative conducted by health officials, 6 to 8 months before Cyclone Idai made landfall. These community locations were used to extract pre- and post-cyclone travel time for each community to the nearest functional health center.

The geographic coordinates of all health facilities were sourced from the health management information system, Ministry of Health in Mozambique (SIS-MA). Data cleaning was undertaken in cases where the geographic coordinates for health facilitates were located outside the international border of Mozambique or for coordinates falling on barriers to movement (Supplementary 1). Information on damaged health facilities was provided in tabular format by the World Health Organization (WHO). The health system in Mozambique comprises four levels; the primary level consists of urban and rural health centers, the secondary level consists of general, rural and district hospitals, the tertiary level comprises provincial capital hospitals, and quaternary facilities comprise the central and specialized hospitals [31]. Health facilities of all levels were included in the model.

Districts that were most affected by Cyclones Idai and Kenneth ("cyclone-affected districts", thereafter) were identified in close collaboration with UNICEF and humanitarian responders.

All statistics presented below were calculated for these identified districts, with 26 such districts in the Idai-affected region and 11 districts in the Kenneth-affected region (Figure 1).

2.3 Geographical accessibility modelling

To model travel times and population coverages, we used AccessMod 5 (version 5.6.30) [23,32]. AccessMod models geographic accessibility using terrain-based least-cost path distance calculation. This open-source software has been successfully applied in many different settings, among which accessibility and referral assessments of health facility networks, optimization modelling of health programs in obstetric and neonatal care (EmONC) [33], primary health care [34], emergency care [35], referral times [36], and treatment of fever cases [37].

Using the data preparation modules in AccessMod, we overlaid the roads, rivers, lakes, flood extent, and landcover datasets to obtain a single 30-m resolution raster data set, to which different travel scenarios were applied.

The travel scenarios (presented in Supplementary 2) were derived using local information as model inputs on pre-cyclone and post-cyclone travel speeds and travel modes. Both scenarios were developed in close collaboration with UNICEF Mozambique, with focus on geographic accessibility to functional health facilities for the target population of children under 5. Post-cyclone travel speeds were adjusted for wet weather conditions as heavy rains persisted in the direct aftermath of both cyclones. During the post-cyclone situation, restricted and closed roads were assumed to be unpassable by any vehicle; but where flood waters were not inundating roads, they were perceived to be accessible by foot. All landcover classes outside of the road network and the barriers were considered as passable. We assumed a functional bridge where a road segment crossed a river.

To account for uncertainty of the assumed travel speeds, we also considered both pre- and post-cyclone motorized travel speeds with a 20% slower and 20% faster speed, as adapted from Ouma et al. (2018) [35]. Population coverage of the network of health centers was calculated at the 2-hour maximum travel time limit. This limit was deemed appropriate to capture the extent of effective access, and is often used in health accessibility studies, notably in maternal health (Ebener et al., 2019). A paired T-test was used to check for statistically significant difference between pre-cyclone and post-cyclone population coverage (R version 3.5.2).

FIGURE 1

2.4 Patients and the public involvement

There was no patient or public involvement in this study. Health facility functionality status was shared in tabular format by WHO. All other geospatial data were publicly available.

3. RESULTS

3.1 Pre-cyclone accessibility

Pre-cyclone coverage in Idai-affected districts (Figure 3a) was highest in Cidade De Chimoio and Cidade Da Beira, with 99.8% and 99.5% of all children under 5 covered within the 2 hours catchment limit, respectively (Supplementary 3). However, this coverage ranged from 35.8-99.8% in all Idai-affected districts (Supplementary 3). Absolute pre-cyclone coverage was also highest in Cidade De Chimoio and Cidade Da Beira, where 57,476, and 66,135 children were within 2 hours travel time from a health facility (Figure 2). In Kenneth-affected districts (Figure 1b), pre-cyclone coverage was highest in Cidade De Pemba, where 100% of the children under 5 were expected to be able to reach a health facility within 2 hours travel time (Supplementary 4). The lowest pre-cyclone coverage was seen in Mazeze, where only 52.6% of children under 5 were within 2 hours travel time from a health facility (Supplementary 4). Absolute pre-cyclone coverage in Kenneth-affected districts was highest in Cidade De Pemba (n = 35,467 children) and Chiure (n= 18,257 children) (Figure 2). Figure 3a and Figure 4a present the pre-cyclone travel time rasters for the cyclone-affected areas.

FIGURE 2

3.2 Accessibility losses in affected districts

Geographical accessibility to health care significantly decreased in the cyclone affected districts, as a result of reduced travel speeds, road constraints and non-functional health facilities (Figure 3B and Figure 4B). In Figure 3C, ratios of pre-cyclone and post-cyclone travel time rasters are mapped for Idai-affected districts, with ratios close to 1 indicating similar travel times pre- and post-cyclone, and ratios closer to 0 indicating large pre- and post-cyclone accessibility differences. Figure 4C presents the same results for Kenneth-affected districts. Regions shown in red indicate localities with relatively large differences between pre- and post-cyclone travel times (Figure 3C). In the Idai-affected region, especially in the districts surrounding the flood water and closed roads, accessibility is severely impacted. In Idai affected districts, the percentage of children under 5 covered within 2 hours travel time, generally decreased from 78.8% to 52.5%, implying that 136,941 previously covered children under 5, lost timely access to health care (Table 2).

Table 2- Overview of pre- and post-cyclone population coverage in Idai and Kenneth affected districts.

			Pre-cyclone		Post-cyclone			
Cyclone	**Travel time**	**P-value***	**Children <5 covered (nr.)**	**Children <5 covered (%)**	**Children <5 covered (nr.)**	**Children <5 covered (%)**	**Children <5 coverage loss (nr.)**	**Children <5 coverage loss (%)**
Idai	30 minutes	0.009	298432	57.3	153842	29.5	144591	27.7
	1 hour	0.002	346409	66.5	206610	39.6	139799	26.8
	2 hours	< 0.001	410696	78.8	273755	52.5	136941	26.3
Kenneth	30 minutes	0.001	131120	72.0	63953	48.8	30415	23.2
	1 hour	0.010	99056	73.8	86997	64.8	12060	9.0
	2 hours	0.039	110348	82.2	96019	71.5	14330	10.7

*P-values were obtained through a paired T-test.

The largest relative population coverage decline, within 2 hours travel time, was observed in Machanga, where 77.6% of the previously covered population was no longer able to access a facility under 2 hours in the aftermath of Idai (Figure 2). In terms of absolute coverage, Nhamatanda was the heaviest affected district, with a coverage loss of 25,121 children under 5, followed by Morrumbala (n = 19,554 children), Cidade Da Beira (n = 17,355 children), and Buzi (n= 9,949 children) (Figure 2). Uncertainty modelling, by accounting for 20% slower and 20% faster motorized travel speeds, indicated localities with travel time differences up to 3-hours comparing slower and faster travel speeds (Figure 3D). This information indicates where accessibility and coverage losses may be either under- or overestimated, which can help guide resource allocation for decreasing this uncertainty.

Relative population coverage in all Kenneth-affected districts decreased from 82.2% to 71.5%, corresponding to 14,330 children having lost access to the nearest facility within 2 hours travel time (Table 2). The most affected district in terms of relative coverage loss was Macomia, where 88.9% of previously covered children lost access (Supplementary 3-Supplementary 4). Mazeze was the heaviest affected district in terms of absolute coverage loss, as 5,496 children lost access in the aftermath of cyclone Kenneth, followed by Macomia (n= 3,727 children), Chiure (n= 2,307 children), Quissanga (n= 1,270 children) and Mueda (n= 750 children) (Figure 2). Pre-cyclone population coverage significantly ($p < 0.05$) differed from post-cyclone population coverage under all travel time limits (30 minutes, 1 hour, 2 hours) and for both cyclones (Table 2). Since flood waters slowly receded in the days/weeks after the cyclones, we ran an additional scenario where flood waters were passable at a 1.5km/h walking speed. Considering this scenario, absolute coverage losses for Idai-affected districts within 2 hours travel time were highest in Morrumbala (n= 29,566 children), Nhamatanda (n= 25,758 children), Dacata (n= 8,914 children), and Bùzi (n= 8,757 children). In Kenneth-affected districts, Mazeze (n= 6,167 children), Chiure (n= 4,684 children) and Macomia (n= 3,727 children) had the highest coverage losses in 2 hours catchments under the passable scenario.

3.3 Travel time in affected communities

The most affected villages in Idai-affected districts, in terms of reduced accessibility to the nearest health facility were communities located in the district Bùzi and Muanza in Sofala province. The community Mucinemo in Bùzi was found to have a pre-cyclone travel time of 1.3 hours to the nearest health facility. However, this travel time upsurged to 63.6 hours in the direct aftermath of cyclone Idai (Supplementary 5-Supplementary 6). Generally, the 6 most affected communities in terms of accessibility in Idai affected districts all had a pre-cyclone travel time between 1 hour and 3 hours, while all post-cyclone travel times increased to over 55 hours (Supplementary 6). Overall, post-cyclone accessibility ranged from some minutes up to 78 hours, with the highest travel time for the community of Chipota, Muanza.

FIGURE 3 & 4

3.4 Health facility closures

The sole effect of non-functionality of health facilities was isolated by comparing two separate scenarios; 1) a post-cyclone scenario where all health facilities were considered functional, and 2) a post-cyclone scenario where functionality status was considered. By comparing these scenarios to the pre-cyclone accessibility, the coverage losses caused by the disruption to transportation only (i.e. adjusted travel speeds and road constraints) could be isolated from the reduction in coverage due to the damage to health facilities (i.e. non-functional health facilities), providing a way to assess the likely impact of future programs aimed at reinforcing health facilities for disasters. In order to make these comparisons, both scenarios were run under the assumption that flood waters were fully passable. In case all health facilities remained functional in Idai-affected districts (i.e. disruption was due to transportation only), the overall coverage within 2 hours travel time would decrease from 79.3% to 57.7%, a difference of 21.6% (n = 112,538 children). Damage to health facilities caused an additional coverage decline of 5.3% (n = 27,840 children) in Idai-affected districts. However, hospital closures did not evenly affect all districts. In 17 out of 26 Idai-affected districts, hospital closures had no additional effect on accessibility, implying that coverage losses were only caused by disruption to transportation networks. However, in the remaining 9 Idai-affected districts, hospital closures were responsible for an additional 1.9-59.7% coverage loss within 2 hours catchment. Health facility closures in Machanga affected the relative coverage the most, with 59.7% coverage loss (n= 3,642 children) caused by non-functionality of 3 out of 6 health facilities. Absolute coverage losses as an effect of non-functional health facilities, were highest in Nhamatanda, where 12,946 (31.0%) children under 5 years old lost access due to health facility closures. In Nhamatanda, 9 out of 16 health facilities became unfunctional as a consequence of Cyclone Idai. Health facility closures did not have an additional effect on post-cyclone accessibility in Kenneth affected districts.

4. DISCUSSION

Population coverage significantly decreased ($p < 0.05$) and travel times substantially increased in the direct aftermath of the cyclones. Damage to transport networks and reduced travel speeds resulted in the most substantial population coverage losses in both Idai- and Kenneth-affected districts.

In a post-disaster setting, access to health care is essential for effective response and recovery [38]. The results of our study can be implemented beyond the response phase of the cyclones. Although the emphasis of the results is on identification of population coverage losses on district level directly post-cyclone, the information presented here also provides a platform for discussing health system recovery, mitigation and preparedness [39].

Early identification of underserved districts in the response phase can help reduce the impacts caused by health service interruption, through targeted deployment of medical services in districts with largest coverage losses and lowest baseline accessibility [40]. Information on population coverage losses per cyclone affected district can support decision-making in the prioritization and planning of these medical services, by targeting where the deployment of medical services reaches the highest number of people. Growing access to open data and post-disaster information enables prompt accessibility modelling in the aftermath of a natural disaster and the growing ability to quickly assemble this data provides an opportunity to integrate accessibility modelling in the early response phase of a natural disaster, so resources can be allocated in an informed way and health impacts can be reduced.

Although flood waters receded in the weeks after the disasters, there were still 94 unsafe and non-functional health facilities in June 2019 as a consequence of substantial damages from the 2 cylones [14,41]. While it is critical to restore access to essential health services as soon as possible, the WHO reported that the reconstruction of all destructed and damaged facilities may take up to 5 years [14].

Furthermore, the extensive damages to the road network will continue to limit movements of the population, further complicating physical accessibility [5]. Our results have clearly pointed that road damages are responsible for a relatively larger loss of accessibility compared to the non-functionality of facilities. This calls for a concerted effort between road and health authorities when prioritizing reconstruction efforts. It was estimated by WHO that damages to (health) infrastructure translated into 200,000 people living more than 5 kilometers from a functioning health facility [41]. However, our results, which provide a more realistic representation of accessibility, by accounting for topography, barriers to movement, and population distribution suggest this is an underestimate. We estimated that as a result of the damage to infrastructure and barriers to movement, 314,591 children under 5 live further than 1 hour travelling from a functioning health facility.

Fourteen percent of all health facilities in cyclone-affected districts have been damaged or fully destroyed. Rebuilding more resilient facilities and infrastructure, both in terms of physical structure and in coping capacity, are needed to prevent similar impacts in future disasters [41]. The results presented here show the importance of joint efforts to reduce both impacts on health facilities and the existing road network. However, resources are limited, and efficient financial planning is needed to outline health system investment plans [5,11]. The results of our accessibility modelling can be used to prioritize health facility reconstruction for facilities with highest population coverages. Cyclone Idai for instance, caused the destruction of the only tertiary hospital in four affected provinces that serves an estimated 12 million people [38]. Targeting hospitals with coverage numbers like these, to be strengthened for future disaster impacts and to support them in providing continuity of care in the aftermath of future disasters can help reduce coverage losses and health impacts subsequently [42].

Due to the persisting health system disruption, humanitarian responders have identified the need to deploy community health workers (CHWs) and mobile outreach services to cover accessibility losses caused by the cyclones and to extend the reach of existing functional services [38,43]. These study findings can assist policymakers in identifying and prioritizing severely impacted districts and communities and regions where CHWs deployment can make a difference. Supplementary material 3 to 6 present the most affected communities in terms of increased travel time and coverage losses, directly post-cyclone. These analyses can be routinely updated to assess the effect of health system recovery on accessibility.

The districts that were most affected by Cyclone Idai and Kenneth were historically and are in the future also prone to disasters [38,41]. Ideally, accessibility modelling could be applied to simulate the effects of historical disasters on accessibility, as indicated in Supplementary 5 and Supplementary 6, so targeted preventive measures can be taken for future disasters. Post-disaster accessibility modelling can help identify weak spots in the geographical accessibility to the health system and helps to distinguish pre-existing accessibility gaps (Figure 3A and 4A) from coverage losses as a result of disasters (Figure 3B and 4B). This information is essential in health system recovery, strengthening and preparing for future disasters.

Limitations and uncertainties of this study were primarily linked to the data. The unfortunate event of natural disaster generally accelerates data availability in affected countries, but with the challenges of data quality, consistency, and format [44]. In this study, data from various sources were combined to represent the post-cyclone situation as realistically as possible, but since data gathering was ongoing, it was expected that some data were incomplete or not fully processed at the time of usage. Health facility coordinates for instance had duplicate occurrences in the database and health facility damages were solely indicated by name, which resulted in manual spatial merging. Co-occurrences of rivers that were indicated as floods were seen in the flood extent layer, minimally overestimating actual flood extents in some parts of the affected regions. Besides post-disaster data uncertainty, pre-disaster spatial data were also checked against background satellite imagery. The hydrography of primary rivers stored in the data was found not to be fully representative for actual hydrography in some regions, this could be a consequence of digitizing against a less granular spatial resolution [45]. In some cases, passages and bridges were detected on satellite background imagery where the OpenStreetMap road layer did not present presence of roads. The absence of roads in places were hydrography is potentially overestimated, results in isolated land pockets, where accessibility cannot be modelled, and the population is assumed to be fully isolated.

Next to data uncertainties, travel scenarios present a source of uncertainty as assumptions on travel speeds and modes are uniformly generalized across regions. In addition, we assumed that roads indicated as being restricted or closed, were considered only passable by foot if they were not inundated. However, some of the restricted roads were in fact passable by 4x4 vehicles. Since car ownership and access to motorized transport by the target population was expected to be very low, especially post-cyclone, it was decided to run the accessibility model for restricted and closed roads only by means of walking.

Our accessibility modelling assumes that patients always travel to the nearest health facility. However, literature has shown that patients sometimes bypass health facilities in search of higher quality care in Mozambique [46,47]. Previous research, has shown that 30.8% of pregnant women bypassed the nearest health facility in search of better prenatal care [46]. Our results can therefore present slight underestimations of actual travel times.

Despite some of the limitations, the results presented here provide important initial information for post-cyclone health system recovery which can be expanded through future research. Since post-disaster needs continuously change based on the nature of the event (e.g. receding flood waters, reconstruction efforts, and deployment of temporary medical services), following studies should also be focused on the ability to dynamically model accessibility based on these changes, so accessibility can be continuously monitored. Additionally, it would be interesting to assess the effect of CHW deployment and mobile outreach communities on improved accessibility and population coverage statistics, to quantify the effect of these interventions.

Post-disaster accessibility modelling can increase our understanding of spatial differences in health care needs in the direct aftermath of a disaster and can help target limited resources efficiently. Currently, there is no standardized approach among humanitarian agencies to assess post-disaster accessibility losses, potentially resulting in uncoordinated decision making for temporary health facility locations which could result in duplicated efforts by humanitarian actors on the ground. The results in this paper not only reflect the importance of incorporating accessibility modelling in early disaster response, but also provide a platform for discussing health system recovery, mitigation and preparedness.

AUTHOR CONTRIBUTION

Fleur Hierink: conceptualization, methodology, formal analysis, writing, editing, visualization, supervision. **Nelson Rodrigues:** data sharing, methodology, writing, editing, validation. **Maria Muñiz**: writing, editing. **Rocco Panciera:** methodology, writing, editing. **Nicolas Ray:** conceptualization, methodology, writing, editing, validation, supervision.

DATA SHARING STATEMENT

Data available upon request.

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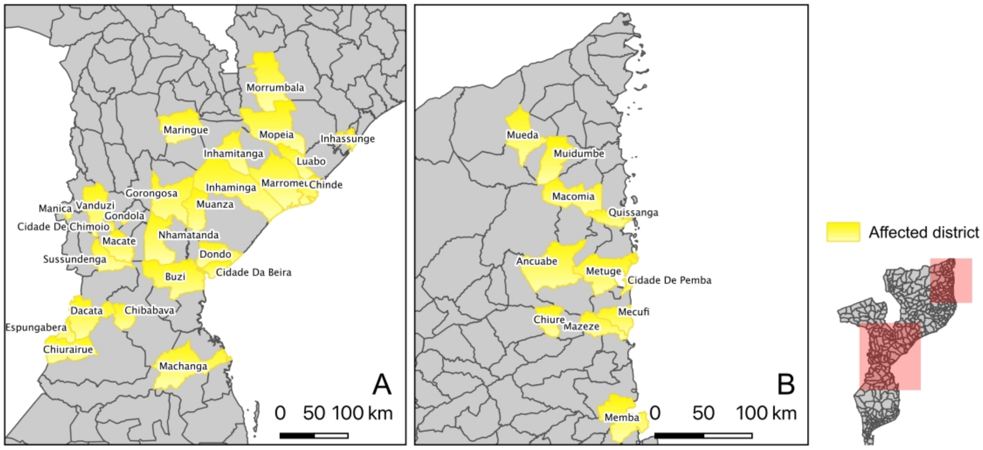


Figure 1 - Cyclone affected districts. (A) Idai affected districts. (B) Kenneth affected districts.

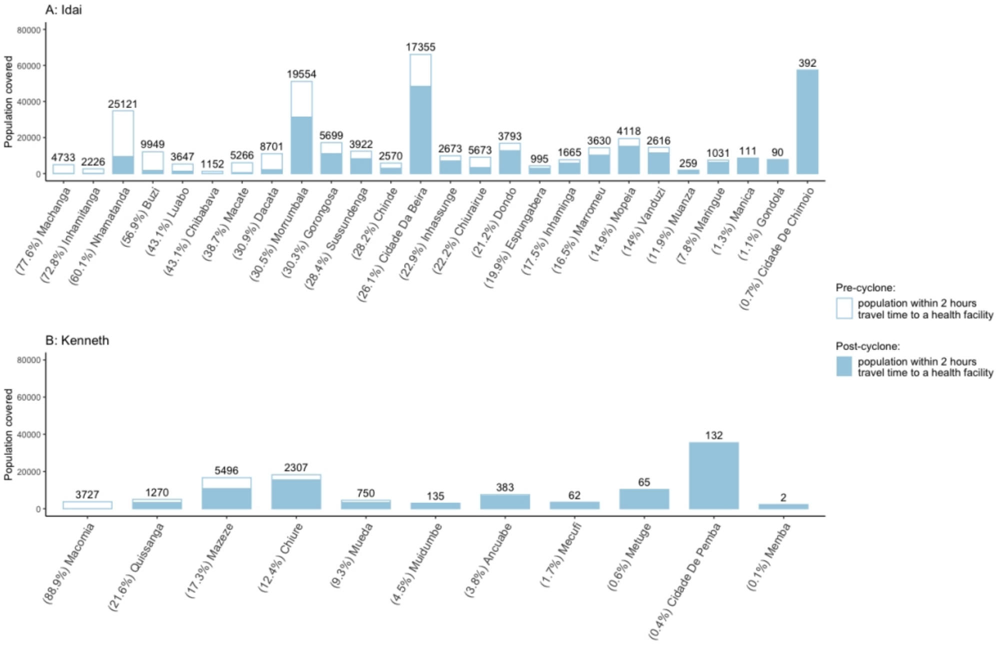


Figure 2- Absolute and relative reduction in population coverage pre- and post-cyclone Idai (A) and Kenneth (B). Labels on top of bars indicate absolute reduction in population coverage of children under 5. Labels under districts indicate relative reduction in population coverage. Maximum limits of the bars indicate the absolute pre-cyclone coverage within 2 hours travel time. Limits of the blue filled bar indicate the absolute post-cyclone coverage. The x-axis is ordered according to relative reduction in population coverage.

482x318mm (72 x 72 DPI)

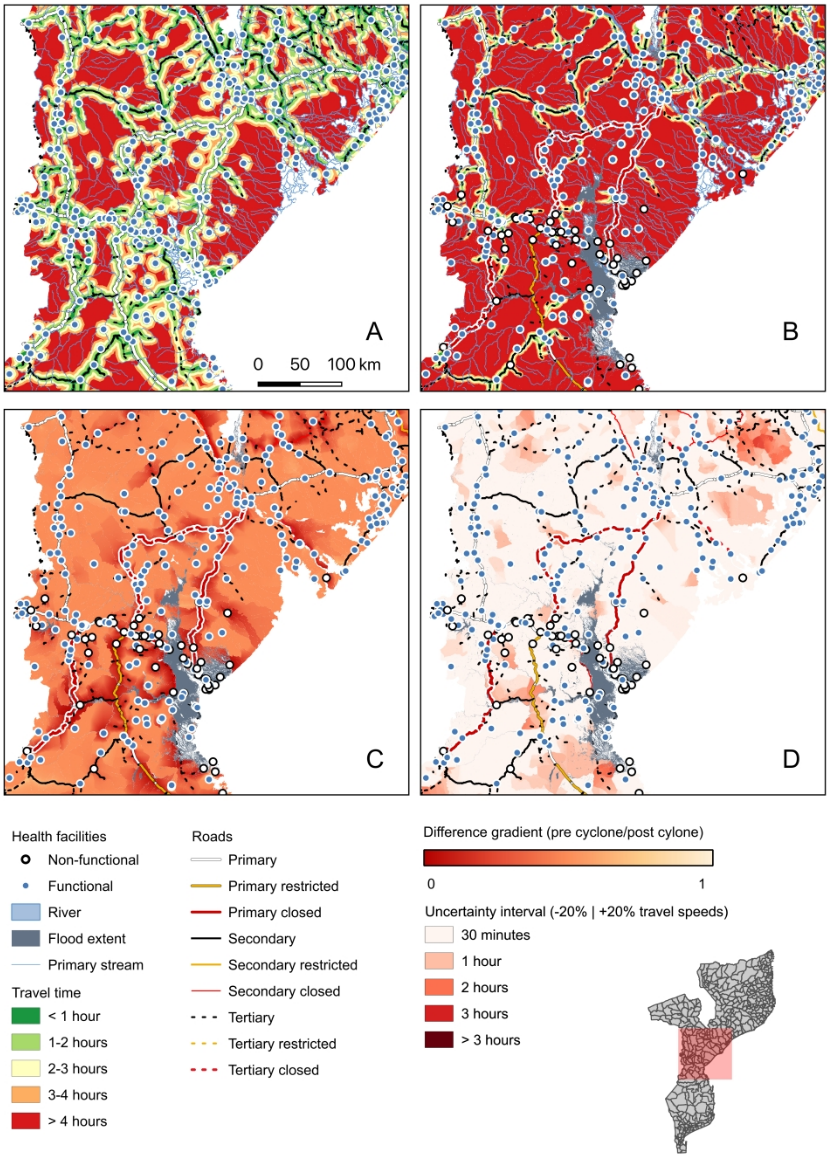


Figure 3 – Accessibility modelling results for Idai districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).

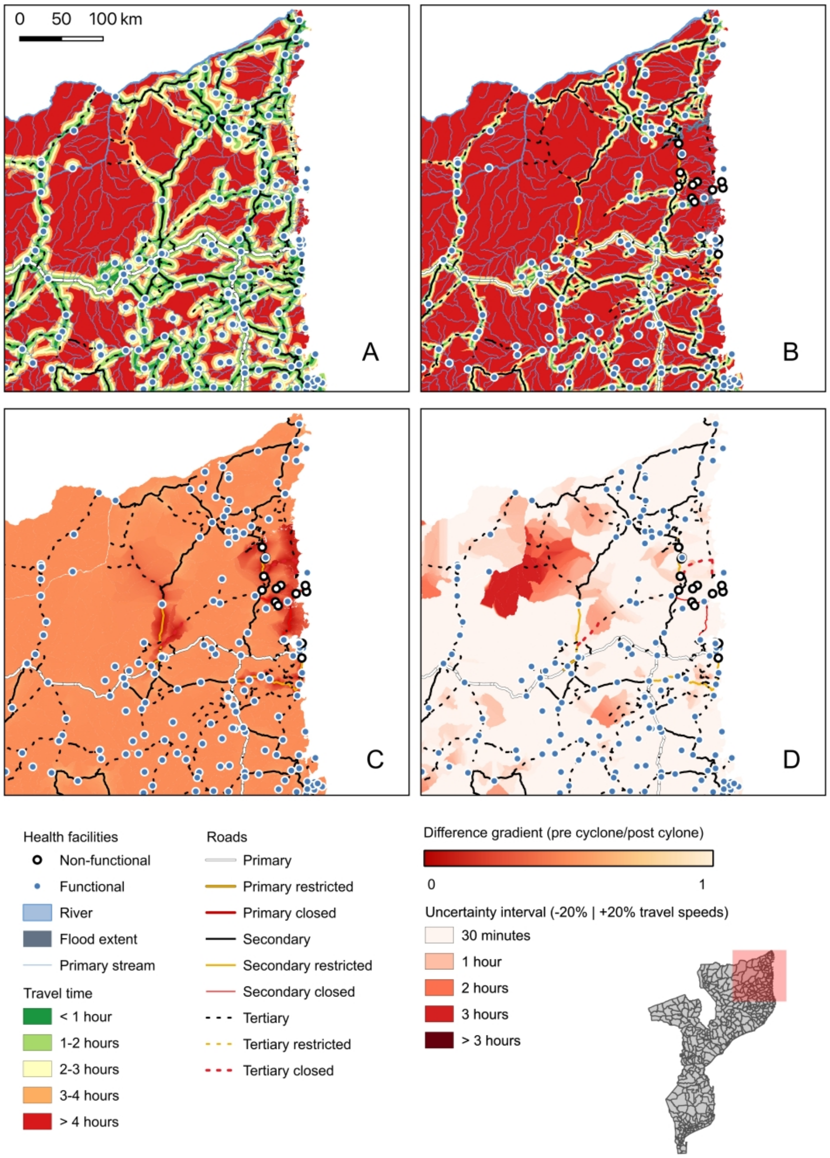


Figure 4 – Accessibility modelling results Kenneth districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).

SUPPLEMENTARY MATERIAL

S1-Data preparation for use in AccessMod

All data preparation was carried out in Quantum Geographical Information System (QGIS) (version 3.4) [24] in limited combination with R (version 3.5.2) [25]. As indicated in Table 1, most data layers were retrieved from open data platforms. All raster- and shapefiles were saved in the projection system of Mozambique, i.e. UTM-37S [EPSG:32737]. All raster files were aligned using the digital elevation model (DEM) as reference. The data preparation process is fully described below for each data set.

Elevation

Anisotropic accessibility analyses, in other words analyses accounting for travel speeds on slopes, were carried out for this study. The digital elevation model (DEM) data were obtained in tiles at a resolution of 30 meters [26]. All separate tiles were first mosaiced in QGIS 3.4.

Land cover

The land cover data set of the African continent [27] was clipped to the extent of Mozambique, leaving a small buffer around the country to prevent loss of data cells at the border. The data set was resampled at a resolution of 30 meters using nearest neighbor interpolation.

Road network

The pre-cyclone road network dataset was retrieved from Open Street Map (OSM) through the Geonode Platform of the National Institute for Disaster Management Mozambique (INGC), as this dataset was perceived to represent the most recent information on the roads and could be linked to the damaged roads, as indicated by the Logistics Cluster of the World Food Program (LOG-WFP). Road classes that were not indicated as official classification by OSM, were removed from the data [48].

LOG-WFP provided the most up to date data on road network damages. However, the road constraint shapefile was updated frequently by overwriting previous versions, without

storing data historically. Therefore, historical post-cyclone status of roads and road segments was manually digitized from pdf maps provided by LOG-WFP [28 29]. The pdf maps were manually cross-referenced with the OSM road network layer, to include post-cyclone status, i.e. 1) open 2) restricted 3) closed.

Roads were then reclassified based on the unique combination of road type and post-cyclone status, resulting in 34 unique road classes (e.g. primary road, primary road restricted, secondary road closed). All roads were given a specific travel speed, accounting for the different scenarios. In the pre-cyclone scenario for instance, all primary road classes (i.e. primary road, primary road restricted, primary road closed) had the same travel speed. Whereas in the post cyclone scenario, the restricted and closed road types had a travel speed and travel mode accounted for their damages, as can be seen from Supplementary 2.

Barriers to movement

Rivers and lake shapefiles were obtained as lines and polygons from the National Directorate for Water Resource Management (DNGRH) and accuracy was checked using satellite imagery as a reference. Only primary rivers and lakes were taken for the analyses, under the assumption that smaller rivers and streams were passable by the population. Water bodies were perceived as being impassable at all scales.

Flood extent caused by Cyclone Idai was taken from 19 March 2019 and flood extent for Cyclone Kenneth was taken from 2 May 2019, because extents were visually inspected and found to be largest on those dates and thus represent the biggest constraints for health care access. All flooded areas were treated as impassable at those dates, considering the depth and extent of the floods.

Population data

High resolution population density estimates for children under five were downloaded at 30 meter resolution from the Facebook Connectivity Lab and Center for International Earth Science Information network [30]. The raster was projected in Mozambique's projection system, UTM-37S [EPSG:32737], by using nearest neighbor interpolation. Loss of population caused by reprojection and clipping to country borders, was corrected for by smoothing the lost population equally over the raster cells, using the raster calculator.

Health facilities

The geographic coordinates of all health facilities were obtained through the Humanitarian Data Exchange platform (HDX) and were originally sourced from the Ministry of Health in Mozambique (SIS-MA). The data was cleaned to exclude coordinates far outside of the country borders. Coordinates that fell just outside Mozambique were relocated within the country extents. Five health facilities were cross-referenced with other data sources (e.g. Neonatal Inventory Survey UNICEF, OpenStreetMap, Google Maps) because they were located on barriers, such as open sea, rivers or lakes.

Information on damaged health facilities was provided by the World Health Organization (WHO). This data did not include GPS coordinates, thus names of the damaged health facilities were cross referenced with the original health facility shapefile to include post-cyclone status of each facility, i.e. functional or non-functional. For damaged health facilities that were not included in the original health facility shapefile, coordinates were retrieved from a neonatal inventory performed by United Nations Children Fund (UNICEF) and also added as facility to the original health facility data, representing the pre-cyclone situation. Non-functional health facilities were filtered-out for geographical accessibility analyses reflecting the post-cyclone scenarios.

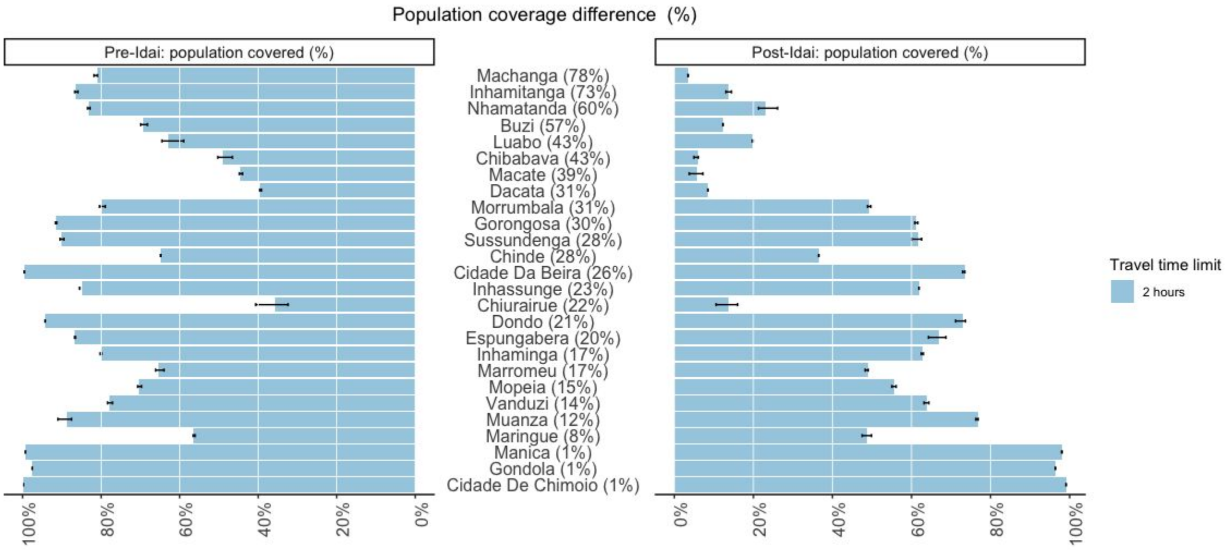
Travel scenario

Both our travel scenarios were developed in close collaboration with country representatives from UNICEF and were adapted to our target population, namely children under five accompanied by a parent (Supplementary 2). Flood waters were assumed to be a full barrier to movement to the target population, thus health facilities located in flooded zones were completely inaccessible and flood waters were impassable.

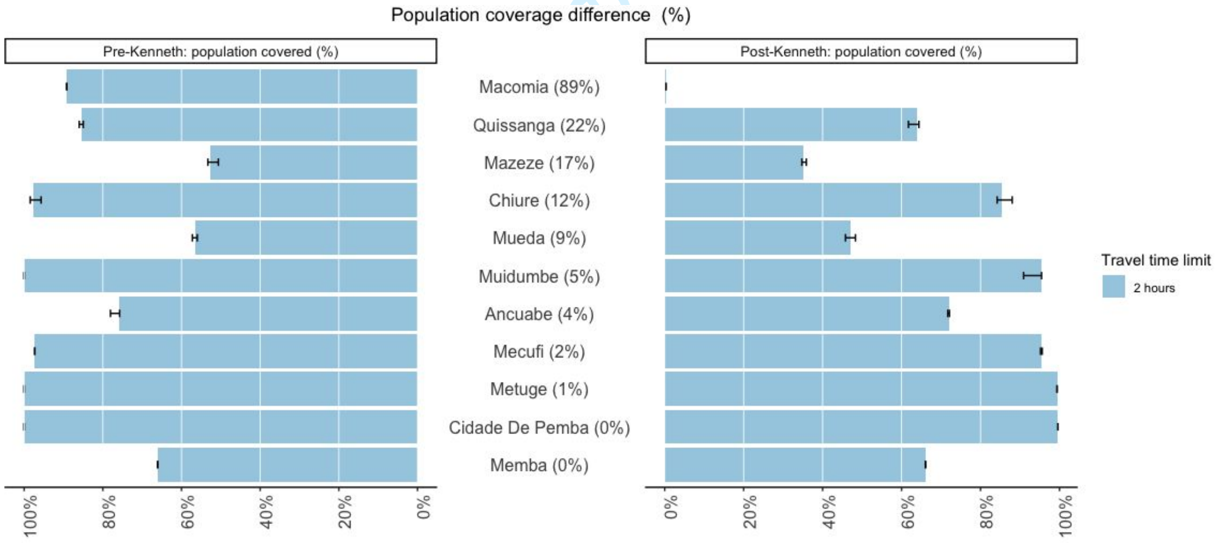
Supplementary 2- Travel scenarios pre-cyclone and post-cyclone

Label	Pre-cyclone		Post-cyclone	
	Travel speed (km/h)	Travel mode	Travel speed (km/h)	Travel mode
Shrubs	3	Walking	1.5	Walking
Herbaceous Vegetation	3	Walking	1.5	Walking
Cultivated and Managed Vegetation Agriculture Cropland	3	Walking	1.5	Walking
Urban Built Up	3	Walking	1.5	Walking
Bare Sparse Vegetation	3	Walking	1.5	Walking
Permanent Water Bodies	3	Walking	1.5	Walking
Temporary Water Bodies	3	Walking	1.5	Walking
Herbaceous Wetland	3	Walking	1.5	Walking
Closed Forest Evergreen Broad Leaf	3	Walking	1.5	Walking
Closed Forest Deciduous Broad Leaf	3	Walking	1.5	Walking
Open Forest Evergreen Broad Leaf	3	Walking	1.5	Walking
Open Forest Deciduous Broad Leaf	3	Walking	1.5	Walking
Open Sea	3	Walking	1.5	Walking
Trunk	80	Motorized	50	Motorized
Trunk Restricted	80	Motorized	1.5	Walking
Trunk Closed	80	Motorized	1.5	Walking
Primary	80	Motorized	50	Motorized
Primary Restricted	80	Motorized	1.5	Walking
Primary Closed	80	Motorized	1.5	Walking
Secondary	50	Motorized	40	Motorized
Secondary Restricted	50	Motorized	1.5	Walking
Secondary Closed	50	Motorized	1.5	Walking
Tertiary	30	Motorized	15	Motorized
Tertiary Closed	30	Motorized	1.5	Walking
Tertiary Restricted	30	Motorized	1.5	Walking
Road	20	Motorized	10	Motorized
Raceway	3	Walking	3	Walking
Residential	20	Motorized	10	Motorized
Residential Closed	20	Motorized	1.5	Walking
Living Street	20	Motorized	10	Motorized
Service	3	Walking	1.5	Walking
Track	15	Motorized	10	Motorized
Pedestrian	3	Walking	1.5	Walking
Pier	3	Walking	1.5	Walking
Path Closed	3	Walking	1.5	Walking
Path	3	Walking	1.5	Walking
Footway	3	Walking	1.5	Walking
Bridleway	3	Walking	1.5	Walking
Cycleway	3	Walking	1.5	Walking
Steps	3	Walking	1.5	Walking
Unclassified	3	Walking	1.5	Walking

Supplementary 3- Relative population coverage pre- and post-cyclone Idai. Ordered on relative difference. Difference indicated between parentheses. Error bars indicate the coverage uncertainty, considering -20% and +20% travel speeds.



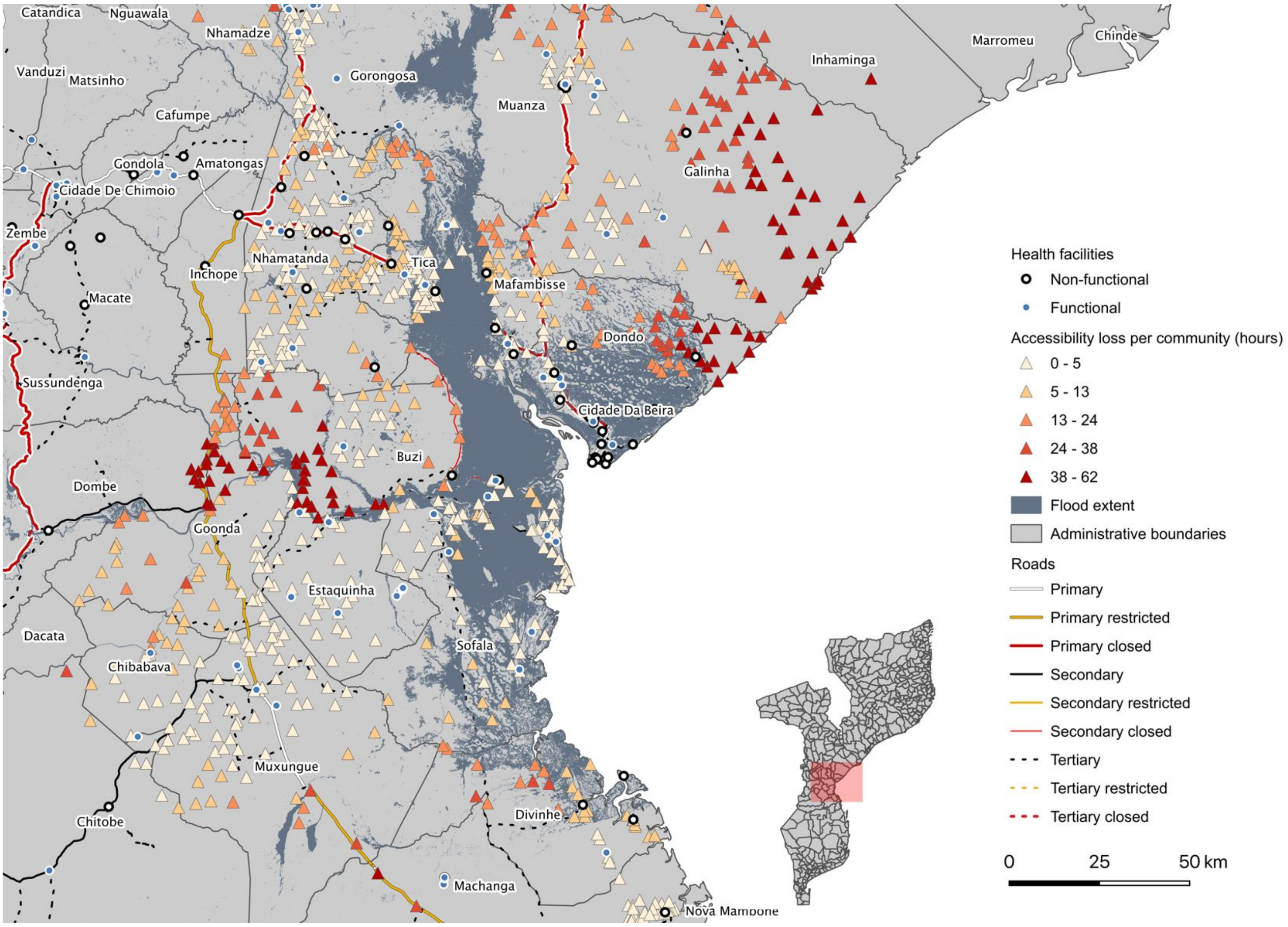
Supplementary 4- Relative population coverage pre- and post-cyclone Kenneth. Ordered on relative difference. Difference indicated between parentheses. Error bars indicate the coverage uncertainty, considering -20% and +20% travel speeds.



Supplementary 5- Travel time per community in Idai affected districts. Fifty most affected communities by means of accessibility loss. Ordered on absolute travel time difference.

Community	District	Pre-cyclone travel time (h)	Post-cyclone travel time (h)	Difference pre- and post-cyclone (h)
Mucinemo	Buzi	1.3	63.6	62.3
Bupira	Buzi	1.1	62.3	61.3
Massuinda	Buzi	1.2	60.1	58.9
Njanga	Buzi	4.3	59.1	54.7
Guenje-Sede	Buzi	2.9	57.3	54.4
Mbereaizique	Buzi	2.9	57.3	54.4
Shiniziua Chinhale	Muanza	24.0	77.8	53.8
Chipota	Muanza	24.4	78.0	53.6
Wiriquizi	Muanza	22.2	74.1	51.9
Chingamuzi	Muanza	22.7	74.5	51.8
Mussacazwidje	Buzi	3.5	55.3	51.8
Mussacazwidje	Buzi	3.5	55.3	51.8
Magua	Buzi	4.8	56.6	51.8
Nkolone Praia	Muanza	20.7	72.3	51.7
Mukulumba 1	Muanza	20.4	71.8	51.4
Mukulumba cidade	Muanza	20.2	71.4	51.2
Nhanganga	Muanza	19.9	70.8	50.9
Mutanda	Buzi	5.4	55.3	49.9
Macova-Mutanda	Buzi	6.3	55.1	48.9
Puanda	Buzi	2.9	51.6	48.7
Luanda 1	Muanza	18.8	67.4	48.6
Nhamacalango	Muanza	17.4	65.8	48.4
Sengo	Dondo	5.3	53.5	48.2
Luanda 2	Muanza	18.0	65.8	47.8
Praia Nova	Dondo	3.9	51.5	47.6
Praia Farol	Dondo	3.8	51.4	47.6
Bingue Sede	Muanza	16.4	63.8	47.4
Nkonde 2	Muanza	16.4	63.8	47.4
Massitche	Dondo	7.1	54.5	47.4
Goonda Majaca	Chibabava	6.5	53.3	46.8
Ngomole	Muanza	10.1	56.7	46.6
Ngalazi	Dondo	6.0	52.3	46.3
Nhacudjica	Buzi	6.3	52.4	46.1
Chitundo	Dondo	2.0	47.7	45.7
Macarate	Chibabava	5.3	51.0	45.7
Nhamissassa	Muanza	15.9	61.5	45.6
Docue	Buzi	5.7	51.3	45.6
Khome 1	Dondo	1.4	46.8	45.4
Nherere 2	Muanza	14.0	59.0	45.0
Parange	Buzi	3.6	48.6	45.0
Njocho	Buzi	5.9	50.9	45.0
Binda	Machanga	0.7	45.2	44.6
Khome 2	Dondo	0.6	45.2	44.6
Veruca	Chibabava	4.1	48.6	44.5
Mamunge	Buzi	5.1	49.2	44.1
Birirane	Muanza	13.1	57.2	44.1
Vala-vala	Buzi	5.2	49.2	44.1
Muche	Gorongosa	1.5	45.5	44.0
Machiquire	Buzi	2.6	46.1	43.5
Nhazwicasse	Gorongosa	1.0	44.5	43.5

Supplementary 6- Travel time per community in Idai affected districts. Point locations of communities in Idai affected districts.



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Modelling geographical accessibility to support disaster response and rehabilitation of a health care system:

An impact analysis of Cyclones Idai and Kenneth in Mozambique

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International health services, organization of health services, geographical mapping, risk management

ABSTRACT

Objectives

Modelling and assessing the loss of geographical accessibility is key to support disaster response and rehabilitation of the health care system. The aim of this study was therefore to estimate post-disaster travel times to functional health facilities and analyze losses in accessibility coverage after Cyclones Idai and Kenneth in Mozambique in 2019.

Setting

We modeled travel time of vulnerable population to the nearest functional health facility in two cyclone-affected regions in Mozambique. Modelling was done using AccessMod 5, where roads, rivers, lakes, flood extent, topography, and land cover datasets were overlaid with health facility coordinates and high-resolution population data to obtain accessibility coverage estimates under different travel scenarios.

Outcome measures

Travel time to functional health facilities and accessibility coverage estimates were used to identify spatial differences between pre-disaster and post-disaster geographical accessibility.

Results

We found that accessibility coverage decreased in the flood affected districts, as a result of reduced travel speeds, road constraints and non-functional health facilities. In Idai-affected districts, accessibility coverage decreased from 78.8% to 52.5%, implying that 136,941 children under 5 were no longer able to reach the nearest facility within 2 hours travel time. In Kenneth-affected districts, accessibility coverage decreased from 82.2% to 71.5%, corresponding to 14,330 children under 5 having to travel more than 2 hours to reach the nearest facility. Damage to transport networks and reduced travel speeds resulted in the most substantial accessibility coverage losses in both Idai and Kenneth-affected districts.

Conclusions

Post-disaster accessibility modelling can increase our understanding of spatial differences in geographic access to care in the direct aftermath of a disaster and can inform targeting and prioritization of limited resources. Our results reflect opportunities for integrating accessibility modelling in early disaster response, and to inform discussions on health system recovery, mitigation and preparedness.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- This is the first study presenting the applicability of post-disaster geographical accessibility modelling.
- The approach enables quantification of disaster impacts on geographical health care accessibility to prioritize post-disaster interventions and to build resilience for future disasters.
- To account for uncertainty of the assumed travel speeds, we considered -20% and +20% intervals on motorized travel speeds.
- Data from various sources and administrative levels were combined to represent the post-cyclone situation as realistically as possible, but since data gathering was ongoing, it was expected that some data were incomplete or not fully processed at the time of usage.
- Our accessibility modelling assumes that patients always travel to the nearest health facility. However, literature has shown that patients sometimes bypass health facilities in search of higher quality care in Mozambique.

1. INTRODUCTION

Geographical proximity to health facilities is a crucial aspect of accessibility, utilization and the provision of health services to populations in need[1]. Road networks and natural barriers (such as rivers, water bodies, and flooded areas) are important factors that determine the geographical (i.e. physical) accessibility of a population to the network of functional health facilities. During natural disasters, roads and health facilities are often damaged, yet health care demand rises substantially at the same time due to injuries and increased communicable disease risks[2,3]. The interplay between the disruption of health infrastructure, transport network, and the rise in health care demand, is known to disable a large portion of the population's access to care they need in the aftermath of a disaster[3,4]. This is especially the case in already medically underserved regions, where the event can lead to new health disparities or exacerbate existing ones[2].

In March and April 2019, two cyclones made landfall in Mozambique. This was the first time in history that two strong cyclones hit Mozambique consecutively in the same season[5]. On 14 March 2019 Tropical Cyclone Idai made landfall in Beira, followed by a week of heavy rains and winds, the storm ended on 21 March 2019[6]. In the middle of the humanitarian emergency response for Cyclone Idai, a second cyclone hit Northern Mozambique. Cyclone Kenneth, a category 4 cyclone and the strongest recorded cyclone on the African continent, made landfall in Pemba, Cabo Delgado on 25 April 2019[7,8]. The two cyclones combined had a death toll of 648, with 603 fatalities due to Idai and 45 deaths caused by Kenneth, and left over 2.2 million people in need of humanitarian assistance[5]. The cyclone's destruction isolated entire communities for weeks due to flood waters, destroyed telecommunication networks, and extensive road damage[9,10]. In addition, stagnant waters, inability in accessing safe water and sanitation, and overcrowding in temporary accommodation led to a cholera outbreak and a significant increase in malaria cases[5,8,11,12]. Major damage to 113 health facilities were reported after both cyclones, causing severe disruption in health service provision and restricting the population's access to adequate health care[13,14]. Although many humanitarian actors have estimated substantial losses in health care accessibility and availability[5,9,10,13,15], the quantitative impact of Cyclone Idai and Kenneth on geographical accessibility to health care remains unknown.

Since 2005 the humanitarian sector applies a *cluster approach* to coordinate emergency operations between all humanitarian response organizations involved[16]. This means that all humanitarian organizations are cooperating in the main sectors of humanitarian action (e.g. water, health, logistics) and have clear responsibilities for coordination[16]. A post disaster needs assessment (PDNA) is the first step in the humanitarian response cycle to formulate a disaster response and recovery plan[17]. Guidelines from the World Health Organization (WHO) for a PDNA for the health cluster specifically, advise on a comparison between baseline and post-disaster accessibility through the evaluation of key indicators in their presented framework[18]. However, the suggested key indicators reflect rather static measures of accessibility, such as hospital beds per 10,000 population or number of damaged health facilities[18]. Yet, international efforts to support humanitarian responses on the ground accelerate post-disaster data gathering, enabling a more realistic quantification of accessibility to health care by means of health facility damages, loss of road access, and barriers to movement such as flood waters[19]. Guidance on assessing loss in geographical accessibility while considering spatial barriers remains abstract or even lacking in disaster management frameworks. Meanwhile, geographical accessibility models hold actionable information and have the potential to quantify gaps and overlaps in (temporary) service provisioning, enabling coordinated, targeted and centralized decision making for humanitarian action[20], enhancing both financial and operational efficiency[21,22].

This study therefore presents a data processing and spatial accessibility modelling method to assess post-disaster accessibility to health facilities and analyze accessibility coverage losses as a result of cyclones Idai and Kenneth in Mozambique. The approach enables quantification of disaster impacts on geographical health care accessibility to prioritize post-disaster interventions and to build resilience for future disasters. This is the first study presenting the applicability of post-disaster geographical accessibility modelling.

2. METHODS

2.1 Overall methodology

In this study, *accessibility* is measured as the travel time to health facilities and *accessibility coverage* (i.e. coverage) is defined as the estimated number or percentage of people covered or located within a travel time catchment area[23]. To model accessibility to health facilities, we consider topography, road networks, constraints to movement (e.g. rivers, lakes and flood extent), target population distribution, and the locations of functional health facilities. We accessed and prepared multiple data layers (Table 1) assembled in the aftermath of Cyclone Idai and Kenneth, between April-September 2019. A total of three scenarios were prepared, representing 1) pre-Idai and pre-Kenneth (before March 2019), 2) post-Idai (up to one-week post-cyclone), and 3) post-Kenneth (up to one-week post-cyclone) situations. We modeled population travel time to the nearest health facility and accessibility coverage, for two cyclone-affected regions.

Table 1 – Overview of data layers and data sources

Layer name	Source[a]	Source date[b]	Download date	Type	Original resolution
Administrative boundaries	INE & UN-OCHA ROSEA (HDX)[24]	02.04.19	31.07.19	Polygon	-
Cyclone trajectory (Idai/Kenneth)	GDACS[25,26]	15.03.19/ 25.04.19	08.03.2020	Polygon	-
Land cover	Copernicus[27]	15.11.18	31.07.19	Raster	100 meters
Elevation	SRTM CGIAR[28]	25.11.18	20.09.19	Raster	30 meters
Rivers and lakes	DNGRH	12.8.19	19.9.19	Polygon	-
Primary streams	DNGRH	12.8.19	19.9.19	Lines	-
Flood extent, Idai	UNOSAT/Sentinel -1 (HDX)[29]	19.03.19	31.07.19	Polygon	-
Flood extent, Kenneth	Copernicus EMSR354 (INGC Geonode)[30]	02.05.19	31.07.19	Polygon	-
Roads	OpenStreetMap (INGC Geonode)[31]	25.11.18	07.08.19	Lines	-
Road damages (Idai/Kenneth)	LOG-WFP[32,33]	19.03.19/ 03.05.19	23.09.19	PDF file	-
Health facilities	SIS-MA (HDX)[34]	31.12.17	08.08.19	Points	-
Health facilities damages	Provided by WHO-Mozambique	Represents health facility status 48h until 1 week post cyclone	17.09.19	Points	-
Population density	Facebook/CIESIN population density[35]	01.10.18	06.08.19	Raster	30 meters

[a] Abbreviations: CIESN = Center for International Earth Science Information Network, DNGRH = National Directorate for Water Resource Management, HDX = Humanitarian Data Exchange, GDACS = Global Disaster Alert and Coordination System, INE = National Institute for Statistics Mozambique, INGC = National Institute for Disaster Management Mozambique, SIS-MA = Ministry of Health Mozambique, SRTM = Shuttle Radar Topography Mission, UN-OCHA ROSEA = United Nations Office for the Coordination of Humanitarian Affairs Southern and Eastern Africa, UNOSAT = United Nations Operational Satellite Applications Program, LOG-WFP = Logistics Cluster World Food Program

[b] Source date represents the imagery acquisition date for the flood extents and the release date for all other data**2.2**

Data sources and preparation

The projection, resolution and alignment of geospatial data was processed using Quantum Geographical Information System (QGIS) (version 3.4)[36] and, to a limited extent, R (version 3.5.2)[37]. As indicated in Table 1, most data layers were retrieved from open data platforms. All rasters and shapefiles were saved in the projection system of Mozambique, i.e. UTM-37S [EPSG:32737]. The data preparation process is briefly described below, and fully detailed in Supplement 1.

Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) in tiles at a resolution of 30 meters and mosaiced to cover the whole country[38]. Slopes were derived from it and accounted for when modelling walking movements.

Land cover data was downloaded for the whole African continent at 100 meter resolution from Copernicus Global Land Service[27] and was clipped to the extent of Mozambique. As analyses were carried out at 30-meter resolution the land cover raster was resampled at a resolution of 30 meters, using nearest neighbor interpolation.

The pre-cyclone road network dataset was retrieved from Open Street Map (OSM) through the Geonode Platform of the National Institute for Disaster Management Mozambique (INGC), and linked to the road damage information as indicated by the Logistics Cluster of the World Food Program (LOG-WFP)[39,40]. Historical post-cyclone status of roads and road segments were manually digitized from PDF maps provided by LOG-WFP. The maps were cross-referenced with the OSM road network layer, to include post-cyclone road damage status, (i.e. 1) open, 2) restricted, and 3) closed). Road damages as a consequence of cyclones Idai and Kenneth were taken from maps dated March 19 and May 3, 2019, respectively (Table 1)[39,40]. Information on road type and damage were combined in order to obtain unique road type-damage combinations (Supplement 2).

Information on rivers and lake layout were obtained as shapefiles from the National Directorate for Water Resource Management (DNGRH). Only primary rivers and lakes were considered as barriers to movement, under the informed assumption that smaller rivers and streams were passable by the population. This assumption was checked for several instances against background satellite imagery. Flood extents for Idai (on 19 March 2019)[29] and Kenneth (on 2 May 2019)[30] were sourced as shapefiles from Sentinel-1 and Copernicus EMSR354, respectively. The flood extents were visually inspected and found to be largest on those two dates, and thus represent the biggest constraints for health care access. All flooded areas were treated under two scenarios: 1) as being impassable, under the assumption that people avoid traversing flood water to prevent further injury, 2) as being passable by foot at an average walking speed of 1.5 km/h. In the first scenario, health facilities located on flood extents were always treated as inaccessible since they are located on barriers.

While cyclones impact entire populations, the burden disproportionately affects children and women [41]. It is estimated that for cyclones Idai and Kenneth more than 50% of the affected population were children, and with flood waters rising above 6 meters, their movements to safety and health care were particularly limited [5]. Moreover, children under 5 represent the age group used as benchmark for child survival targets in both the Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs), as such this cohort is frequently used as baseline[42]. In this context and through the collaborative work with UNICEF, this analysis aimed at informing the impact of the disasters on the burden for specific child health services that target children under 5, (e.g. immunization). We therefore focused our analyses on children under 5.

High-resolution population density estimates for children under five were obtained from the Facebook Connectivity Lab and Center for International Earth Science Information Network (CIESN)[35] with a 30-meter resolution. Although several gridded populations datasets are available, the Facebook CIESN dataset was assumed to have the most realistic reallocation of population to settlements[43]. In addition, other frequently used high resolution gridded population datasets, such as WorldPop[44], use distances from roads and villages as covariates, and this can produce collinearity when used in conjunction with accessibility models. Population density was used to run zonal statistics on the cyclone-affected districts. In this step the total population per district is summed and the estimated absolute number of children under 5 that are able to reach a facility in a pre-defined travel time catchment are calculated.

Additionally, geographic coordinates of all villages (i.e. communities) in Idai-affected districts were obtained from UNICEF Mozambique, which had gathered this information through a community mapping initiative conducted by health officials, 6 to 8 months before Cyclone Idai made landfall. These community locations were used to extract pre- and post-cyclone travel time for each community to the nearest functional health center. Unfortunately, geographic coordinates of villages in Kenneth-affected districts were not available at the time of study.

The geographic coordinates of all health facilities were sourced from the health management information system, Ministry of Health in Mozambique (SIS-MA). Data cleaning was undertaken in cases where the geographic coordinates for health facilities were located outside the international border of Mozambique or for coordinates falling on barriers to movement (Supplement 1). Information on damaged health facilities was provided in tabular format by the World Health Organization (WHO). The health system in Mozambique comprises 4 levels; the primary level consists of urban and rural health centers, the secondary level consists of general, rural and district hospitals, the tertiary level comprises provincial capital hospitals, and quaternary facilities comprise the central and specialized hospitals[45]. Health facilities of all levels were included in the model.

Districts that were most affected by Cyclones Idai and Kenneth ("cyclone-affected districts", thereafter) were identified in close collaboration with UNICEF and humanitarian responders. All statistics presented below were calculated for these identified districts, with 26 such districts in the Idai-affected region and 11 districts in the Kenneth-affected region (Figure 1a & 1b). Storm trajectories of both cyclones and road damages in both districts are also presented (Figure 1c-1f).

2.3 Geographical accessibility modelling

To model travel times and accessibility coverages, we used AccessMod 5 (version 5.6.30), in particular the “accessibility” and “zonal statistics” modules[23,46]. AccessMod models geographic accessibility using terrain-based least-cost path distance calculation. This open-source software has been successfully applied in many different settings, among which accessibility and referral assessments of health facility networks, optimization modelling of health programs in obstetric and neonatal care (EmONC)[47], primary health care[48], emergency care[49], referral times[50], and treatment of fever cases[51].

Using the “merge land cover” module in AccessMod, we overlaid the roads, rivers, lakes, flood extent, and landcover datasets to obtain a single 30-m resolution raster dataset, to which different travel scenarios were applied.

The travel scenarios (presented in Supplement 2) were derived using local information as model inputs on pre-cyclone and post-cyclone travel speeds and travel modes. Both scenarios were developed in close collaboration with UNICEF Mozambique, with focus on geographical accessibility to functional health facilities for the target population of children under 5. Post-cyclone travel speeds were adjusted for wet weather conditions as heavy rains persisted in the direct aftermath of both cyclones. During the post-cyclone situation, restricted and closed roads that were not inundated were assumed to be unpassable by any vehicle; but they were perceived to be accessible by foot. All landcover classes outside of the road network and the barriers were considered as passable. We assumed a functional bridge where a road segment crossed a river.

To account for uncertainty of the assumed travel speeds, we also considered both pre- and post-cyclone motorized travel speeds with a 20% slower and 20% faster speed, as adapted from Ouma et al.[49]. Accessibility coverage of the network of health centers was calculated at the 2-hour maximum travel time limit. This limit was deemed appropriate to capture the extent of effective access, and is often used in health accessibility studies, notably in maternal health[47].

FIGURE 1

2.4 Patients and the public involvement

There was no patient or public involvement in this study. Health facility functionality status was shared in tabular format by WHO. All other geospatial data were publicly available.

3. RESULTS

All statistics mentioned in the results are estimates of children covered by functional health facilities based on our accessibility model.

3.1 Pre-cyclone accessibility

Pre-cyclone coverage in Idai-affected districts (Figure 2a) was highest in Cidade De Chimoio and Cidade Da Beira, with 99.8% and 99.5% of all children under 5 covered within the 2 hour catchment limit, respectively (Supplement 3). However, this coverage ranged from 35.8-99.8% in all Idai-affected districts (Supplement 3). Absolute pre-cyclone coverage was also highest in Cidade De Chimoio and Cidade Da Beira, where 57,476, and 66,135 children were within 2 hours travel time from a health facility (Figure 2). In Kenneth-affected districts (Figure 2b), pre-cyclone coverage was highest in Cidade De Pemba, where 100% of the children under 5 were expected to be able to reach a health facility within 2 hours travel time (Supplement 4). The lowest pre-cyclone coverage was seen in Mazeze, where only 52.6% of children under 5 were within 2 hours travel time from a health facility (Supplement 4). Absolute pre-cyclone coverage in Kenneth-affected districts was highest in Cidade De Pemba (n = 35,467 children) and Chiure (n= 18,257 children) (Figure 2). Pre-cyclone travel time rasters for the cyclone-affected areas were mapped (Figure 3A & Figure 4A).

FIGURE 2

3.2 Losses in accessibility coverage

Geographical accessibility to health care decreased in the cyclone-affected districts, as a result of reduced travel speeds, road constraints and non-functional health facilities (Figure 3B and Figure 4B). Ratios of pre-cyclone and post-cyclone travel time rasters are mapped for Idai-affected districts, with ratios close to 1 indicating similar travel times pre- and post-cyclone, and ratios closer to 0 indicating large pre- and post-cyclone accessibility differences

(Figure 3C). The same results for Kenneth-affected districts are presented (Figure 4C). Regions shown in red indicate localities with relatively large differences between pre- and post-cyclone travel times (Figure 3C). In the Idai-affected region, especially in the districts surrounding the flood water and closed roads, accessibility is severely impacted. In Idai-affected districts, the percentage of children under 5 covered within 2 hours travel time, generally decreased from 78.8% to 52.5%, implying that 136,941 previously covered children under 5, lost timely access to health care (Table 2).

Table 2- Overview of pre- and post-cyclone accessibility coverage in Idai and Kenneth-affected districts.

		Pre-cyclone		Post-cyclone			
Cyclone	**Travel time**	**Children <5 covered (nr.)**	**Children <5 covered (%)**	**Children <5 covered (nr.)**	**Children <5 covered (%)**	**Children <5 coverage loss (nr.)**	**Children <5 coverage loss (%)**
Idai	30 minutes	298,432	57.3	153,842	29.5	144,591	27.7
	1 hour	346,409	66.5	206,610	39.6	139,799	26.8
	2 hours	410,696	78.8	273,755	52.5	136,941	26.3
Kenneth	30 minutes	131,120	72.0	63,953	48.8	304,15	23.2
	1 hour	99,056	73.8	86,997	64.8	12,060	9.0
	2 hours	110,348	82.2	96,019	71.5	14,330	10.7

The largest relative accessibility coverage decline, within 2 hours travel time, was observed in Machanga, where 77.6% of the previously covered population was no longer able to access a facility under 2 hours in the aftermath of Idai (Figure 2). In terms of absolute coverage, Nhamatanda was the most affected district, with a coverage loss of 25,121 children under 5, followed by Morrumbala (n = 19,554 children), Cidade Da Beira (n = 17,355 children), and Buzi (n= 9,949 children) (Figure 2). Uncertainty modelling, by accounting for 20% slower and 20% faster motorized travel speeds[49], indicated localities with travel time differences up to 3-hours comparing slower and faster travel speeds (Figure 3D & Figure 4D). This information indicates where our travel time assumptions have the largest effect on accessibility and coverage losses and where this may be either under- or overestimated based which can help guide resource allocation for decreasing this uncertainty.

Relative accessibility coverage in all Kenneth-affected districts decreased from 82.2% to 71.5%, corresponding to 14,330 children having lost access to the nearest facility within 2 hours travel time (Table 2). The most affected district in terms of relative coverage loss was Macomia, where 88.9% of the children that were covered pre-cyclone lost access (Supplement 3 & 4). Mazeze was the most affected district in terms of absolute coverage loss, as 5,496 children lost access in the aftermath of cyclone Kenneth, followed by Macomia (n= 3,727 children), Chiure (n= 2,307 children), Quissanga (n= 1,270 children) and Mueda (n= 750 children) (Figure 2).

Since flood waters slowly receded in the days/weeks after the cyclones, we ran an additional scenario where flood waters were passable at a 1.5km/h walking speed. Considering this scenario, absolute coverage losses for Idai-affected districts within 2 hours travel time were highest in Morrumbala (n= 29,566 children), Nhamatanda (n= 25,758 children), Dacata (n= 8,914 children), and Bùzi (n= 8,757 children). In Kenneth-affected districts, Mazeze (n= 6,167 children), Chiure (n= 4,684 children) and Macomia (n= 3,727 children) had the highest coverage losses in 2 hour catchments under the passable scenario.

3.3 Travel time in affected communities

The most affected villages in Idai-affected districts, in terms of reduced accessibility to the nearest health facility were communities located in Bùzi and Muanza districts in Sofala province. Mucinemo in Bùzi district was found to have a pre-cyclone travel time of 1.3 hours to the nearest health facility. However, this travel time upsurged to 63.6 hours in the direct aftermath of cyclone Idai (Supplements 5 & 6). Generally, the 6 most affected communities in terms of accessibility in Idai-affected districts all had a pre-cyclone travel time between 1 hour and 3 hours, while all post-cyclone travel times increased to over 55 hours (Supplement 6). Overall, post-cyclone accessibility ranged from some minutes up to 78 hours, with the highest travel time found in Chipota, in Muanza district.

FIGURE 3 & 4

3.4 Health facility closures

The effect of non-functioning health facilities were isolated by comparing two separate scenarios; 1) a post-cyclone scenario where all health facilities were considered functional, and 2) a post-cyclone scenario where modified functionality status was considered. By comparing these pre-cyclone and post-cyclone scenarios, the coverage losses caused by the transportation-specific disruptions (i.e. adjusted travel speeds and road constraints) could be isolated from the reduction in coverage due to the damage to health facilities (i.e. non-functional health facilities), providing a way to assess the likely impact of future programs aimed at reinforcing health facilities for disasters. In order to make these comparisons in this specific example, both scenarios were run under the assumption that flood waters were fully passable. In all other instances throughout the paper, flood waters were considered impassable. In case all health facilities remained functional in Idai-affected districts (i.e. disruption was due to transportation only), the overall coverage within 2 hours travel time would decrease from 79.3% to 57.7%, a difference of 21.6% (n = 112,538 children). Damage to health facilities caused an additional coverage decline of 5.3% (n = 27,840 children) in Idai-affected districts. However, hospital closures did not evenly affect all districts. In 17 out of 26 Idai-affected districts, hospital closures had no additional effect on accessibility. However, in the remaining 9 Idai-affected districts, hospital closures were responsible for an additional 1.9-59.7% coverage loss within 2 hours catchment. Health facility closures in Machanga affected the relative coverage the most, with 59.7% coverage loss (n= 3,642 children) caused by non-functionality of 3 out of 6 health facilities. Absolute coverage losses as an effect of non-functional health facilities, were highest in Nhamatanda, where 12,946 (31.0%) children under 5 years old lost access due to health facility closures. In Nhamatanda, 9 out of 16 health facilities became unfunctional as a consequence of Cyclone Idai. Health facility closures did not have an additional effect on post-cyclone accessibility in Kenneth-affected districts.

4. DISCUSSION

Accessibility coverage decreased and travel times substantially increased, in the direct aftermath of the cyclones. Damage to transport networks and reduced travel speeds resulted in the most substantial accessibility coverage losses in both Idai- and Kenneth-affected districts. In Kenneth-affected districts, it was found that hospital closures did not have an additional effect on post-cyclone accessibility this is likely caused by the fact that flood extents and hospital closures were of much smaller magnitudes in the Kenneth-affected region than in the Idai-affected region.

In a post-disaster setting, access to health care is essential for effective response and recovery[52]. The results of our study can be implemented beyond the response phase of the cyclones. Although the emphasis of the results is on identification of decreased accessibility coverage directly after the cyclones, the information presented here also provides a platform for discussing health system recovery, mitigation and preparedness[53].

Early identification of underserved districts in the response phase can help reduce the impacts caused by health service interruption, through targeted deployment of medical services in districts with largest accessibility coverage losses and lowest baseline accessibility[54]. Information on accessibility coverage losses per cyclone-affected district can support decision-making in the prioritization and planning of these medical services, by targeting where the deployment of medical services reaches the highest number of people. Growing access to open data and post-disaster information enables prompt accessibility modelling in the aftermath of a natural disaster and the growing ability to quickly assemble this data provides an opportunity to integrate accessibility modelling in the early response phase of a natural disaster, so resources can be allocated in an informed way and health impacts can be reduced. In this specific study, all data for an initial post-cyclone accessibility study became available between 1 week and 1 month post-disaster (Table 1). This allows for an accessibility analysis in the early stages of a disaster response. Generally, data on flood extents and road damages, acquired from satellite imagery, were downloadable within 1 week post-disaster. Whereas information that had to be ground validated, such as health facility functionality, became available approximately 1 month post-disaster.

Furthermore, the extensive damages to the road network will continue to limit movements of the population, further complicating physical accessibility[5]. Our results indicate that road damages are responsible for a relatively large loss of accessibility. This calls for a concerted effort between road and health authorities when prioritizing reconstruction efforts. It was estimated by WHO that damages to (health) infrastructure translated into 200,000 people living more than 5 kilometers from a functioning health facility[55]. However, our results, which provide a more realistic representation of accessibility, by accounting for topography, barriers to movement, and population distribution, suggest this figure is an underestimate. We estimated that as a result of the damage to infrastructure and barriers to movement, 314,591 children under 5 live further than 1 hour travelling from a functioning health facility.

Fourteen percent of all health facilities in Cyclone Idai- and Kenneth-affected cyclone-districts have been damaged or fully destroyed, although more health facilities were temporarily impacted in service provisioning due to flooding, electricity constraints or damage to equipment [14,56]. While it is critical to restore access to essential health services as soon as possible, the WHO reported that the reconstruction of all destructed and damaged facilities may take up to 5 years[14]. To restore baseline accessibility, the establishment of mobile outreach units, deployment of community health workers (CHWs), together with the reconstruction of damaged facilities should be implemented. However, under the umbrella of *Building Back Better* (BBB), rebuilding more resilient facilities and infrastructure, that are able to withstand future hazards under the “Hospitals Safe from Disasters” approach, are needed to prevent similar impacts in future disasters[55,56]. The results presented here show the importance of joint efforts to reduce both impacts on health facilities and the existing road network. However, resources are limited, and efficient financial planning is needed to outline health system investment plans[5,11]. The results of our accessibility modelling can be used to prioritize health facility reconstruction for facilities with highest accessibility coverages. Cyclone Idai for instance, caused the destruction of the only tertiary hospital in 4 affected provinces that serves an estimated 12 million people[52]. Targeting hospitals with coverage numbers like these, to be strengthened for future disaster impacts and to support them in providing continuity of care in the aftermath of future disasters can help reduce health losses[57].

Due to the persisting health system disruption, humanitarian responders have identified the need to deploy community health workers (CHWs) and mobile outreach services to cover accessibility losses caused by the cyclones and to extend the reach of existing functional services[52,58]. These study findings can assist policymakers in identifying and prioritizing severely impacted districts and communities and regions where deployment of CHWs can make a difference. Supplementary material 3 to 6 present the most affected communities in terms of increased travel time and coverage losses, directly post-cyclone. These analyses can be routinely updated to assess the effect of health system recovery on accessibility. The districts that were most affected by Cyclone Idai and Kenneth were historically, and are in the future, also prone to disasters due to their topography (i.e. coastal cities, cyclone belt Indian Ocean, and low elevation)[52,55]. Ideally, accessibility modelling could be applied to simulate the effects of historical disasters on accessibility, as indicated in Supplement 5 and Supplement 6, so targeted preventive measures can be taken for future disasters. Post-disaster accessibility modelling can help identify weak spots in geographical accessibility to the health system and helps to distinguish pre-existing accessibility gaps (Figure 3A and 4A) from accessibility coverage losses as a result of disasters (Figure 3B and 4B). This information is essential in health system recovery, strengthening and preparing for future disasters.

Limitations and uncertainties of this study were primarily linked to the data. While the occurrence of natural disasters generally accelerates data availability in affected countries, there also are challenges of data quality, consistency, and format[59]. In this study, data from various sources were combined to represent the post-cyclone situation as realistically as possible, but since data gathering was ongoing, it was expected that some data were incomplete or not fully processed at the time of usage. Health facility coordinates for instance had duplicate occurrences in the database and health facility damages were solely indicated by name, which resulted in manual spatial merging. Co-occurrences of rivers that were indicated as floods were seen in the flood extent layer, minimally overestimating actual flood extents in some parts of the affected regions. Besides post-disaster data uncertainty, pre-disaster spatial data were also checked against background satellite imagery. The hydrography of primary rivers stored in the data was found not to be fully representative for actual hydrography in some regions. This could be a consequence of digitizing against a less granular spatial resolution[60]. In some cases, passages and bridges were detected on satellite background imagery where the OpenStreetMap road layer did not present presence of roads. In places where hydrography is potentially overestimated and not all roads are mapped, isolated land pockets are created in the merged land cover. When modelling accessibility in these land pockets the population is assumed to be fully isolated from health care.

Next to data uncertainties, travel scenarios present a source of uncertainty as assumptions on travel speeds and modes are uniformly generalized across regions. In addition, we assumed that roads indicated as being restricted or closed, were considered only passable by foot if they were not inundated. However, some of the restricted roads were in fact passable by 4x4 vehicles. Other means of transport (e.g., bicycle, motorcycle) may also have been used in some places, which would increase accessibility to health centres. Since car ownership and access to motorized transport by the target population was expected to be very low, especially post-cyclone, it was decided to run the accessibility model for restricted and closed roads only by means of walking.

Our accessibility modelling assumes that patients always travel to the nearest health facility. However, literature has shown that patients sometimes bypass health facilities in search of higher quality care in Mozambique[61,62]. Previous research, has shown that 30.8% of pregnant women bypassed the nearest health facility in search of better prenatal care[61]. Our results can therefore present slight underestimations of actual travel times.

Despite some of the limitations, the results presented here provide important initial information for post-cyclone health system recovery which can be expanded through future research. Since post-disaster needs continuously change based on the nature of the event (e.g. receding flood waters, reconstruction efforts, and deployment of temporary medical services), following studies should also be focused on the ability to dynamically model accessibility based on these changes, so accessibility can be continuously monitored and humanitarian service delivery can be updated accordingly in disaster-affected districts. Additionally, it would be interesting to assess the effect of CHW deployment and mobile outreach communities on improved accessibility and accessibility coverage estimates, to quantify the effect of these interventions.

Post-disaster accessibility modelling can increase our understanding of spatial differences in health care needs in the direct aftermath of a disaster and can help target limited resources efficiently. Currently, there is no standardized approach in the humanitarian program cycle to assess post-disaster accessibility losses against baseline accessibility[18]. The lack of a standardized methodology to spatially assess disaster impacts on accessibility can result in uncoordinated decision making for temporary health facility locations, introducing duplication probability, and complicates prioritization in recovery efforts. The results in this paper not only reflect the importance of incorporating accessibility modelling in early disaster response, but also provide a platform for discussing health system recovery, mitigation and preparedness.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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AUTHOR CONTRIBUTION

Fleur Hierink: conceptualization, methodology, formal analysis, writing, editing, visualization, supervision. **Nelson Rodrigues:** data sharing, methodology, writing, editing, validation. **Maria Muñiz**: writing, editing. **Rocco Panciera:** methodology, writing, editing. **Nicolas Ray:** conceptualization, methodology, writing, editing, validation, supervision.

DATA SHARING STATEMENT

Data available upon request.

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Figure legends:

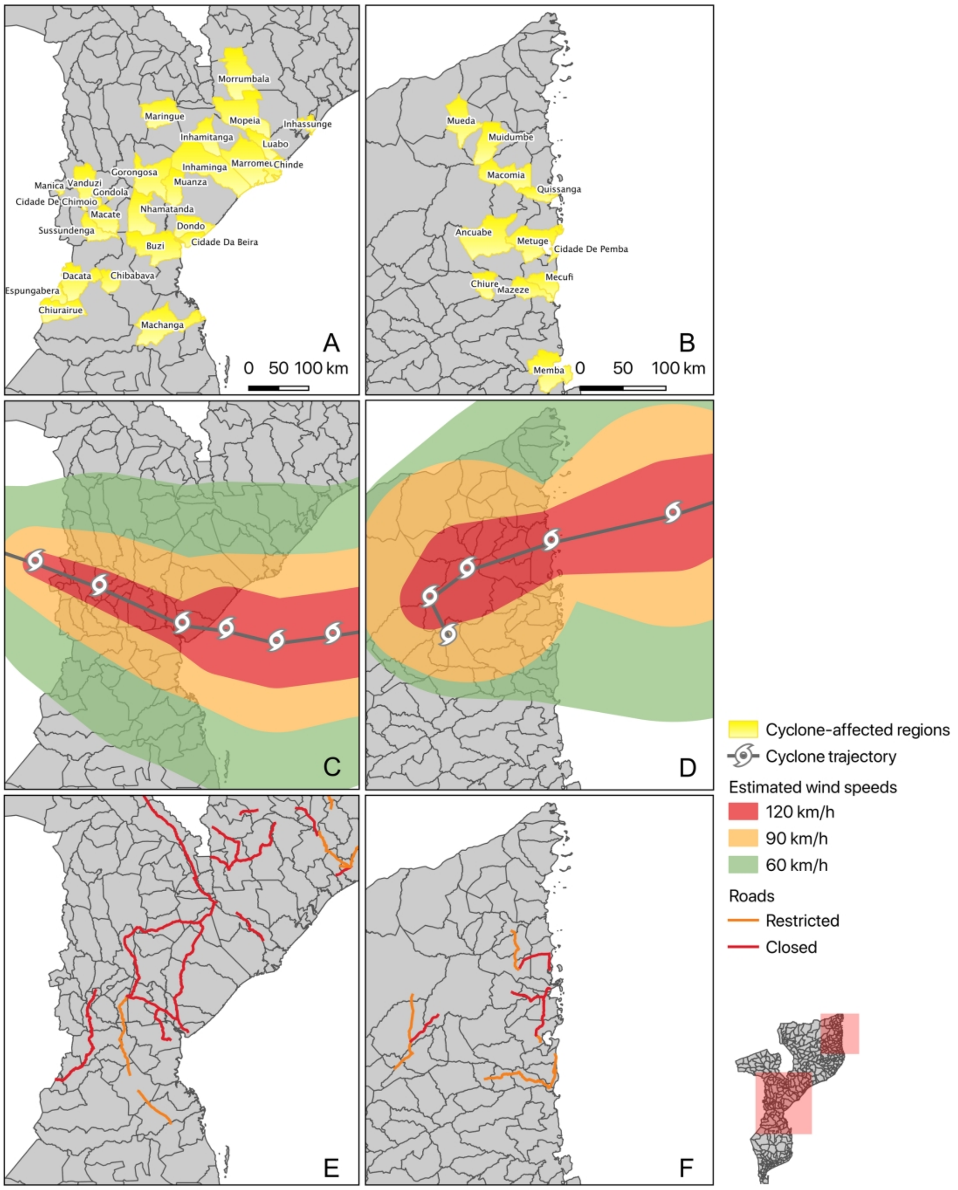
Figure 1 - Cyclone affected districts, cyclone trajectory, and road damages. (A) Idai affected districts. (B) Kenneth affected districts. (C) Idai cyclone trajectory*. (D) Kenneth cyclone trajectory*. (E) Road damages in Idai-affected districts. (F) Road damages in Kenneth-affected districts.

*Cyclone paths as reported on Global Disaster Alert and Coordination System (GDACS)[25,26].

Figure 2- Absolute and relative reduction in population coverage pre- and post-cyclone Idai (A) and Kenneth (B). Labels on top of bars indicate absolute reduction in population coverage of children under 5. Labels under districts indicate relative reduction in population coverage. Maximum limits of the bars indicate the absolute pre-cyclone coverage within 2 hours travel time. Limits of the blue filled bar indicate the absolute post-cyclone coverage. The x-axis is ordered according to relative reduction in population coverage.

Figure 3 – Accessibility modelling results for Idai districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).

Figure 4 – Accessibility modelling results Kenneth districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).



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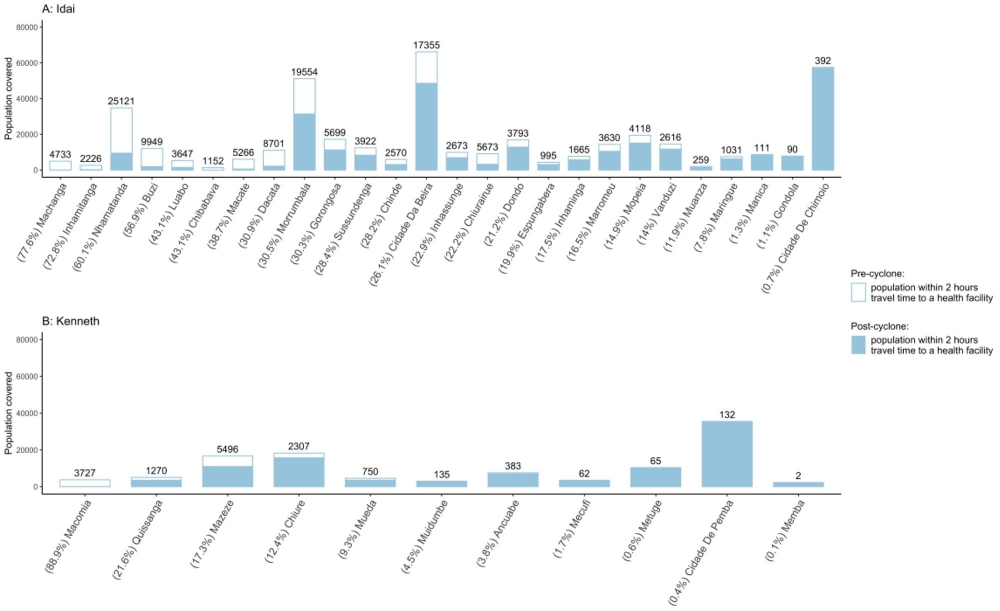

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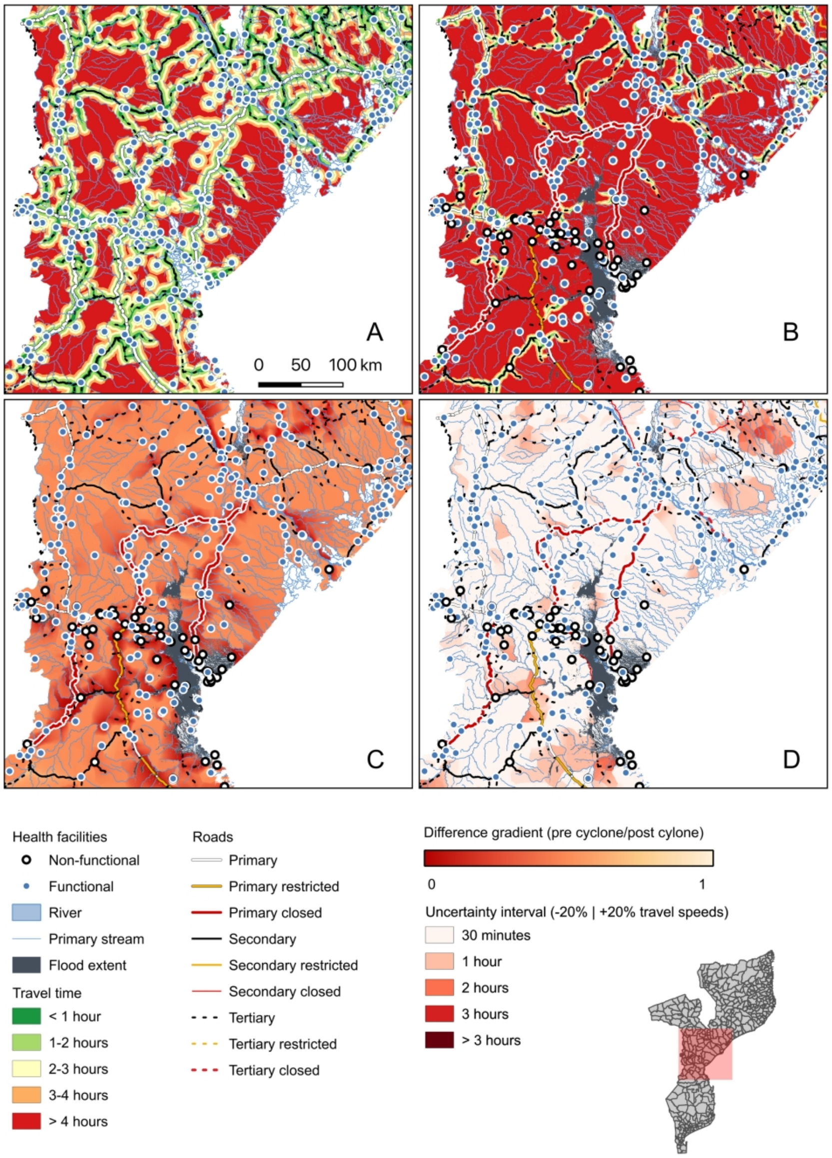

Figure 3 – Accessibility modelling results for Idai districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).

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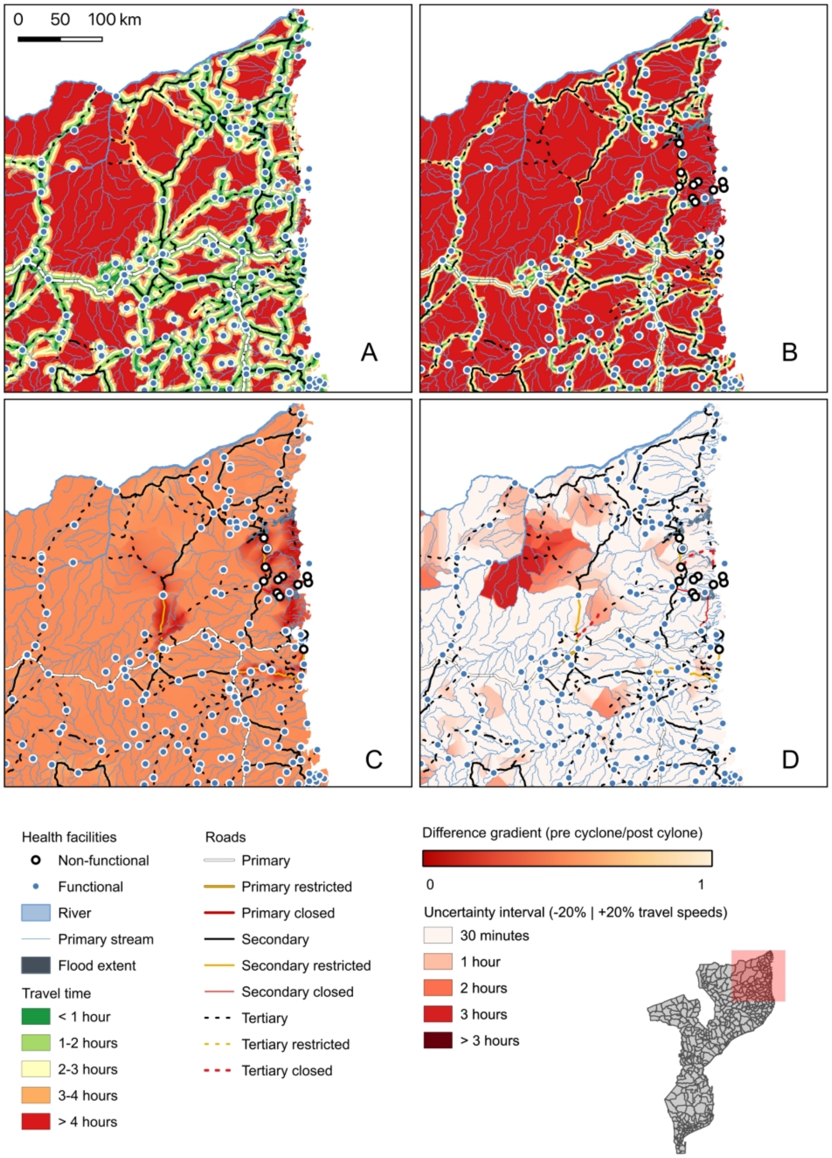

Figure 4 – Accessibility modelling results Kenneth districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).

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SUPLEMENTARY MATERIAL

Supplement 1-Data preparation for use in AccessMod

All data preparation was carried out in Quantum Geographical Information System (QGIS) (version 3.4)[24] in limited combination with R (version 3.5.2)[25]. As indicated in Table 1, most data layers were retrieved from open data platforms. All raster- and shapefiles were saved in the projection system of Mozambique, i.e. UTM-37S [EPSG:32737]. All raster files were aligned using the digital elevation model (DEM) as reference. The data preparation process is fully described below for each data set.

Elevation

Anisotropic accessibility analyses, in other words analyses accounting for travel speeds on slopes, were carried out for this study. Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) in tiles at a resolution of 30 meters and mosaiced to cover the whole country[38]. Slopes were derived from it and accounted for when modelling walking movements.

Land cover

The land cover data set of the African continent[27] was clipped to the extent of Mozambique, leaving a small buffer around the country to prevent loss of data cells at the border. The data set was resampled at a resolution of 30 meters using nearest neighbor interpolation.

Road network

The pre-cyclone road network dataset was retrieved from Open Street Map (OSM) through the Geonode Platform of the National Institute for Disaster Management Mozambique (INGC), as this dataset was perceived to represent the most recent information on the roads and could be linked to the damaged roads, as indicated by the Logistics Cluster of the World Food Program (LOG-WFP). Road classes that were not indicated as official classification by OSM, were removed from the data[48].

LOG-WFP provided the most up to date data on road network damages. However, the road constraint shapefile was updated frequently by overwriting previous versions, without

storing data historically. Therefore, historical post-cyclone status of roads and road segments was manually digitized from PDF maps provided by LOG-WFP[28,29]. The PDF maps were manually cross-referenced with the OSM road network layer, to include post-cyclone status, i.e. 1) open 2) restricted 3) closed.

Roads were then reclassified based on the unique combination of road type and post-cyclone status, resulting in 34 unique road classes (e.g. primary road, primary road restricted, secondary road closed). All roads were given a specific travel speed, accounting for the different scenarios. In the pre-cyclone scenario for instance, all primary road classes (i.e. primary road, primary road restricted, primary road closed) had the same travel speed. Whereas in the post cyclone scenario, the restricted and closed road types had a travel speed and travel mode accounted for their damages, as can be seen from Suplement 2.

Barriers to movement

Rivers and lake shapefiles were obtained as lines and polygons from the National Directorate for Water Resource Management (DNGRH) and accuracy was checked using satellite imagery as a reference, using Microsoft Bing Imagery as a background through the QGIS QuickMapServices Plugin. Only primary rivers and lakes were taken for the analyses, under the assumption that smaller rivers and streams were passable by the population. Water bodies were perceived as being impassable at all scales.

Flood extent caused by Cyclone Idai was taken from 19 March 2019 and flood extent for Cyclone Kenneth was taken from 2 May 2019, because extents were visually inspected and found to be largest on those dates and thus represent the biggest constraints for health care access. All flooded areas were treated as impassable at those dates, considering the depth and extent of the floods.

Population data

High resolution population density estimates for children under five were downloaded at 30 meter resolution from the Facebook Connectivity Lab and Center for International Earth Science Information network[30]. The raster was projected in Mozambique's projection system, UTM-37S [EPSG:32737], by using nearest neighbor interpolation. Loss of population caused by reprojection and clipping to country borders, was corrected for by smoothing the lost population equally over the raster cells. This was done by using a multiplication factor of the difference between the total sum of population before and after data processing using the raster calculator.

Health facilities

The geographic coordinates of all health facilities were obtained through the Humanitarian Data Exchange platform (HDX) and were originally sourced from the Ministry of Health in Mozambique (SIS-MA)[34]. The data was cleaned to exclude coordinates far outside of the country borders. Coordinates that fell just outside Mozambique were relocated within the country extents. Five health facilities were cross-referenced with other data sources (e.g. Neonatal Inventory Survey UNICEF, OpenStreetMap, Google Maps) because they were located on barriers, such as open sea, rivers or lakes.

Information on damaged health facilities was provided by the World Health Organization (WHO). This data did not include GPS coordinates, thus names of the damaged health facilities were cross referenced with the original health facility shapefile to include post-cyclone status of each facility, i.e. functional or non-functional. For damaged health facilities that were not included in the original health facility shapefile, coordinates were retrieved from a neonatal inventory performed by United Nations Children Fund (UNICEF) and also added as facility to the original health facility data, representing the pre-cyclone situation. Non-functional health facilities were filtered-out for geographical accessibility analyses reflecting the post-cyclone scenarios.

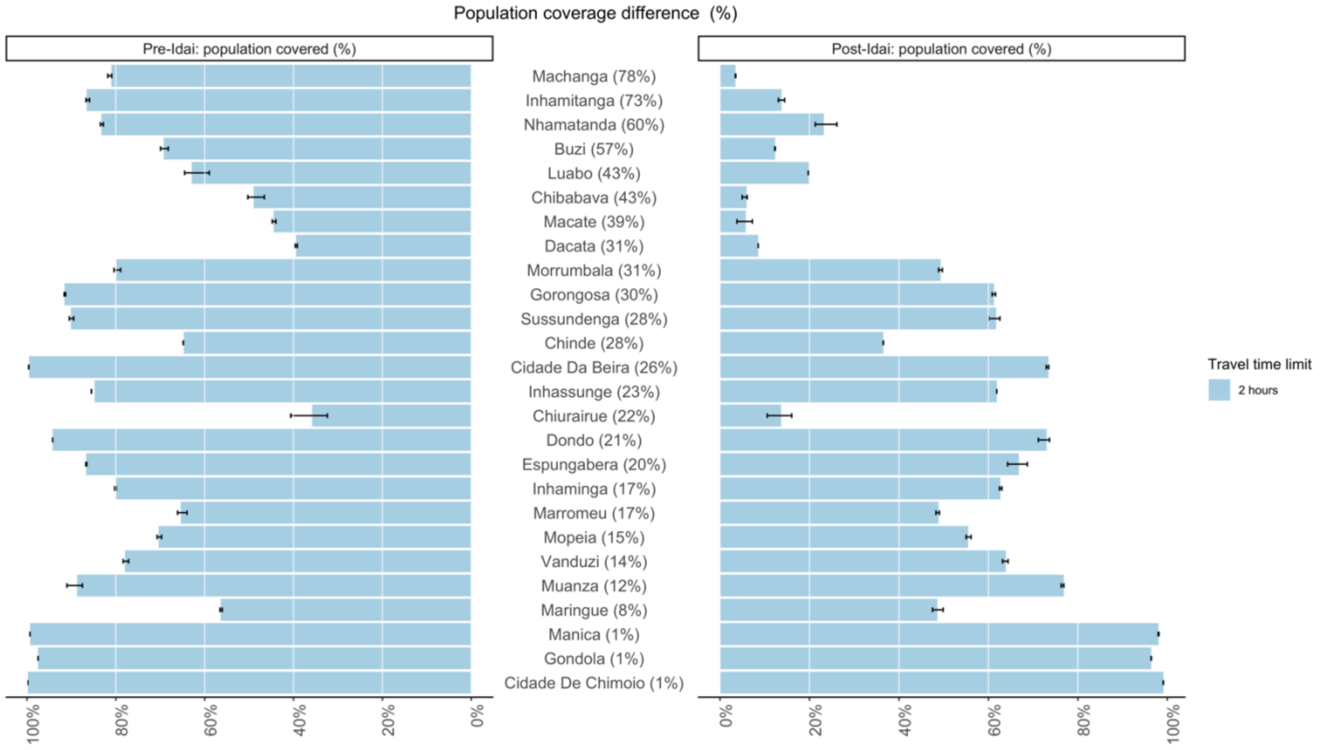
Travel scenario

Both our travel scenarios were developed in close collaboration with country representatives from UNICEF and were adapted to our target population, namely children under five accompanied by a parent (Suplement 2). Flood waters were assumed to be a full barrier to movement to the target population, thus health facilities located in flooded zones were completely inaccessible and flood waters were impassable.

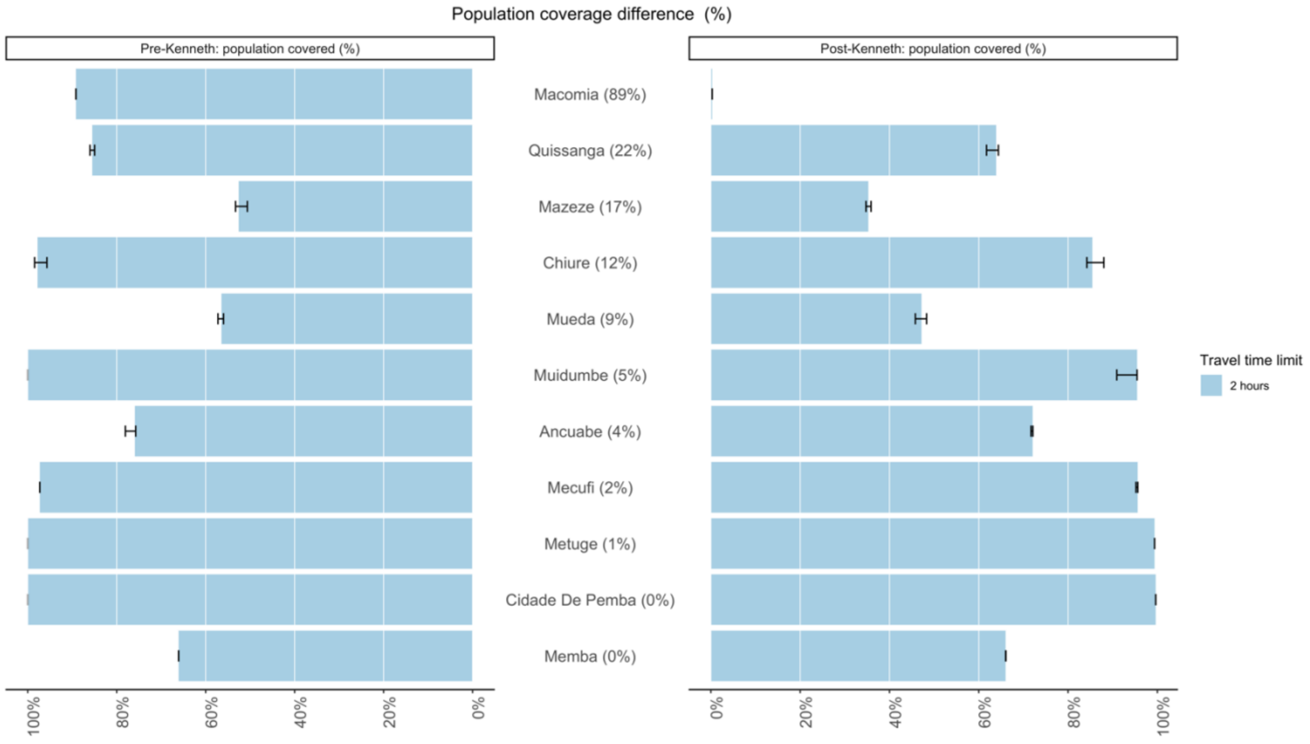
Supplement 2- Travel scenarios pre-cyclone and post-cyclone

Label	Pre-cyclone		Post-cyclone	
	Travel speed (km/h)	Travel mode	Travel speed (km/h)	Travel mode
Shrubs	3	Walking	1.5	Walking
Herbaceous Vegetation	3	Walking	1.5	Walking
Cultivated and Managed Vegetation Agriculture Cropland	3	Walking	1.5	Walking
Urban Built Up	3	Walking	1.5	Walking
Bare Sparse Vegetation	3	Walking	1.5	Walking
Permanent Water Bodies	3	Walking	1.5	Walking
Temporary Water Bodies	3	Walking	1.5	Walking
Herbaceous Wetland	3	Walking	1.5	Walking
Closed Forest Evergreen Broad Leaf	3	Walking	1.5	Walking
Closed Forest Deciduous Broad Leaf	3	Walking	1.5	Walking
Open Forest Evergreen Broad Leaf	3	Walking	1.5	Walking
Open Forest Deciduous Broad Leaf	3	Walking	1.5	Walking
Open Sea	3	Walking	1.5	Walking
Trunk	80	Motorized	50	Motorized
Trunk Restricted	80	Motorized	1.5	Walking
Trunk Closed	80	Motorized	1.5	Walking
Primary	80	Motorized	50	Motorized
Primary Restricted	80	Motorized	1.5	Walking
Primary Closed	80	Motorized	1.5	Walking
Secondary	50	Motorized	40	Motorized
Secondary Restricted	50	Motorized	1.5	Walking
Secondary Closed	50	Motorized	1.5	Walking
Tertiary	30	Motorized	15	Motorized
Tertiary Closed	30	Motorized	1.5	Walking
Tertiary Restricted	30	Motorized	1.5	Walking
Road	20	Motorized	10	Motorized
Raceway	3	Walking	3	Walking
Residential	20	Motorized	10	Motorized
Residential Closed	20	Motorized	1.5	Walking
Living Street	20	Motorized	10	Motorized
Service	3	Walking	1.5	Walking
Track	15	Motorized	10	Motorized
Pedestrian	3	Walking	1.5	Walking
Pier	3	Walking	1.5	Walking
Path Closed	3	Walking	1.5	Walking
Path	3	Walking	1.5	Walking
Footway	3	Walking	1.5	Walking
Bridleway	3	Walking	1.5	Walking
Cycleway	3	Walking	1.5	Walking
Steps	3	Walking	1.5	Walking
Unclassified	3	Walking	1.5	Walking

Supplement 3- Relative population coverage pre- and post-cyclone Idai. Ordered on relative difference. Difference indicated between parentheses. Error bars indicate the coverage uncertainty, considering -20% and +20% travel speeds.



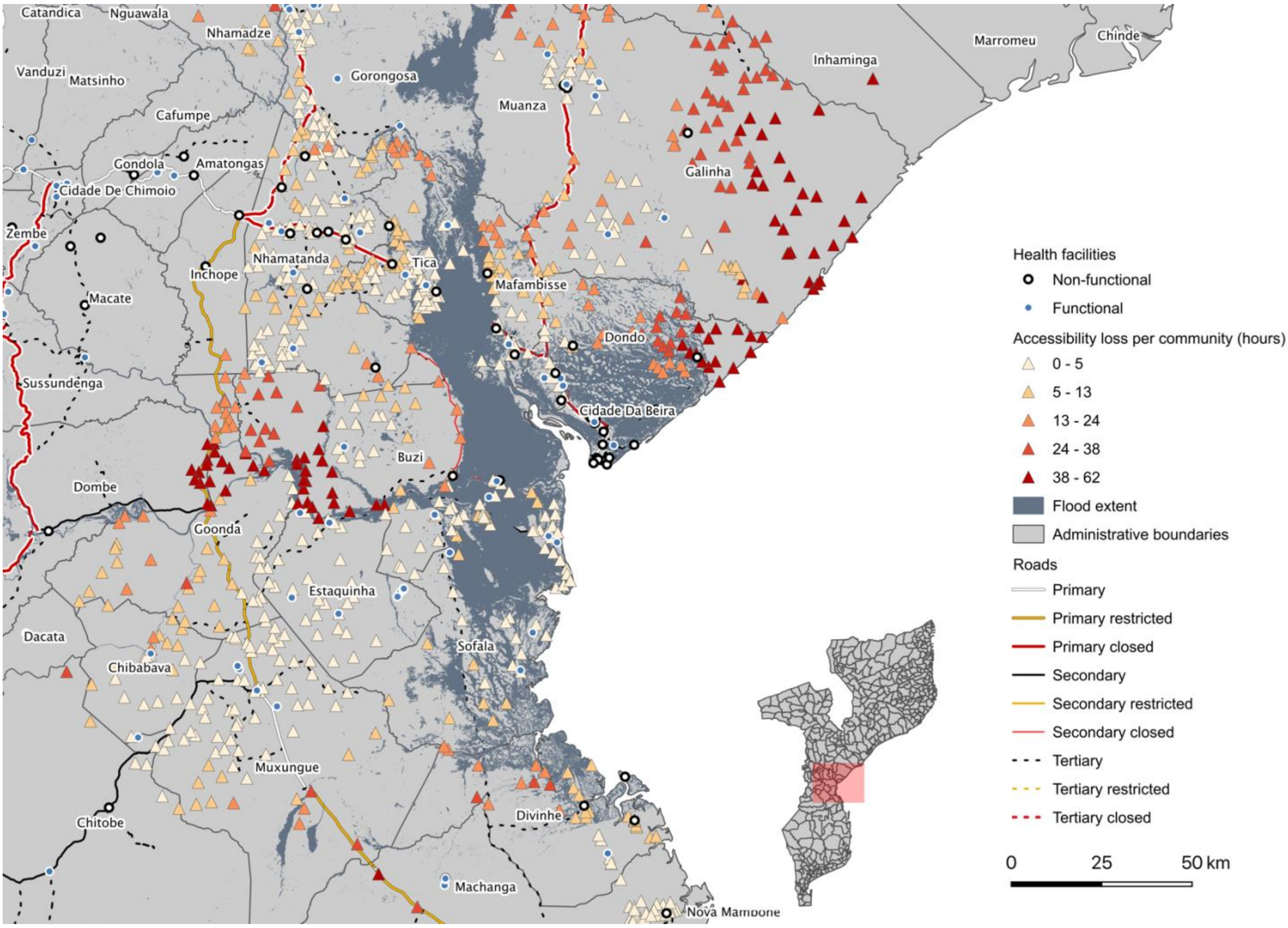
Supplement 4- Relative population coverage pre- and post-cyclone Kenneth. Ordered on relative difference. Difference indicated between parentheses. Error bars indicate the coverage uncertainty, considering -20% and +20% travel speeds.



Supplement 5- Travel time per community in Idai affected districts. Fifty most affected communities by means of accessibility loss. Ordered on absolute travel time difference.

Community	District	Pre-cyclone travel time (h)	Post-cyclone travel time (h)	Difference pre- and post-cyclone (h)
Mucinemo	Buzi	1.3	63.6	62.3
Bupira	Buzi	1.1	62.3	61.3
Massuinda	Buzi	1.2	60.1	58.9
Njanga	Buzi	4.3	59.1	54.7
Guenje-Sede	Buzi	2.9	57.3	54.4
Mbereaizique	Buzi	2.9	57.3	54.4
Shiniziua Chinhale	Muanza	24.0	77.8	53.8
Chipota	Muanza	24.4	78.0	53.6
Wiriquizi	Muanza	22.2	74.1	51.9
Chingamuzi	Muanza	22.7	74.5	51.8
Mussacazwidje	Buzi	3.5	55.3	51.8
Mussacazwidje	Buzi	3.5	55.3	51.8
Magua	Buzi	4.8	56.6	51.8
Nkolone Praia	Muanza	20.7	72.3	51.7
Mukulumba 1	Muanza	20.4	71.8	51.4
Mukulumba cidade	Muanza	20.2	71.4	51.2
Nhanganga	Muanza	19.9	70.8	50.9
Mutanda	Buzi	5.4	55.3	49.9
Macova-Mutanda	Buzi	6.3	55.1	48.9
Puanda	Buzi	2.9	51.6	48.7
Luanda 1	Muanza	18.8	67.4	48.6
Nhamacalango	Muanza	17.4	65.8	48.4
Sengo	Dondo	5.3	53.5	48.2
Luanda 2	Muanza	18.0	65.8	47.8
Praia Nova	Dondo	3.9	51.5	47.6
Praia Farol	Dondo	3.8	51.4	47.6
Bingue Sede	Muanza	16.4	63.8	47.4
Nkonde 2	Muanza	16.4	63.8	47.4
Massitche	Dondo	7.1	54.5	47.4
Goonda Majaca	Chibabava	6.5	53.3	46.8
Ngomole	Muanza	10.1	56.7	46.6
Ngalazi	Dondo	6.0	52.3	46.3
Nhacudjica	Buzi	6.3	52.4	46.1
Chitundo	Dondo	2.0	47.7	45.7
Macarate	Chibabava	5.3	51.0	45.7
Nhamissassa	Muanza	15.9	61.5	45.6
Docue	Buzi	5.7	51.3	45.6
Khome 1	Dondo	1.4	46.8	45.4
Nherere 2	Muanza	14.0	59.0	45.0
Parange	Buzi	3.6	48.6	45.0
Njocho	Buzi	5.9	50.9	45.0
Binda	Machanga	0.7	45.2	44.6
Khome 2	Dondo	0.6	45.2	44.6
Veruca	Chibabava	4.1	48.6	44.5
Mamunge	Buzi	5.1	49.2	44.1
Birirane	Muanza	13.1	57.2	44.1
Vala-vala	Buzi	5.2	49.2	44.1
Muche	Gorongosa	1.5	45.5	44.0
Machiquire	Buzi	2.6	46.1	43.5
Nhazwicasse	Gorongosa	1.0	44.5	43.5

Supplement 6- Travel time per community in Idai affected districts. Point locations of communities in Idai affected districts.



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Modelling geographical accessibility to support disaster response and rehabilitation of a health care system:

An impact analysis of Cyclones Idai and Kenneth in Mozambique

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ABSTRACT

Objectives

Modelling and assessing the loss of geographical accessibility is key to support disaster response and rehabilitation of the health care system. The aim of this study was therefore to estimate post-disaster travel times to functional health facilities and analyze losses in accessibility coverage after Cyclones Idai and Kenneth in Mozambique in 2019.

Setting

We modeled travel time of vulnerable population to the nearest functional health facility in two cyclone-affected regions in Mozambique. Modelling was done using AccessMod version 5.6.30, where roads, rivers, lakes, flood extent, topography, and land cover datasets were overlaid with health facility coordinates and high-resolution population data to obtain accessibility coverage estimates under different travel scenarios.

Outcome measures

Travel time to functional health facilities and accessibility coverage estimates were used to identify spatial differences between pre-disaster and post-disaster geographical accessibility.

Results

We found that accessibility coverage decreased in the flood affected districts, as a result of reduced travel speeds, road constraints and non-functional health facilities. In Idai-affected districts, accessibility coverage decreased from 78.8% to 52.5%, implying that 136,941 children under 5 were no longer able to reach the nearest facility within 2 hours travel time. In Kenneth-affected districts, accessibility coverage decreased from 82.2% to 71.5%, corresponding to 14,330 children under 5 having to travel more than 2 hours to reach the nearest facility. Damage to transport networks and reduced travel speeds resulted in the most substantial accessibility coverage losses in both Idai and Kenneth-affected districts.

Conclusions

Post-disaster accessibility modelling can increase our understanding of spatial differences in geographic access to care in the direct aftermath of a disaster and can inform targeting and prioritization of limited resources. Our results reflect opportunities for integrating accessibility modelling in early disaster response, and to inform discussions on health system recovery, mitigation and preparedness.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- This is the first study presenting the applicability of post-disaster geographical accessibility modelling.
- The approach enables quantification of disaster impacts on geographical health care accessibility to prioritize post-disaster interventions and to build resilience for future disasters.
- To account for uncertainty of the assumed travel speeds, we considered -20% and +20% intervals on motorized travel speeds.
- Data from various sources and administrative levels were combined to represent the post-cyclone situation as realistically as possible, but since data gathering was ongoing, it was expected that some data were incomplete or not fully processed at the time of usage.
- Our accessibility modelling assumes that patients always travel to the nearest health facility. However, literature has shown that patients sometimes bypass health facilities in search of higher-quality care in Mozambique.

1. INTRODUCTION

Geographical proximity to health facilities is a crucial aspect of accessibility, utilization and the provision of health services to populations in need[1]. Road networks and natural barriers (such as rivers, water bodies, and flooded areas) are important factors that determine the geographical (i.e. physical) accessibility of a population to the network of functional health facilities. During natural disasters, roads and health facilities are often damaged, yet health care demand rises substantially at the same time due to injuries and increased communicable disease risks[2,3]. The interplay between the disruption of health infrastructure, transport network, and the rise in health care demand, is known to disable a large portion of the population's access to care they need in the aftermath of a disaster[3,4]. This is especially the case in already medically underserved regions, where the event can lead to new health disparities or exacerbate existing ones[2].

In March and April 2019, two cyclones made landfall in Mozambique. This was the first time in history that two strong cyclones hit Mozambique consecutively in the same season[5]. On 14 March 2019, Tropical Cyclone Idai made landfall in Beira. Followed by a week of heavy rains and winds the storm ended on 21 March 2019[6]. In the middle of the humanitarian emergency response for Cyclone Idai, a second cyclone hit Northern Mozambique. Cyclone Kenneth, a category 4 cyclone and the strongest recorded cyclone on the African continent, made landfall in Pemba, Cabo Delgado on 25 April 2019[7,8]. The two cyclones combined had a death toll of 648, with 603 fatalities due to Idai and 45 deaths caused by Kenneth, and left over 2.2 million people in need of humanitarian assistance[5]. The cyclone's destruction isolated entire communities for weeks due to flood waters, destroyed telecommunication networks, and extensive road damage[9,10]. In addition, stagnant waters, inability in accessing safe water and sanitation, and overcrowding in temporary accommodation led to a cholera outbreak and a significant increase in malaria cases[5,8,11,12]. Major damage to 113 health facilities were reported after both cyclones, causing severe disruption in health service provision and restricting the population's access to adequate health care[13,14]. Although many humanitarian actors have estimated substantial losses in health care accessibility and availability[5,9,10,13,15], the quantitative impact of Cyclone Idai and Kenneth on geographical accessibility to health care remains unknown. Modelling geographical accessibility and population coverage by means of travel time to health facilities, can give important insights for targeting humanitarian action and preparing for future disasters in a coordinated manner [16].

Currently, quantitative post-disaster accessibility assessments are not a part of standardized response guidelines, preventing coordinated and centralized decision making on temporary facility location to serve beneficiaries in the most optimal way [16].Guidelines for a post-disaster needs assessment from the World Health Organization (WHO)[17], advise on a comparison between baseline and post-disaster accessibility through the evaluation of key indicators. However, the suggested key indicators reflect rather static measures of accessibility, such as hospital beds per 10,000 population or number of damaged health facilities[17].

Yet, international efforts to support humanitarian responses on the ground accelerate post-disaster data gathering, enabling a more realistic quantification of accessibility to health care by means of health facility damages, loss of road access, and barriers to movement such as flood waters[18]. Guidance on assessing loss in geographical accessibility while considering spatial barriers remains abstract or even lacking in disaster management frameworks. Meanwhile, geographical accessibility models hold actionable information and have the potential to quantify gaps and overlaps in (temporary) service provisioning, enabling coordinated, targeted and centralized decision making for humanitarian action[16], enhancing both financial and operational efficiency[19,20].

This study therefore presents a data processing and spatial accessibility modelling method to assess post-disaster accessibility to health facilities and analyze accessibility coverage losses as a result of cyclones Idai and Kenneth in Mozambique. The approach enables quantification of disaster impacts on geographical health care accessibility to prioritize post-disaster interventions and to build resilience for future disasters. This is the first study presenting the applicability of post-disaster geographical accessibility modelling.

2. METHODS

2.1 Overall methodology

In this study, *accessibility* is measured as the travel time to health facilities and *accessibility coverage* (i.e. coverage) is defined as the estimated number or percentage of people covered or located within a travel time catchment area[21]. To model accessibility to health facilities, we consider topography, road networks, constraints to movement (e.g. rivers, lakes and flood extent), target population distribution, and the locations of functional health facilities. We accessed and prepared multiple data layers (Table 1) assembled in the aftermath of Cyclones Idai and Kenneth, between April-September 2019. A total of three scenarios were prepared, representing 1) pre-Idai and pre-Kenneth (before March 2019), 2) post-Idai (up to one-week post-cyclone), and 3) post-Kenneth (up to one-week post-cyclone) situations. We modeled population travel time to the nearest health facility and accessibility coverage, for two cyclone-affected regions.

Table 1 – Overview of data layers and data sources

Layer name	Source[a]	Source date[b]	Download date	Type	Original resolution
Administrative boundaries	INE & UN-OCHA ROSEA (HDX)[22]	02.04.19	31.07.19	Polygon	-
Cyclone trajectory (Idai/Kenneth)	GDACS[23,24]	15.03.19/ 25.04.19	08.03.2020	Polygon	-
Land cover	Copernicus[25]	15.11.18	31.07.19	Raster	100 meters
Elevation	SRTM CGIAR[26]	25.11.18	20.09.19	Raster	30 meters
Rivers and lakes	DNGRH	12.8.19	19.9.19	Polygon	-
Primary streams	DNGRH	12.8.19	19.9.19	Lines	-
Flood extent, Idai	UNOSAT/Sentinel -1 (HDX)[27]	19.03.19	31.07.19	Polygon	-
Flood extent, Kenneth	Copernicus EMSR354 (INGC Geonode)[28]	02.05.19	31.07.19	Polygon	-
Roads	OpenStreetMap (INGC Geonode)[29]	25.11.18	07.08.19	Lines	-
Road damages (Idai/Kenneth)	LOG-WFP[30,31]	19.03.19/ 03.05.19	23.09.19	PDF file	-
Health facilities	SIS-MA (HDX)[32]	31.12.17	08.08.19	Points	-
Health facilities damages	Provided by WHO-Mozambique	Represents health facility status 48h until 1 week post-cyclone	17.09.19	Points	-
Population density	Facebook/CIESIN population density[33]	01.10.18	06.08.19	Raster	30 meters

[a] Abbreviations: CIESN = Center for International Earth Science Information Network, DNGRH = National Directorate for Water Resource Management, HDX = Humanitarian Data Exchange, GDACS = Global Disaster Alert and Coordination System, INE = National Institute for Statistics Mozambique, INGC = National Institute for Disaster Management Mozambique, SIS-MA = Ministry of Health Mozambique, SRTM = Shuttle Radar Topography Mission, UN-OCHA ROSEA = United Nations Office for the Coordination of Humanitarian Affairs Southern and Eastern Africa, UNOSAT = United Nations Operational Satellite Applications Program, LOG-WFP = Logistics Cluster World Food Program

[b] Source date represents the imagery acquisition date for the flood extents and the release date for all other data

2.2 Data sources and preparation

The projection, resolution and alignment of geospatial data was processed using Quantum Geographical Information System (QGIS) (version 3.4)[34] and, to a limited extent, R (version 3.5.2)[35]. As indicated in Table 1, most data layers were retrieved from open data platforms. All rasters and shapefiles were saved in the projection system of Mozambique, i.e. UTM-37S [EPSG:32737]. The data preparation process is briefly described below and is fully detailed in Supplement 1.

Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) in tiles at a resolution of 30 meters and mosaiced to cover the whole country[36]. Slopes were derived from it and were accounted for when modelling walking movements.

Land cover data was downloaded for the whole African continent at 100 meter resolution from Copernicus Global Land Service[25] and was clipped to the extent of Mozambique. As analyses were carried out at 30-meter resolution, the land cover raster was resampled at a resolution of 30 meters, using nearest neighbor interpolation.

The pre-cyclone road network dataset was retrieved from Open Street Map (OSM) through the Geonode Platform of the National Institute for Disaster Management Mozambique (INGC), and linked to the road damage information as indicated by the Logistics Cluster of the World Food Program (LOG-WFP)[37,38]. Historical post-cyclone status of roads and road segments were manually digitized from PDF maps provided by LOG-WFP. The maps were cross-referenced with the OSM road network layer, to include post-cyclone road damage status, (i.e. 1) open, 2) restricted, and 3) closed). Road damages as a consequence of cyclones Idai and Kenneth were taken from maps dated March 19 and May 3, 2019, respectively (Table 1)[37,38]. Information on road type and damage were combined in order to obtain unique road type-damage combinations (Supplement 2).

Information on rivers and lake layout were obtained as shapefiles from the National Directorate for Water Resource Management (DNGRH). Only primary rivers and lakes were considered as barriers to movement, under the informed assumption that smaller rivers and streams were passable by the population. This assumption was checked for several instances against background satellite imagery. Flood extents for Idai (on 19 March 2019) and Kenneth (on 2 May 2019) were sourced as shapefiles from Sentinel-1 and Copernicus EMSR354, respectively[27,28]. The flood extents were visually inspected and found to be largest on those two dates, and thus represent the biggest constraints for health care access. All flooded areas were treated under two scenarios: 1) as being impassable, under the assumption that people avoid traversing flood water to prevent further injury, 2) as being passable by foot at an average walking speed of 1.5 km/h. In the first scenario, health facilities located on flood extents were always treated as inaccessible since they are located on barriers.

While cyclones impact entire populations, the burden disproportionately affects children and women[39]. It is estimated that for cyclones Idai and Kenneth more than 50% of the affected population were children, and with flood waters rising above 6 meters, their movements to safety and health care were particularly limited[5]. Moreover, children under 5 represent the age group used as benchmark for child survival targets in both the Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs)[40]. In this context and through the collaborative work with UNICEF, this analysis aimed at informing the impact of the disasters on the burden for specific child health services that target children under 5 (e.g. immunization).

High-resolution population density estimates for children under five were obtained from the Facebook Connectivity Lab and Center for International Earth Science Information Network (CIESN)[33] with a 30-meter resolution. Although several gridded populations datasets are available, the Facebook CIESN dataset was assumed to have the most realistic reallocation of population to settlements[41]. In addition, other frequently used high-resolution gridded population datasets, such as WorldPop[42], use distances from roads and villages as covariates, and this can produce collinearity when used in conjunction with accessibility models. Population density was used to run zonal statistics on the cyclone-affected districts. In this step the total population per district is summed and the estimated absolute number of children under 5 that are able to reach a facility in a pre-defined travel time catchment are calculated.

Additionally, geographic coordinates of all villages (i.e. communities) in Idai-affected districts were obtained from UNICEF Mozambique, which had gathered this information through a community mapping initiative conducted by health officials, 6 to 8 months before Cyclone Idai made landfall. These community locations were used to extract pre- and post-cyclone travel time for each community to the nearest functional health center. Unfortunately, geographic coordinates of villages in Kenneth-affected districts were not available at the time of study.

The geographic coordinates of all health facilities were sourced from the health management information system, Ministry of Health in Mozambique (SIS-MA)[32]. Data cleaning was undertaken in cases where the geographic coordinates for health facilities were located outside the international border of Mozambique or for coordinates falling on barriers to movement (Supplement 1). Information on damaged health facilities was provided in tabular format by the World Health Organization (WHO). The health system in Mozambique comprises 4 levels; the primary level consists of urban and rural health centers, the secondary level consists of general, rural and district hospitals, the tertiary level comprises provincial capital hospitals, and quaternary facilities comprise the central and specialized hospitals[43]. Health facilities of all levels were included in the model.

Districts that were most affected by Cyclones Idai and Kenneth ("cyclone-affected districts", thereafter) were identified in close collaboration with UNICEF and humanitarian responders. All statistics presented below were calculated for these identified districts, with 26 such districts in the Idai-affected region and 11 districts in the Kenneth-affected region (Figures 1a & 1b). Storm trajectories of both cyclones and road damages in both districts are also presented (Figure 1c-1f).

2.3 Geographical accessibility modelling

To model travel times and accessibility coverages, we used AccessMod 5 (version 5.6.30), in particular the “accessibility” and “zonal statistics” modules[21,44]. AccessMod models geographical accessibility using terrain-based least-cost path distance calculation. This open-source software has been successfully applied in many different settings, among which accessibility and referral assessments of health facility networks, optimization modelling of health programs in obstetric and neonatal care (EmONC)[45], primary health care[46], emergency care[47], referral times[48], and treatment of fever cases[49].

Using the “merge land cover” module in AccessMod, we overlaid the roads, rivers, lakes, flood extent, and landcover datasets to obtain a single 30-m resolution raster dataset, to which different travel scenarios were applied.

The travel scenarios (presented in Supplement 2) were derived using local information as model inputs on pre-cyclone and post-cyclone travel speeds and travel modes. Both scenarios were developed in close collaboration with UNICEF Mozambique, with focus on geographical accessibility to functional health facilities for the target population of children under 5. Post-cyclone travel speeds were adjusted for wet weather conditions as heavy rains persisted in the direct aftermath of both cyclones. During the post-cyclone situation, restricted and closed roads that were not inundated were assumed to be unpassable by any vehicle; but they were perceived to be accessible by foot. All landcover classes outside of the road network and the barriers were considered as passable. We assumed a functional bridge where a road segment crossed a river.

To account for uncertainty of the assumed travel speeds, we also considered both pre- and post-cyclone motorized travel speeds with a 20% slower and 20% faster speed, as adapted from Ouma et al.[47]. Accessibility coverage of the network of health centers was calculated at the 2-hour maximum travel time limit. This limit was deemed appropriate to capture the extent of effective access, and is often used in health accessibility studies, notably in maternal health[45].

FIGURE 1

2.4 Patients and the public involvement

There was no patient or public involvement in this study. Health facility functionality status was shared in tabular format by WHO. All other geospatial data were publicly available.

3. RESULTS

All statistics mentioned in the results are estimates of children covered by functional health facilities based on our accessibility model.

3.1 Pre-cyclone accessibility

Pre-cyclone coverage in Idai-affected districts (Figure 2a) was highest in Cidade De Chimoio and Cidade Da Beira, with 99.8% and 99.5% of all children under 5 covered within the 2 hour catchment limit, respectively (Supplement 3). However, this coverage ranged from 35.8-99.8% in all Idai-affected districts (Supplement 3). Absolute pre-cyclone coverage was also highest in Cidade De Chimoio and Cidade Da Beira, where 57,476, and 66,135 children were within 2 hours travel time from a health facility (Figure 2). In Kenneth-affected districts (Figure 2b), pre-cyclone coverage was highest in Cidade De Pemba, where 100% of the children under 5 were expected to be able to reach a health facility within 2 hours travel time (Supplement 4). The lowest pre-cyclone coverage was seen in Mazeze, where only 52.6% of children under 5 were within 2 hours travel time from a health facility (Supplement 4). Absolute pre-cyclone coverage in Kenneth-affected districts was highest in Cidade De Pemba (n = 35,467 children) and Chiure (n= 18,257 children) (Figure 2). Pre-cyclone travel time rasters for the cyclone-affected areas were mapped (Figure 3A & Figure 4A).

FIGURE 2

3.2 Losses in accessibility coverage

Geographical accessibility to health care decreased in the cyclone-affected districts, as a result of reduced travel speeds, road constraints and non-functional health facilities (Figure

3B and Figure 4B). Ratios of pre-cyclone and post-cyclone travel time rasters are mapped for Idai-affected districts, with ratios close to 1 indicating similar travel times pre- and post-cyclone, and ratios closer to 0 indicating large pre- and post-cyclone accessibility differences (Figure 3C). The same results for Kenneth-affected districts are presented (Figure 4C). Regions shown in red indicate localities with relatively large differences between pre- and post-cyclone travel times (Figure 3C). In the Idai-affected region, especially in the districts surrounding the flood water and closed roads, accessibility is severely impacted. In Idai-affected districts, the percentage of children under 5 covered within 2 hours travel time, generally decreased from 78.8% to 52.5%, implying that 136,941 previously-covered children under 5, lost timely access to health care (Table 2).

Table 2- Overview of pre- and post-cyclone accessibility coverage in Idai and Kenneth-affected districts.

		Pre-cyclone		Post-cyclone			
Cyclone	**Travel time**	**Children <5 covered (nr.)**	**Children <5 covered (%)**	**Children <5 covered (nr.)**	**Children <5 covered (%)**	**Children <5 coverage loss (nr.)**	**Children <5 coverage loss (%)**
Idai	30 minutes	298,432	57.3	153,842	29.5	144,591	27.7
	1 hour	346,409	66.5	206,610	39.6	139,799	26.8
	2 hours	410,696	78.8	273,755	52.5	136,941	26.3
Kenneth	30 minutes	131,120	72.0	63,953	48.8	304,15	23.2
	1 hour	99,056	73.8	86,997	64.8	12,060	9.0
	2 hours	110,348	82.2	96,019	71.5	14,330	10.7

The largest relative accessibility coverage decline, within 2 hours travel time, was observed in Machanga, where 77.6% of the previously covered population was no longer able to access a facility under 2 hours in the aftermath of Idai (Figure 2). In terms of absolute coverage, Nhamatanda was the most affected district, with a coverage loss of 25,121 children under 5, followed by Morrumbala (n = 19,554 children), Cidade Da Beira (n = 17,355 children), and Buzi (n= 9,949 children) (Figure 2). Uncertainty modelling, by accounting for 20% slower and 20% faster motorized travel speeds[47], indicated localities with travel time differences up to 3-hours comparing slower and faster travel speeds (Figure 3D & Figure 4D). This information indicates where our travel time assumptions have the largest effect on accessibility and coverage losses and where this may be either under- or overestimated which can help guide resource allocation for decreasing this uncertainty.

Relative accessibility coverage in all Kenneth-affected districts decreased from 82.2% to 71.5%, corresponding to 14,330 children having lost access to the nearest facility within 2 hours travel time (Table 2). The most affected district in terms of relative coverage loss was Macomia, where 88.9% of the children that were covered pre-cyclone lost access (Supplement 3 & 4). Mazeze was the most affected district in terms of absolute coverage loss, as 5,496 children lost access in the aftermath of cyclone Kenneth, followed by Macomia (n= 3,727 children), Chiure (n= 2,307 children), Quissanga (n= 1,270 children) and Mueda (n= 750 children) (Figure 2).

Since flood waters slowly receded in the days/weeks after the cyclones, we ran an additional scenario where flood waters were passable at a 1.5km/h walking speed. Considering this scenario, absolute coverage losses for Idai-affected districts within 2 hours travel time were highest in Morrumbala (n= 29,566 children), Nhamatanda (n= 25,758 children), Dacata (n= 8,914 children), and Bùzi (n= 8,757 children). In Kenneth-affected districts, Mazeze (n= 6,167 children), Chiure (n= 4,684 children) and Macomia (n= 3,727 children) had the highest coverage losses in 2 hour catchments under the passable scenario.

3.3 Travel time in affected communities

The most affected villages in Idai-affected districts, in terms of reduced accessibility to the nearest health facility were communities located in Bùzi and Muanza districts in Sofala province. Mucinemo in Bùzi district was found to have a pre-cyclone travel time of 1.3 hours to the nearest health facility. However, this travel time upsurged to 63.6 hours in the direct aftermath of cyclone Idai (Supplements 5 & 6). Generally, the 6 most affected communities in terms of accessibility in Idai-affected districts all had a pre-cyclone travel time between 1 hour and 3 hours, while all post-cyclone travel times increased to over 55 hours (Supplement 6). Overall, post-cyclone accessibility ranged from some minutes up to 78 hours, with the highest travel time found in Chipota, in Muanza district.

FIGURE 3 & 4

3.4 Health facility closures

The effects of non-functioning health facilities were isolated by comparing two separate scenarios; 1) a post-cyclone scenario where all health facilities were considered functional, and 2) a post-cyclone scenario where modified functionality status was considered. By comparing these pre-cyclone and post-cyclone scenarios, the coverage losses caused by the transportation-specific disruptions (i.e. adjusted travel speeds and road constraints) could be isolated from the reduction in coverage due to the damage to health facilities (i.e. non-functional health facilities), providing a way to assess the likely impact of future programs aimed at reinforcing health facilities for disasters. In order to make these comparisons in this specific example, both scenarios were run under the assumption that flood waters were fully passable. In all other instances throughout the paper, flood waters were considered impassable. In case all health facilities remained functional in Idai-affected districts (i.e. disruption was due to transportation only), the overall coverage within 2 hours travel time would decrease from 79.3% to 57.7%, a difference of 21.6% (n = 112,538 children). Damage to health facilities caused an additional coverage decline of 5.3% (n = 27,840 children) in Idai-affected districts. However, hospital closures did not evenly affect all districts. In 17 out of 26 Idai-affected districts, hospital closures had no additional effect on accessibility. However, in the remaining 9 Idai-affected districts, hospital closures were responsible for an additional 1.9-59.7% coverage loss within 2 hours catchment. Health facility closures in Machanga affected the relative coverage the most, with 59.7% coverage loss (n= 3,642 children) caused by non-functionality of 3 out of 6 health facilities. Absolute coverage losses as an effect of non-functional health facilities, were highest in Nhamatanda, where 12,946 (31.0%) children under 5 years old lost access due to health facility closures. In Nhamatanda, 9 out of 16 health facilities became unfunctional as a consequence of Cyclone Idai. Health facility closures did not have an additional effect on post-cyclone accessibility in Kenneth-affected districts.

4. DISCUSSION

Accessibility coverage decreased and travel times substantially increased in the direct aftermath of the cyclones. Damage to transport networks and reduced travel speeds resulted in the most substantial accessibility coverage losses in both Idai- and Kenneth-affected districts. In Kenneth-affected districts, it was found that hospital closures did not have an additional effect on post-cyclone accessibility this is likely caused by the fact that flood extents and hospital closures were of much smaller magnitudes in the Kenneth-affected region than in the Idai-affected region.

In a post-disaster setting, access to health care is essential for effective response and recovery[50]. The results of our study can be implemented beyond the response phase of the cyclones. Although the emphasis of the results is on identification of decreased accessibility coverage directly after the cyclones, the information presented here also provides a platform for discussing health system recovery, mitigation and preparedness[51].

Early identification of underserved districts in the response phase can help reduce the impacts caused by health service interruption, through targeted deployment of medical services in districts with the largest accessibility coverage losses and lowest baseline accessibility[52]. Information on accessibility coverage losses per cyclone-affected district can support decision-making in the prioritization and planning of these medical services, by targeting where the deployment of medical services reaches the highest number of people. Growing access to open data and post-disaster information enables prompt accessibility modelling in the aftermath of a natural disaster and the growing ability to quickly assemble this data provides an opportunity to integrate accessibility modelling in the early response phase of a natural disaster, so resources can be allocated in an informed way and health impacts can be reduced. In this specific study, all data for an initial post-cyclone accessibility study became available between 1 week and 1 month post-disaster (Table 1). This allows for an accessibility analysis in the early stages of a disaster response. Generally, data on flood extents and road damages, acquired from satellite imagery, were downloadable within 1 week post-disaster. Whereas information that had to be ground validated, such as health facility functionality, became available approximately 1 month post-disaster.

Furthermore, the extensive damages to the road network will continue to limit movements of the population, further complicating physical accessibility[5]. Our results indicate that road damages are responsible for a relatively large loss of accessibility. This calls for a concerted effort between road and health authorities when prioritizing reconstruction efforts. It was estimated by WHO that damages to (health) infrastructure translated into 200,000 people living more than 5 kilometers from a functioning health facility[53]. However, our results, which provide a more realistic representation of accessibility, by accounting for topography, barriers to movement, and population distribution, suggest this figure is an underestimate. We estimated that as a result of the damage to infrastructure and barriers to movement, 314,591 children under 5 live further than 1 hour travelling from a functioning health facility.

Fourteen percent of all health facilities in Cyclone Idai- and Kenneth-affected cyclone-districts have been damaged or fully destroyed, although more health facilities were temporarily impacted in service provisioning due to flooding, electricity constraints or damage to equipment[14,54]. While it is critical to restore access to essential health services as soon as possible, the WHO reported that the reconstruction of all destructed and damaged facilities may take up to 5 years[14]. To restore baseline accessibility, the establishment of mobile outreach units, deployment of community health workers (CHWs), together with the reconstruction of damaged facilities should be implemented. However, under the umbrella of *Building Back Better* (BBB), rebuilding more resilient facilities and infrastructure, that are able to withstand future hazards under the “Hospitals Safe from Disasters” approach, are needed to prevent similar impacts in future disasters[53,54]. The results presented here show the importance of joint efforts to reduce both impacts on health facilities and the existing road network. However, resources are limited, and efficient financial planning is needed to outline health system investment plans[5,11]. The results of our accessibility modelling can be used to prioritize health facility reconstruction for facilities with highest accessibility coverages. Cyclone Idai for instance, caused the destruction of the only tertiary hospital in 4 affected provinces that serves an estimated 12 million people[50]. Targeting hospitals with coverage numbers like these, to be strengthened for future disaster impacts and to support them in providing continuity of care in the aftermath of future disasters can help reduce health losses[55].

Due to the persisting health system disruption, humanitarian responders have identified the need to deploy CHWs and mobile outreach services to cover accessibility losses caused by the cyclones and to extend the reach of existing functional services[50,56]. These study findings can assist policymakers in identifying and prioritizing severely impacted districts and communities and regions where deployment of CHWs can make a difference. Supplementary materials 3-6 present the most affected communities in terms of increased travel time and coverage losses post-cyclone. These analyses can be routinely updated to assess the effect of health system recovery on accessibility.

The districts that were most affected by Cyclone Idai and Kenneth were historically, and are in the future, also prone to disasters due to their topography (i.e. due to their location as low-lying coastal cities in the cyclone belt near the Indian Ocean)[50,53]. Ideally, accessibility modelling could be applied to simulate the effects of historical disasters on accessibility, as indicated in Supplement 5 and Supplement 6, so targeted preventive measures can be taken for future disasters. Post-disaster accessibility modelling can help identify weak spots in geographical accessibility to the health system and helps to distinguish pre-existing accessibility gaps (Figure 3A and 4A) from accessibility coverage losses as a result of disasters (Figure 3B and 4B). This information is essential in health system recovery, strengthening and preparing for future disasters.

Limitations and uncertainties of this study were primarily linked to the data. While the occurrence of natural disasters generally accelerates data availability in affected countries, there also are challenges of data quality, consistency, and format[57]. In this study, data from various sources were combined to represent the post-cyclone situation as realistically as possible. But since data gathering was ongoing, it was expected that some data were incomplete or not fully processed at the time of usage. Health facility coordinates had duplicate occurrences in the database and health facility damages were solely indicated by name, which resulted in manual spatial merging. Co-occurrences of rivers that were indicated as floods were seen in the flood extent layer, minimally overestimating actual flood extents in some parts of the affected regions. Besides post-disaster data uncertainty, pre-disaster spatial data were also checked against background satellite imagery. The hydrography of primary rivers stored in the data was found not to be fully representative for actual hydrography in some regions. This could be a consequence of digitizing against a less granular spatial resolution[58]. In some cases, passages and bridges were detected on satellite background imagery where the OpenStreetMap road layer did not present presence of roads. In places where hydrography was potentially overestimated and not all roads are mapped, isolated land pockets were created in the merged land cover. When modelling accessibility in these land pockets the population is assumed to be fully isolated from health care. In general, we would advise upon a more rigorous and sustainable data management during and after humanitarian emergency operations to ensure the applicability of spatiotemporal data analyses to quantify disaster impacts.

Next to data uncertainties, travel scenarios present a source of uncertainty as assumptions on travel speeds and modes are uniformly generalized across regions. In addition, we assumed that roads indicated as being restricted or closed were considered only passable by foot if they were not inundated. However, some of the restricted roads were in fact passable by 4x4 vehicles. Other means of transport (e.g., bicycle, motorcycle) may also have been used in some places, which would increase accessibility to health centres. Since car ownership and access to motorized transport by the target population was expected to be very low, especially post-cyclone, it was decided to run the accessibility model for restricted and closed roads only by means of walking.

Our accessibility modelling assumes that patients always travel to the nearest health facility. However, literature has shown that patients sometimes bypass health facilities in search of higher quality care in Mozambique[59,60]. Previous research, has shown that 30.8% of pregnant women bypassed the nearest health facility in search of better prenatal care[59]. Our results can therefore present slight underestimations of actual travel times.

Despite some of the limitations, the results presented here provide important initial information for post-cyclone health system recovery which can be expanded through future research. Since post-disaster needs continuously change based on the nature of the event (e.g. receding flood waters, reconstruction efforts, and deployment of temporary medical services), following studies should also be focused on the ability to dynamically model accessibility based on these changes, so accessibility can be continuously monitored and humanitarian service delivery can be updated accordingly in disaster-affected districts. Additionally, it would be interesting to assess the effect of CHW deployment and mobile outreach communities on improved accessibility and accessibility coverage estimates, to quantify the effect of these interventions.

Post-disaster accessibility modelling can increase our understanding of spatial differences in health care needs in the direct aftermath of a disaster and can help target limited resources efficiently. Currently, there is no standardized approach in the humanitarian program cycle to assess post-disaster accessibility losses against baseline accessibility[17]. The lack of a standardized methodology to spatially assess disaster impacts on accessibility can result in uncoordinated decision making for temporary health facility locations, introducing duplication probability, and complicates prioritization in recovery efforts. The results in this paper not only reflect the importance of incorporating accessibility modelling in early disaster response, but also provide a platform for discussing health system recovery, mitigation and preparedness.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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AUTHOR CONTRIBUTION

Fleur Hierink: conceptualization, methodology, formal analysis, writing, editing, visualization, supervision. **Nelson Rodrigues:** data sharing, methodology, writing, editing, validation. **Maria Muñiz**: writing, editing. **Rocco Panciera:** methodology, writing, editing. **Nicolas Ray:** conceptualization, methodology, writing, editing, validation, supervision.

DATA SHARING STATEMENT

Data available upon reasonable request. Most data used in this study are openly accessible through the indicated data sources in Table 1. Other data are available upon request.

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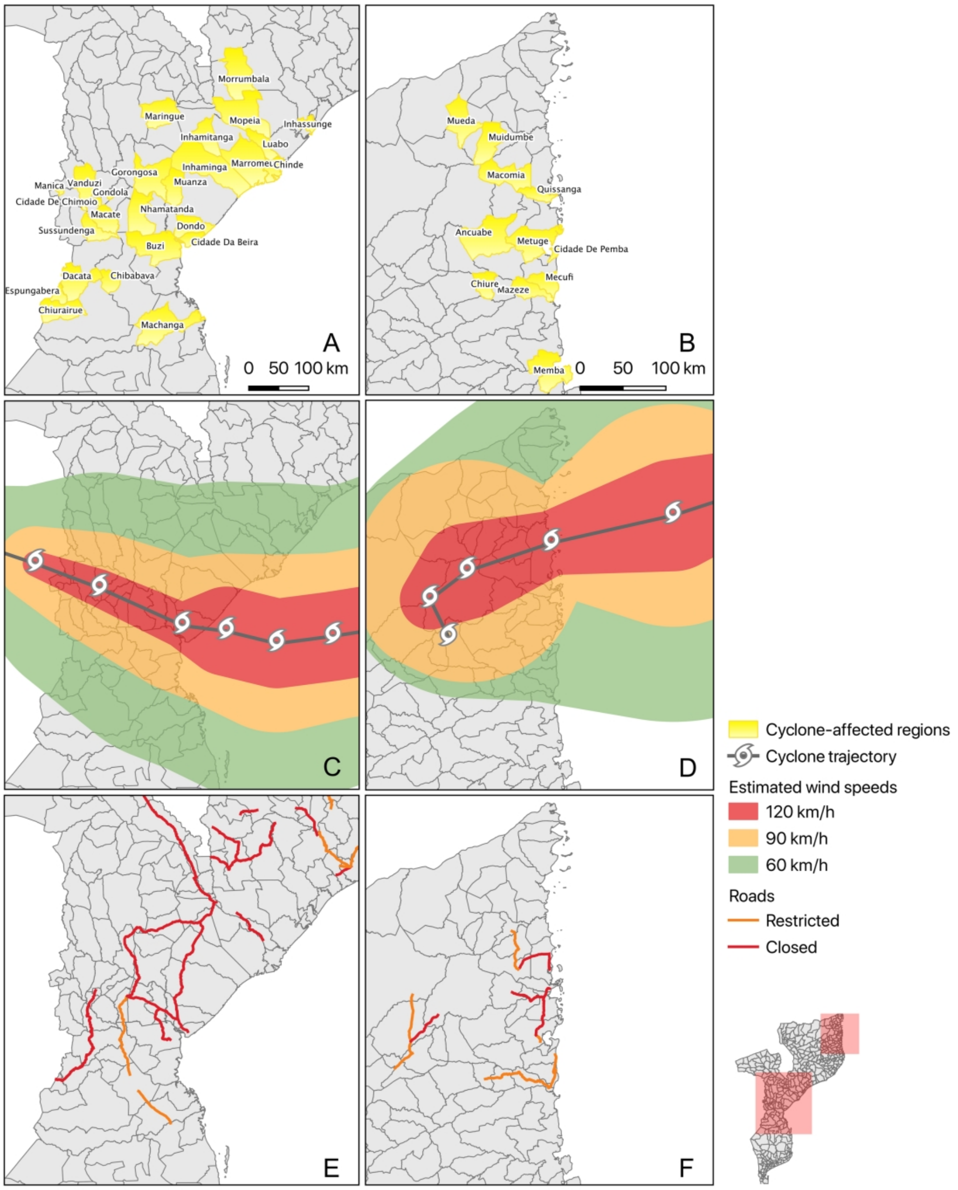
Figure legends:

Figure 1 - Cyclone affected districts, cyclone trajectory, and road damages. (A) Idai affected districts. (B) Kenneth affected districts. (C) Idai cyclone trajectory*. (D) Kenneth cyclone trajectory*. (E) Road damages in Idai-affected districts. (F) Road damages in Kenneth-affected districts. *Cyclone paths as reported on Global Disaster Alert and Coordination System (GDACS)[25,26].

Figure 2- Absolute and relative reduction in population coverage pre- and post-cyclone Idai (A) and Kenneth (B). Labels on top of bars indicate absolute reduction in population coverage of children under 5. Labels under districts indicate relative reduction in population coverage. Maximum limits of the bars indicate the absolute pre-cyclone coverage within 2 hours travel time. Limits of the blue filled bar indicate the absolute post-cyclone coverage. The x-axis is ordered according to relative reduction in population coverage.

Figure 3 – Accessibility modelling results for Idai districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).

Figure 4 – Accessibility modelling results in Kenneth districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).



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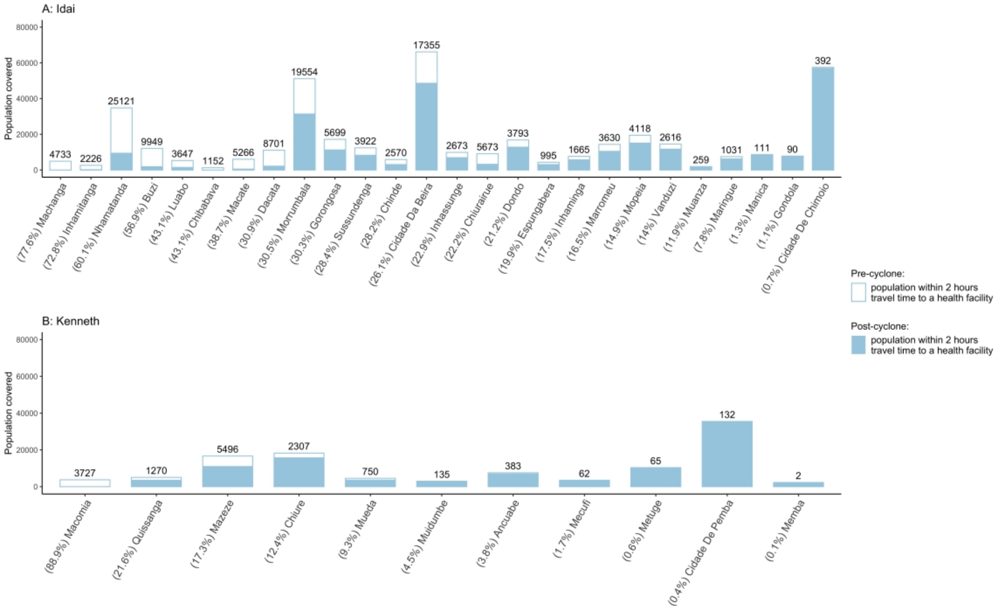

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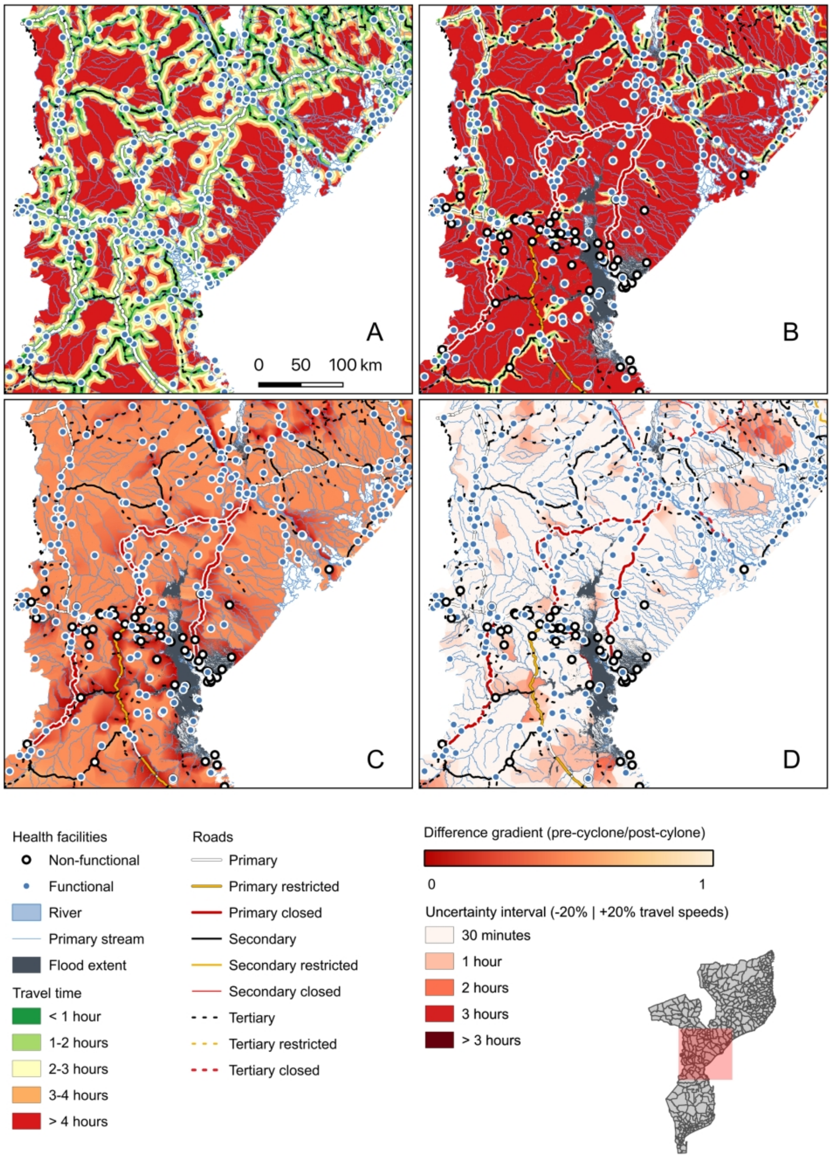


Figure 3 – Accessibility modelling results for Idai districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).

209x296mm (300 x 300 DPI)

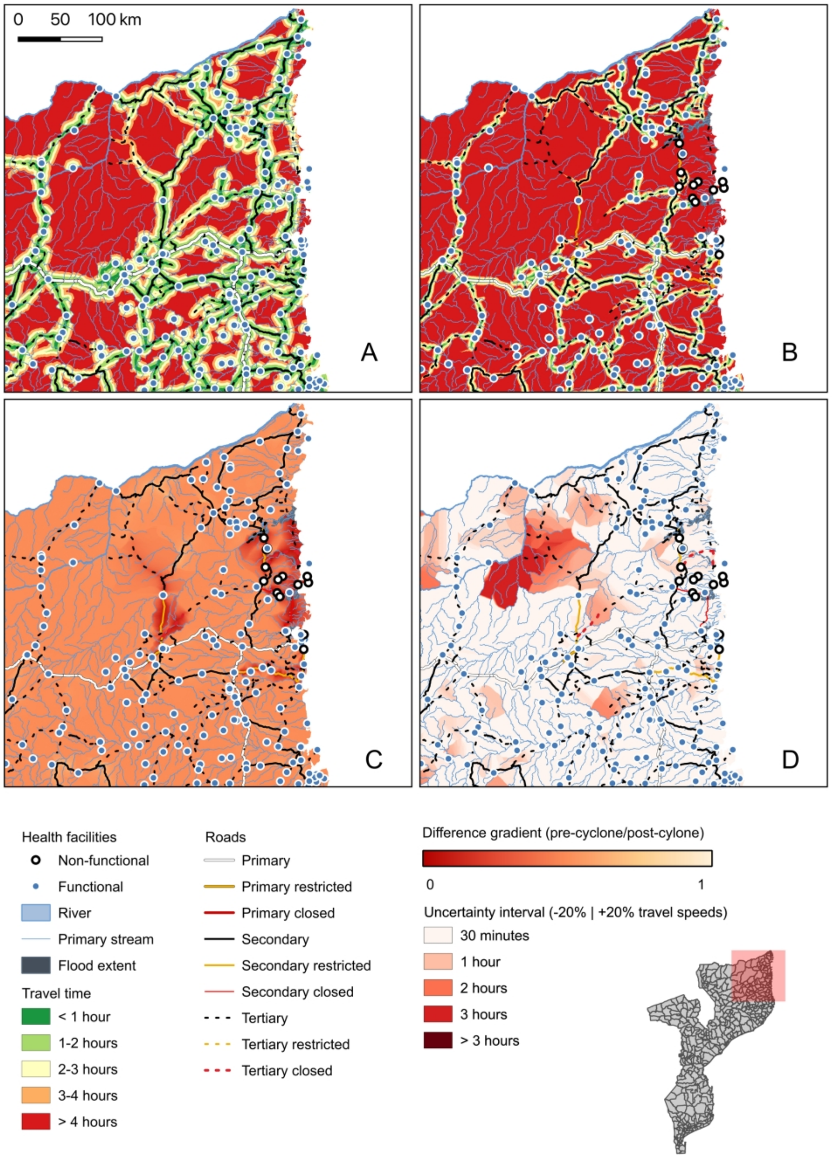


Figure 4 – Accessibility modelling results in Kenneth districts. Pre-cyclone travel time raster (A). Post-cyclone travel time raster (B). Difference ratio raster between pre- and post-cyclone travel time (C). Uncertainty raster, as a result of the difference between -20% and +20% travel speed accessibility (D).

209x296mm (300 x 300 DPI)

SUPLEMENTAL MATERIAL

Supplement 1-Data preparation for use in AccessMod

All data preparation was carried out in Quantum Geographical Information System (QGIS) (version 3.4)[24] in limited combination with R (version 3.5.2)[25]. As indicated in Table 1, most data layers were retrieved from open data platforms. All raster- and shapefiles were saved in the projection system of Mozambique, i.e. UTM-37S [EPSG:32737]. All raster files were aligned using the digital elevation model (DEM) as reference. The data preparation process is fully described below for each data set.

Elevation

Anisotropic accessibility analyses, in other words analyses accounting for travel speeds on slopes, were carried out for this study. Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) in tiles at a resolution of 30 meters and mosaiced to cover the whole country[38]. Slopes were derived from it and accounted for when modelling walking movements.

Land cover

The land cover data set of the African continent[27] was clipped to the extent of Mozambique, leaving a small buffer around the country to prevent loss of data cells at the border. The data set was resampled at a resolution of 30 meters using nearest neighbor interpolation.

Road network

The pre-cyclone road network dataset was retrieved from Open Street Map (OSM) through the Geonode Platform of the National Institute for Disaster Management Mozambique (INGC), as this dataset was perceived to represent the most recent information on the roads and could be linked to the damaged roads, as indicated by the Logistics Cluster of the World Food Program (LOG-WFP). Road classes that were not indicated as official classification by OSM, were removed from the data[48].

LOG-WFP provided the most up to date data on road network damages. However, the road constraint shapefile was updated frequently by overwriting previous versions, without

storing data historically. Therefore, historical post-cyclone status of roads and road segments was manually digitized from PDF maps provided by LOG-WFP[28,29]. The PDF maps were manually cross-referenced with the OSM road network layer, to include post-cyclone status, i.e. 1) open 2) restricted 3) closed.

Roads were then reclassified based on the unique combination of road type and post-cyclone status, resulting in 34 unique road classes (e.g. primary road, primary road restricted, secondary road closed). All roads were given a specific travel speed, accounting for the different scenarios. In the pre-cyclone scenario for instance, all primary road classes (i.e. primary road, primary road restricted, primary road closed) had the same travel speed. Whereas in the post cyclone scenario, the restricted and closed road types had a travel speed and travel mode accounted for their damages, as can be seen from Suplement 2.

Barriers to movement

Rivers and lake shapefiles were obtained as lines and polygons from the National Directorate for Water Resource Management (DNGRH) and accuracy was checked using satellite imagery as a reference, using Microsoft Bing Imagery as a background through the QGIS QuickMapServices Plugin. Only primary rivers and lakes were taken for the analyses, under the assumption that smaller rivers and streams were passable by the population. Water bodies were perceived as being impassable at all scales.

Flood extent caused by Cyclone Idai was taken from 19 March 2019 and flood extent for Cyclone Kenneth was taken from 2 May 2019, because extents were visually inspected and found to be largest on those dates and thus represent the biggest constraints for health care access. All flooded areas were treated as impassable at those dates, considering the depth and extent of the floods.

Population data

High resolution population density estimates for children under five were downloaded at 30 meter resolution from the Facebook Connectivity Lab and Center for International Earth Science Information network[30]. The raster was projected in Mozambique's projection system, UTM-37S [EPSG:32737], by using nearest neighbor interpolation. Loss of population caused by reprojection and clipping to country borders, was corrected for by smoothing the lost population equally over the raster cells. This was done by using a multiplication factor of the difference between the total sum of population before and after data processing using the raster calculator.

Health facilities

The geographic coordinates of all health facilities were obtained through the Humanitarian Data Exchange platform (HDX) and were originally sourced from the Ministry of Health in Mozambique (SIS-MA)[34]. The data was cleaned to exclude coordinates far outside of the country borders. Coordinates that fell just outside Mozambique were relocated within the country extents. Five health facilities were cross-referenced with other data sources (e.g. Neonatal Inventory Survey UNICEF, OpenStreetMap, Google Maps) because they were located on barriers, such as open sea, rivers or lakes.

Information on damaged health facilities was provided by the World Health Organization (WHO). This data did not include GPS coordinates, thus names of the damaged health facilities were cross referenced with the original health facility shapefile to include post-cyclone status of each facility, i.e. functional or non-functional. For damaged health facilities that were not included in the original health facility shapefile, coordinates were retrieved from a neonatal inventory performed by United Nations Children Fund (UNICEF) and also added as facility to the original health facility data, representing the pre-cyclone situation. Non-functional health facilities were filtered-out for geographical accessibility analyses reflecting the post-cyclone scenarios.

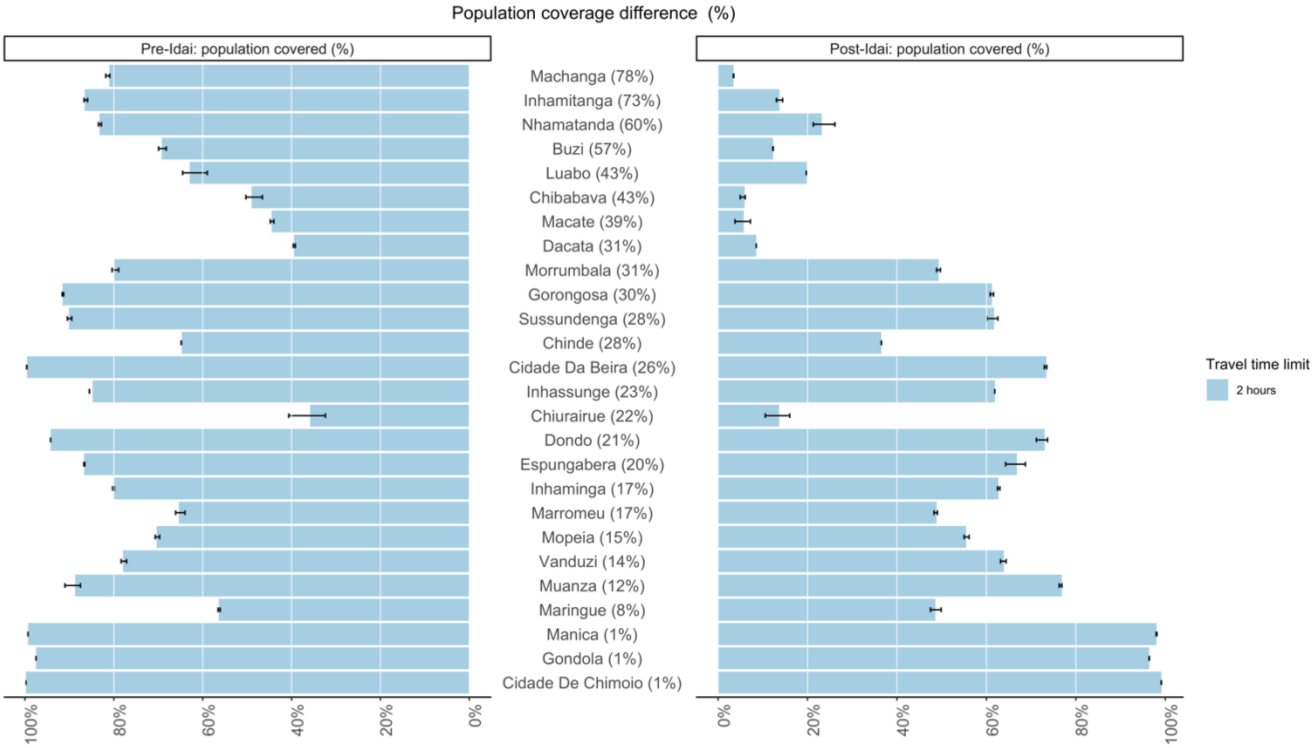
Travel scenario

Both our travel scenarios were developed in close collaboration with country representatives from UNICEF and were adapted to our target population, namely children under five accompanied by a parent (Suplement 2). Flood waters were assumed to be a full barrier to movement to the target population, thus health facilities located in flooded zones were completely inaccessible and flood waters were impassable.

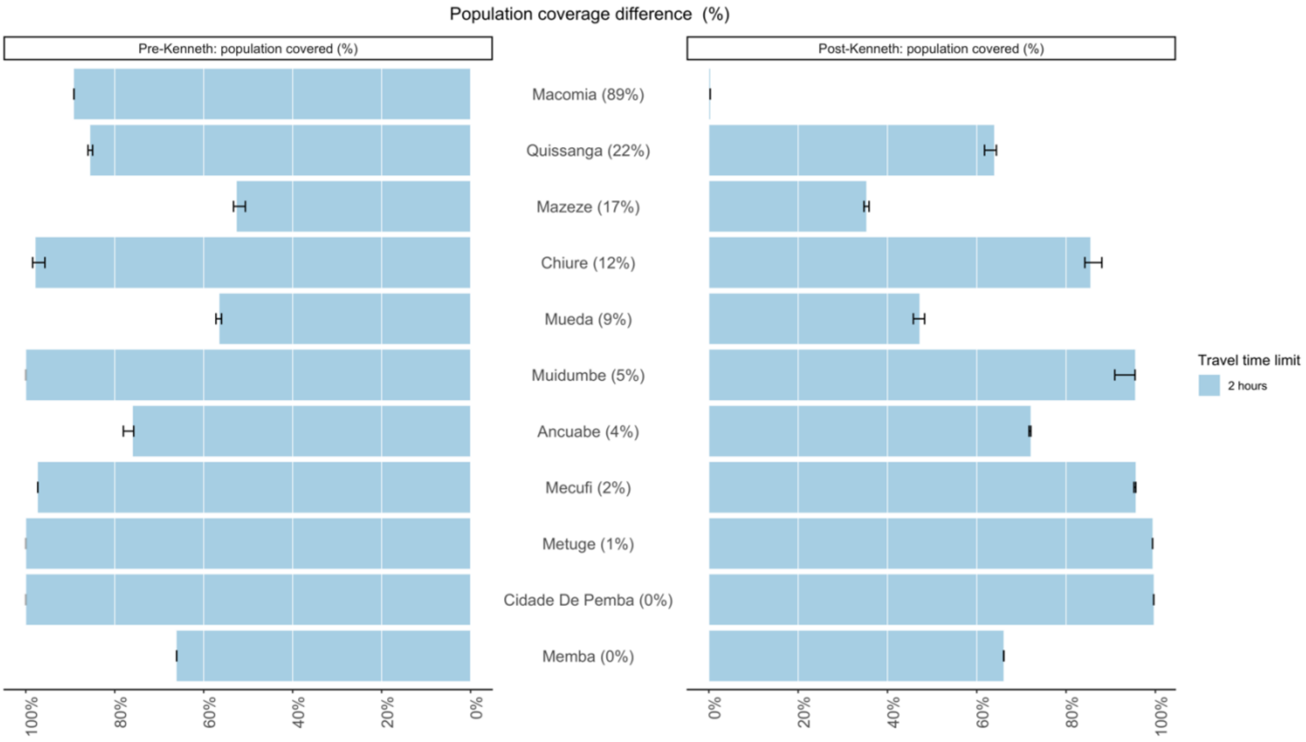
Supplement 2- Travel scenarios pre-cyclone and post-cyclone

Label	Pre-cyclone		Post-cyclone	
	Travel speed (km/h)	Travel mode	Travel speed (km/h)	Travel mode
Shrubs	3	Walking	1.5	Walking
Herbaceous Vegetation	3	Walking	1.5	Walking
Cultivated and Managed Vegetation Agriculture Cropland	3	Walking	1.5	Walking
Urban Built Up	3	Walking	1.5	Walking
Bare Sparse Vegetation	3	Walking	1.5	Walking
Permanent Water Bodies	3	Walking	1.5	Walking
Temporary Water Bodies	3	Walking	1.5	Walking
Herbaceous Wetland	3	Walking	1.5	Walking
Closed Forest Evergreen Broad Leaf	3	Walking	1.5	Walking
Closed Forest Deciduous Broad Leaf	3	Walking	1.5	Walking
Open Forest Evergreen Broad Leaf	3	Walking	1.5	Walking
Open Forest Deciduous Broad Leaf	3	Walking	1.5	Walking
Open Sea	3	Walking	1.5	Walking
Trunk	80	Motorized	50	Motorized
Trunk Restricted	80	Motorized	1.5	Walking
Trunk Closed	80	Motorized	1.5	Walking
Primary	80	Motorized	50	Motorized
Primary Restricted	80	Motorized	1.5	Walking
Primary Closed	80	Motorized	1.5	Walking
Secondary	50	Motorized	40	Motorized
Secondary Restricted	50	Motorized	1.5	Walking
Secondary Closed	50	Motorized	1.5	Walking
Tertiary	30	Motorized	15	Motorized
Tertiary Closed	30	Motorized	1.5	Walking
Tertiary Restricted	30	Motorized	1.5	Walking
Road	20	Motorized	10	Motorized
Raceway	3	Walking	3	Walking
Residential	20	Motorized	10	Motorized
Residential Closed	20	Motorized	1.5	Walking
Living Street	20	Motorized	10	Motorized
Service	3	Walking	1.5	Walking
Track	15	Motorized	10	Motorized
Pedestrian	3	Walking	1.5	Walking
Pier	3	Walking	1.5	Walking
Path Closed	3	Walking	1.5	Walking
Path	3	Walking	1.5	Walking
Footway	3	Walking	1.5	Walking
Bridleway	3	Walking	1.5	Walking
Cycleway	3	Walking	1.5	Walking
Steps	3	Walking	1.5	Walking
Unclassified	3	Walking	1.5	Walking

Supplement 3- Relative population coverage pre- and post-cyclone Idai. Ordered on relative difference. Difference indicated between parentheses. Error bars indicate the coverage uncertainty, considering -20% and +20% travel speeds.



Supplement 4- Relative population coverage pre- and post-cyclone Kenneth. Ordered on relative difference. Difference indicated between parentheses. Error bars indicate the coverage uncertainty, considering -20% and +20% travel speeds.



Supplement 5- Travel time per community in Idai affected districts. Fifty most affected communities by means of accessibility loss. Ordered on absolute travel time difference.

Community	District	Pre-cyclone travel time (h)	Post-cyclone travel time (h)	Difference pre- and post-cyclone (h)
Mucinemo	Buzi	1.3	63.6	62.3
Bupira	Buzi	1.1	62.3	61.3
Massuinda	Buzi	1.2	60.1	58.9
Njanga	Buzi	4.3	59.1	54.7
Guenje-Sede	Buzi	2.9	57.3	54.4
Mbereaizique	Buzi	2.9	57.3	54.4
Shiniziua Chinhale	Muanza	24.0	77.8	53.8
Chipota	Muanza	24.4	78.0	53.6
Wiriquizi	Muanza	22.2	74.1	51.9
Chingamuzi	Muanza	22.7	74.5	51.8
Mussacazwidje	Buzi	3.5	55.3	51.8
Mussacazwidje	Buzi	3.5	55.3	51.8
Magua	Buzi	4.8	56.6	51.8
Nkolone Praia	Muanza	20.7	72.3	51.7
Mukulumba 1	Muanza	20.4	71.8	51.4
Mukulumba cidade	Muanza	20.2	71.4	51.2
Nhanganga	Muanza	19.9	70.8	50.9
Mutanda	Buzi	5.4	55.3	49.9
Macova-Mutanda	Buzi	6.3	55.1	48.9
Puanda	Buzi	2.9	51.6	48.7
Luanda 1	Muanza	18.8	67.4	48.6
Nhamacalango	Muanza	17.4	65.8	48.4
Sengo	Dondo	5.3	53.5	48.2
Luanda 2	Muanza	18.0	65.8	47.8
Praia Nova	Dondo	3.9	51.5	47.6
Praia Farol	Dondo	3.8	51.4	47.6
Bingue Sede	Muanza	16.4	63.8	47.4
Nkonde 2	Muanza	16.4	63.8	47.4
Massitche	Dondo	7.1	54.5	47.4
Goonda Majaca	Chibabava	6.5	53.3	46.8
Ngomole	Muanza	10.1	56.7	46.6
Ngalazi	Dondo	6.0	52.3	46.3
Nhacudjica	Buzi	6.3	52.4	46.1
Chitundo	Dondo	2.0	47.7	45.7
Macarate	Chibabava	5.3	51.0	45.7
Nhamissassa	Muanza	15.9	61.5	45.6
Docue	Buzi	5.7	51.3	45.6
Khome 1	Dondo	1.4	46.8	45.4
Nherere 2	Muanza	14.0	59.0	45.0
Parange	Buzi	3.6	48.6	45.0
Njocho	Buzi	5.9	50.9	45.0
Binda	Machanga	0.7	45.2	44.6
Khome 2	Dondo	0.6	45.2	44.6
Veruca	Chibabava	4.1	48.6	44.5
Mamunge	Buzi	5.1	49.2	44.1
Birirane	Muanza	13.1	57.2	44.1
Vala-vala	Buzi	5.2	49.2	44.1
Muche	Gorongosa	1.5	45.5	44.0
Machiquire	Buzi	2.6	46.1	43.5
Nhazwicasse	Gorongosa	1.0	44.5	43.5

Supplement 6- Travel time per community in Idai-affected districts. Point locations of communities in Idai-affected districts.