Implementing a GIS Based Methodology for Determining Highly Vulnerable Rural Access Roads to a Changing Climate in Ethiopia

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Abstract

Climate-related natural disasters have been steadily increasing in both incidence and intensity across the globe over the last century. This is especially true for Ethiopia given the country's high and recurrent exposure to extreme droughts and floods, the two most notorious disasters that have impacted on the country's development trajectory and the livelihoods of its citizens. Climate-related risks are the major driver of hunger and food insecurity in Ethiopia, with the majority of poor communities being most vulnerable to their impacts. Due to the high degree of food and water insecurity caused partially by climate variability, it is argued that improved rural accessibility is vital to reducing the number of highly vulnerable communities, and increasing rural resilience. In this paper, a geospatial indicator-based risk and vulnerability assessment method was applied as a tool for determining rural access roads that are highly vulnerable to changing climate in Ethiopia. The assessment is intended to help guide, through prioritisation, the identification of highly vulnerable areas where appropriate climate adaptation measures would be most effective in reducing the impacts of climate variability and change. The research methodology relies on using GIS processes and spatial data to calculate a composite vulnerability index, the combined output of a hazard exposure index as well as a road criticality index, for identifying regions most at risk. It was found that almost half of Ethiopia's districts, mostly in the Awash River Basin and southern Somali lowlands, are highly vulnerable to a changing climate in terms of the impact on rural accessibility. The paper further elaborates on the processes used to identify major climate hazards affecting roads in Ethiopia as well as open source data sets used in this analysis. The methodology was validated through an elaborate stakeholder engagement process and was found to be an accurate, efficient and effective way of identifying high-risk regions in terms of community dependence on roads for accessibility and the physical impact of climate on road infrastructure in Ethiopia.

Key Words: GIS; Risk; Vulnerability; Composite Indicator; Rural Access; Resilience; Climate Hazard; Climate Change; Climate Adaptation; Risk Management; Ethiopia

1. Introduction

The last century has seen a steady increase in the frequency and magnitude of extreme weather-related disasters globally, with Africa being one of the most vulnerable regions to the impacts of climate change. Rural communities in sub-Saharan Africa are among of the worst affected by these climate disasters in part due to high socio-economic vulnerability, natural resource dependency and low adaptive capacity. The impacts of a changing climate are already being felt widely across many development sectors. For the transport sector, climate-resilient road infrastructure in rural areas is important for improving economic productivity and quality of life by enabling sustained access to markets and essential service points such as health-care and educational facilities (Hine *et al*., 2016). Ethiopia is no stranger to the devastating effects of climate-related disasters. According to UN Habitat (2014), Ethiopia is among the 15 most vulnerable countries in the world. The country is especially vulnerable to climate hazards and has seen 73 weather-related disasters affecting an estimated 74 million people over the past four decades (1977–2017) (CRED, 2018).

Agriculture forms the foundation of the Ethiopian economy and employs an estimated 80% of the labour force (CSA, 2015). The agricultural sector comprises mainly subsistence farming and predominately rain-fed agriculture, which is extremely vulnerable to climate variability and change. The high socio-economic dependency on rain-fed agriculture makes the country especially vulnerable to hydrological, climatological and meteorological hazards (GFDRR, 2011; IFAD, 2017). High dependency on natural resources, high rural isolation and significant environmental degradation (due to unsustainable land-use practices) have exacerbated the vulnerability of the country's rural population. The reliance of the economy on Ethiopia's small road network of mostly dry-weather roads makes commerce highly vulnerable to floods and heavy rainfall and affects economic and physical access to food, and the availability and stability of supplies (World Bank, 2006). Due to this high degree of food and water insecurity caused partially by climate variability, it is argued that improved rural accessibility is vital to reducing the number of highly vulnerable communities and increasing rural resilience.

A geospatial risk and vulnerability assessment method was developed as a tool to guide the prioritisation process for selecting rural roads to be constructed, adapted and maintained, in order to limit the impacts of climate variability and change and to ensure better rural access by reducing periods of impassability. The paper focuses on the application of such a geospatial indicator-based risk and vulnerability methodology with the purpose of assisting the identification of high-risk rural access roads in Ethiopia. Information and data on historical and projected future climate patterns, the existing road network and the socio-economic landscape were collected, processed and used to determine where roads could potentially be most affected by changes in climate patterns, so as to support prioritisation and climate adaptation decision-making in the most vulnerable areas of the country.

2. Methodology and implementation

For the purpose of this analysis, disaster risk is defined as a function of climate hazards, road exposure and vulnerability in terms of rural community access and road condition. This is adopted from the concept framed by the International Panel on Climate Change Working Group 2 - Fifth Assessment Report (Niang *et al*., 2014). In particular, the following definitions apply:

- **Hazards:** Climate-related events that can possibly cause damage to and/or interruption of service of rural low volume access road infrastructure as well as potential loss of life (e.g. floods)
- **Exposure:** Location and condition of rural access road facilities, the associated structures and road environment as well as rural communities in places that could be adversely affected (e.g. poorly planned development within a hazard footprint, such as a flood plain)
- **Vulnerability:** Propensity to be adversely affected, considering the dependence of rural communities on these rural access roads (e.g. socio-economic poverty and increased vulnerability due to bad land use practices leading to environmental degradation).

Disaster risk is determined by the occurrence of a natural hazard (e.g. flood), which may impact exposed populations and assets (e.g. rural communities and rural access roads located in flood-prone areas). Vulnerability is the characteristic of the population or asset making it particularly susceptible to the damaging effects imposed by the hazard (i.e. rural access roads in poor condition). Poorly planned development, socio-economic vulnerability, environmental degradation and climate change are all driving forces that increase the magnitude of these interactions, increasing the damaging effects of large disaster events (Figure 1) (World Bank, 2013).

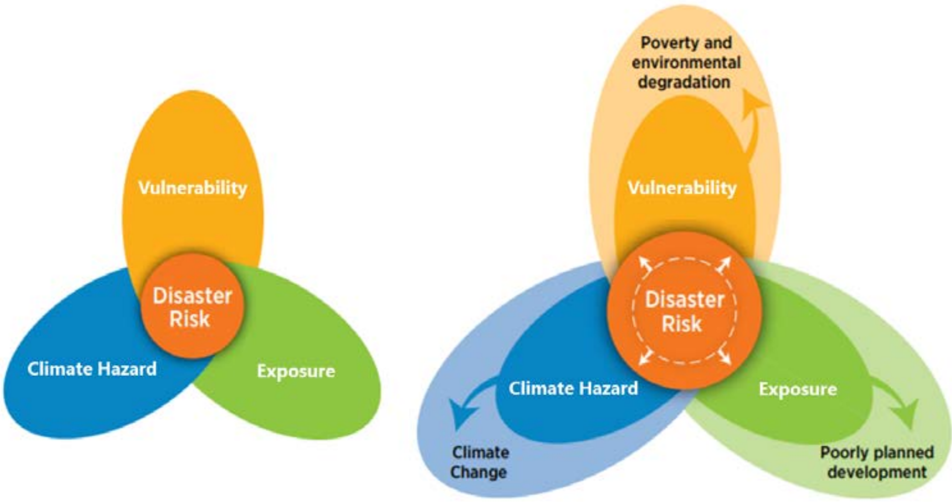

Figure 1. Conceptual framework for climate-related disaster risk as an interaction between climate hazards, exposure and vulnerability of human and natural systems (World Bank, 2013)

A risk and vulnerability assessment method (Figure 2) was developed that delineates districts within a country where roads are most vulnerable to a changing climate (Le Roux *et al*., 2017). High-risk areas can be identified and interpreted as areas that should be prioritised for road construction, adaptation or maintenance. Therefore, the method provides information that can be used to support the development of a climate adaptation strategy for rural access roads and guide investment decisions in Ethiopia.

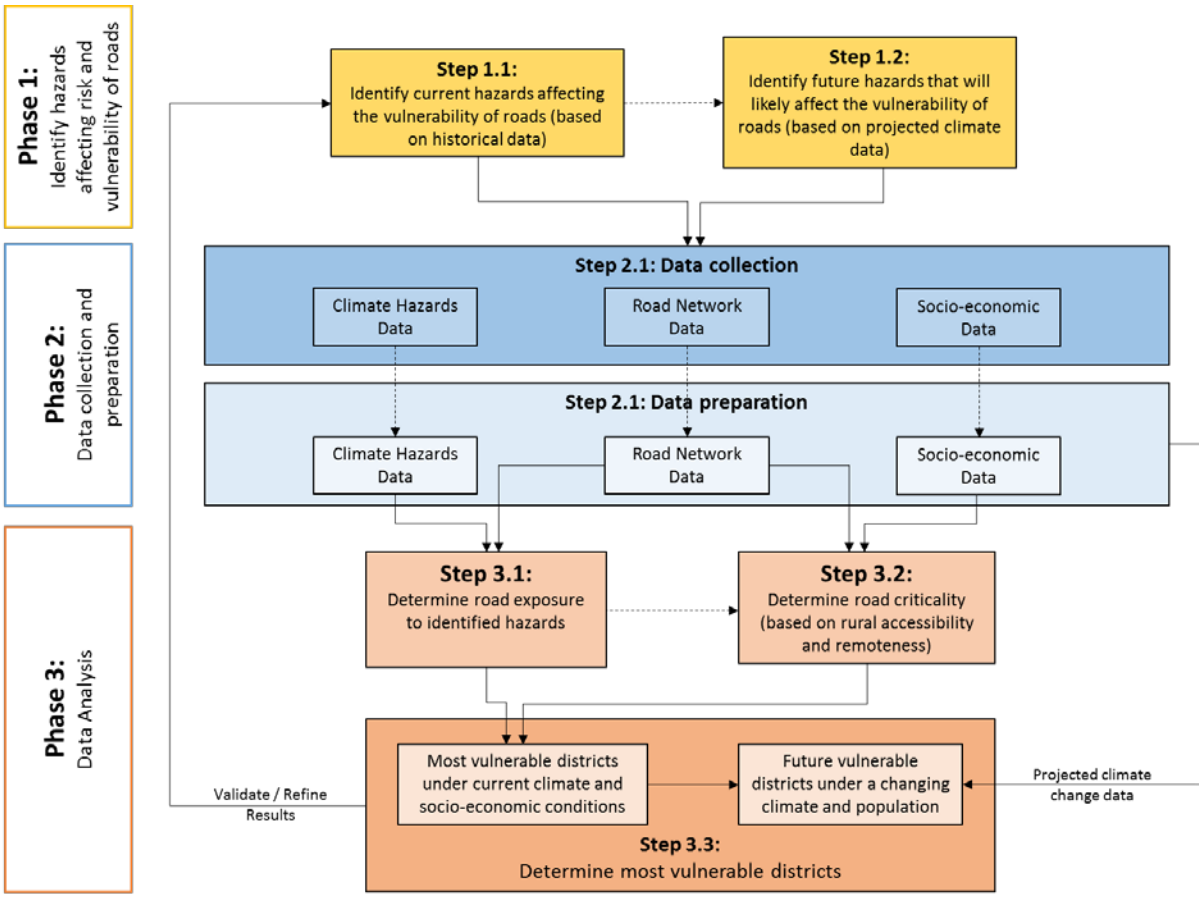

Figure 2. Conceptual framework for the rural access road risk and vulnerability assessment

Based on the framework, a semi-quantitative indicator-based risk and vulnerability assessment method was developed and refined through three full-scale analyses for three African countries, namely Mozambique, Ethiopia and Ghana (ReCAP, 2018). Through the indicator-based method, climate-related risk and vulnerability of rural roads was compartmentalised into key factors, namely the physical impacts of climate on the road, impacts on the surrounding environment and the degree of dependency of the community on the road (accessibility). For each factor, input data were identified and processed, eventually resulting in spatial layers for each factor for which decision theoretic techniques (mainly ranking) could be used for aggregation into a single index of vulnerability (Satta, 2014). The choice of this method was motivated by the need for a method that can be applied to the different rural access road and climate typologies that exist in different countries or regions, bearing in mind the data resource constraints that exist in Africa. The advantage of this method is the use of a geographic information system (GIS) for the curation, management and communication of all input data, composite indicators and the final vulnerability index.

The detailed rural access road risk and vulnerability assessment framework consists of three phases, each with a number of steps, and is based on the core adaptation framework developed by Dowds and Aultman-Hall (2015). Conceptually, the detailed risk assessment is similar to typical protocols used internationally for assessing adaptation needs in the road infrastructure sector (Dowds & Aultman-Hall, 2015). Figure 2 shows the three key phases which may be iterative in some cases, conceived as follows:

Phase1: Identify hazards affecting the risk and vulnerability of roads

The aim of this phase was twofold; firstly, to analyse historical natural disaster data in order to identify the climate hazards that most affect the vulnerability of rural access roads, and secondly to use the identified hazards to inform an investigation into the future hazard risk that could affect the vulnerability of roads under projected climate change conditions (Koetse & Rietveld, 2009). In the context of this case study, the assessment framework was applied in Ethiopia for both the current situation as well as for projected future scenarios, where future refers to the near-future (2021–2050).

The threat identification process started as a desktop literature research exercise in which country level assessment reports were used to contextualise the case study area. Thereafter four decades (1977–2017) of natural disaster data from the EM-DAT international disaster database (CRED, 2018) were analysed by aggregating and mapping natural disasters, severity and affected people at both a continental scale (between African countries) and at a national scale for Ethiopia per hazard. In particular, the occurrence and impact of six climate-related hazards were assessed, including droughts, extreme temperature, floods, landslides, storms (including cyclones) and wildfires. Based on this analysis, flooding disasters were identified as the most frequent climate hazard in Ethiopia (Table 2), and the hazard most damaging to road infrastructure and rural accessibility. According to Chinowsky and Arndt (2012), based on flood return periods in a region, a 100-year flood can be assumed to damage up to 30% of unpaved and 10% of paved roads. Furthermore, flash floods and seasonal river floods are known to pose a significant challenge to Ethiopia's already vulnerable communities (GFDRR, 2011). Approximately 90% of Ethiopia's roads network is composed of dry-weather roads that cannot be used effectively during the four-month-long rainy season due to poor conditions and inadequate river crossings (World Bank, 2006). Flood statistics (frequency and intensity) therefore formed the basis for the climate hazard analysis. Given the challenge in the availability of geospatially referenced design flood statistics, the proposed solution was to infer flood potential based on georeferenced historical recorded flooding events, supported by high-resolution physical climate modelling and locally sourced community knowledge accessed through a series of cross-disciplinary and inter-departmental in-country knowledge-sharing workshops (described in detail under the validation section) between active role-players, including but not limited to the Ethiopian Roads Authority (ERA), Ministry of Transport, National Meteorology Agency and Ministry of Environment.

Phase2: Data collection and preparation

The aim of this phase was to identify, source and collect the data necessary to do the district-level climate risk screening. Several data sets on road assets, climate hazards (both current and future) and socio-economic conditions were sourced and processed. Table 1 shows the list of spatial variables considered for implementing the district-level indicator-based risk and vulnerability assessment. This compendium outlines those variables that would be expected to be available in a basic data set from any country to enable the road risk assessment.

Table 1. A compendium of indicators that are relevant for a district-level* indicator-based geospatial risk and vulnerability assessment of rural access roads to climate change

Risk assessment components	Indicators
Road asset classification	Road network length (disaggregated by class)
Current climate hazards (Historical flood events)	Flood occurrence frequency and intensity Flood-prone areas
Future climate hazards (Projected climate change)	Increases in extreme rainfall events (days per year with rainfall above 20 mm in 24 hours) Increases in extreme temperature events (very hot days) (days per year where the temperature exceeds 35°C)
Socio-economic conditions (Criticality of rural access roads)	Population distribution and density (number of people per 1 km^2) Percentage of population living within 2 km of an access road

* In Ethiopia, administrative district boundaries are formally referred to as zones.

Many open source data repositories were consulted to provide information on the prevailing and historical socio-economic and environmental conditions, as well as the climate hazards. These included boundary data from Diva GIS (2017), basemap images from Esri online map portal (Esri, 2018), population data from WorldPop (2017), flood records from the Dartmouth Flood Observatory (2017) and historically recorded natural disasters from the EM-DAT database (CRED, 2018). These data sets were supplemented with country-specific information and reports about the national road network. Once data were obtained, general data preparation was done to ensure that the data were ready for analysis. This included verification of the accuracy (in terms of its fitness for purpose) of data items and transformation into workable spatial data format.

As part of the future scenario for Ethiopia (until 2050), detailed projected changes in climate were obtained by further downscaling the output of two global climate model simulations (GCMs) that were included in the Coupled Model Intercomparison Project Phase Five (CMIP5) and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (CMIP5) (IPCC, 2013). The downscaled 50 km resolution ACCESS1-0 and CNRM-CM5 global models from Australia and France respectively were selected for further downscaling to very high resolution over the three AfCAP countries selected for research in this project, namely Mozambique, Ethiopia and Ghana. Each of these further downscalings was performed over a domain of 1500 x 1500 km^2 centred over each country, resulting in climate data sets with a spatial resolution of 8 km (Figure 3). The regional climate model used for downscaling was the conformal-cubic atmospheric model (CCAM) of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (McGregor, 2005; Engelbrecht *et al*., 2009). The 8 km high spatial resolution climate simulations correspond to the low-mitigation scenario (Representative Concentration Pathway 8.5; RCP8.5) for the near-future period of 2021–2050, while historical climate simulations were generated for the period 1961–1990 (Engelbrecht *et al*., 2015). Two variables were included for analysing projected changes in climate, namely the annual number of extreme rainfall events (defined as the occurrence of more than 20 mm of rain over a period of 24 hours) and the annual number of very hot days (defined as days when the maximum temperature exceeds 35°C). National projected changes in urban and rural population distribution were obtained from the urban growth rates data published by UN ESA (2014). These were used in the continental scale assessment of climate vulnerability of rural roads, which was used to select the three countries (Mozambique, Ethiopia and Ghana) as case studies. For the sub-national risk assessments, sub-national population projections were not available at the time. Therefore, population data that were used for analysing the current situation were also used for the future situation analysis.

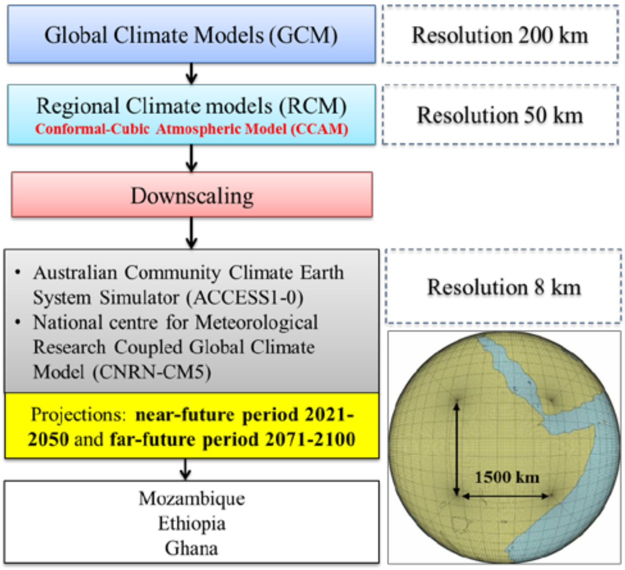

Figure 3. Climate model downscaling

Phase 3: Data analysis

The aim of this phase was to analyse the spatial data collected during the data collection and preparation step using GIS software and principles to analyse the spatially referenced data that were sourced and prepared in Phase 2. The data analysis phase consisted of three integrating steps. The analysis outputs from Step 3.1 (Hazard Exposure) and Step 3.2 (Road Criticality) were combined in Step 3.3 to create a composite indicator for determining which districts are most at risk in terms of current and future climate vulnerability and road accessibility. The computational complexity of this phase required robust GIS analysis, and a validation feedback-loop was therefore incorporated into the framework. These steps are discussed individually below.

Step 3.1: Determine road exposure to identified hazards

As described under the activities of Phase 1, flooding was identified as the climate hazard with the greatest impact on unpaved rural access road infrastructure. To determine the national road exposure to flooding, a flood exposure index was calculated. Here flood potential was inferred by aggregating historically recorded flooding events captured by the Dartmouth Flood Observatory. In the flood index, a lower value indicates a higher vulnerability (Figure 4). The parameterisation of the flood exposure index was a product of the data distribution of national flood events over the past four decades.

Flood events in past 4 decades		Flood Exposure Index
	0 – 3	5
	4 – 6	4
	7 – 9	3
	10 – 12	2
	> 12	1

Figure 4. Parameterisation of flood exposure index

Step 3.2: Determine road criticality (based on rural accessibility and remoteness)

At district level, the road criticality assessment is used to evaluate the importance of rural access roads to the communities (districts) they serve (i.e. number of people a road serves and/or number of people without access). The road criticality index is an aggregation of the Rural Access Index and population isolation, calculated per district (Figure 5). The Rural Access Index (RAI) is a standard indicator developed by the World Bank to measure the rural population who live within 2 km (20–25 minutes of walking time) of an access road as a proportion of the total population (Roberts et al., 2006). Factors that were considered in the RAI included:

- Population distribution and density
- Road network density (coverage)
- Population within 2 km of an access road
- Population without road access (in terms of both number of people and percentage of population).

For this project, it was considered necessary to give preference to districts where larger populations reside and are without adequate access to a road network, leaving these populations isolated and cut off from ready access to essential markets and service towns during flood disasters in which critical roads are inundated with water. For this purpose, an isolation factor was calculated as a component of the road criticality index. Isolated districts were defined as those where more than 50% of the population lives further than 2 km from an access road, and where this accounts for 600,000 people or more. Road criticality is the sum of the Rural Access Index, less the isolation factor.

Percentage of Population within 2 km of an access road		Rural Access Index (RAI)
	< 15%	1
	15% - 30%	2
	30% - 50%	3
	50% - 70%	4
	70% - 100%	5

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Criteria	Isolation Factor
Districts where more than 50% of the population lives further than 2 km from an access road, and where this accounts for 600,000 people or more	1
All other districts	0

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Road Criticality Index

Figure 5. Calculation and parameterisation of road criticality index

Step 3.3: Determine most vulnerable districts

In order to determine the most vulnerable districts, the flood exposure index and road criticality index were aggregated to identify highly vulnerable districts most at risk in terms of current climate vulnerability and accessibility (Figure 6). Furthermore, the exposure of the road network to increases in extreme rainfall events (days with more than 20 mm of rain over a period of 24 hours) as well as the exposure of districts to increases in very hot days (days when the maximum temperature exceeds 35°C) were quantified, indicating districts that are most vulnerable to future changing climate. The current and future scenarios are presented concurrently in the framework (Figure 2), but in practice these can be done as two successive analyses.

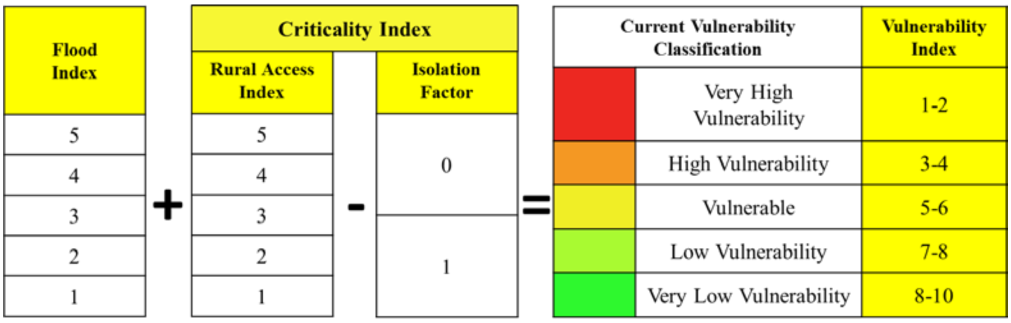

Figure 6. Calculation and classification of composite vulnerability index

The information and maps generated from the vulnerability assessment are used to communicate all the current and future challenges that rural communities and connecting rural access roads face nationally and are further used to inform the prioritisation of roads for construction, adaptation or maintenance.

3. Results

The previous section outlined a geospatial, generic, semi-quantitative and rapid assessment method for risk and vulnerability studies in resource-stricken African countries. The method was designed to facilitate the identification of districts most vulnerable to the current and changing climate in terms of impact on rural accessibility. This methodology was applied and refined for Mozambique, Ethiopia and Ghana. The analysis presented in the subsequent section documents the results of the Ethiopian study. The results of the current situational analysis are provided, followed by the future scenario analysis for the road network and rural accessibility vulnerability under projected climate change scenarios.

3.1 Climate hazards

Flooding and droughts are the most frequent weather-related hazards, posing significant risks to rural communities, infrastructure and rural accessibility in Ethiopia (Table 2). Droughts have been particularly devastating with respect to the loss of lives and livelihoods. Thirteen drought disasters in the past four decades resulted in the death of over 300,000 people and affected almost 71 million people. Floods, in the form of flash floods in the highland areas and riverine floods in the lowlands, are the most frequent climate hazard that the country has to deal with, and the hazard most damaging to road infrastructure and rural accessibility. Fifty-six flooding disasters affected almost 3.1 million people, displaced nearly 200,000 and killed an estimated 2,500 people between 1977 and 2017. Flood disasters are occurring at increasing frequency and greater intensity across the country (Figure 7).

Table 2. Hazard frequency and impact in Ethiopia (1977–2017), calculated from EM-DAT database

Hazard	Number of events (1977–2017)	Total deaths	Total affected
Drought	13	300,367	70,941,879
Riverine flood	32	1,105	1,809,978
Flash flood	8	863	929,358
Other flood	16	564	352,788
Wild fire	1	-	5
Landslide	3	39	194
Total	**73**	**302,938**	**74,034,202**

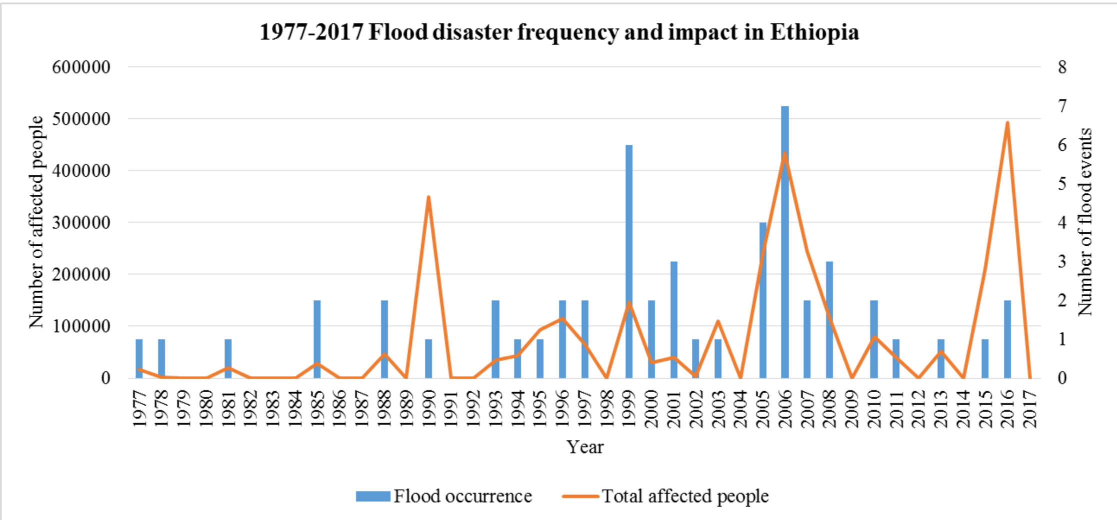

Figure 7. Flood disaster frequency and impact in Ethiopia between 1977 and 2017, calculated from EM-DAT database

3.2 Flood exposure index

The output analysis of the flood exposure index is illustrated in Figure 8. Largescale floods occur mostly in the lowland areas, including the Awash River Basin which forms part of the Rift Valley, and the southern Somali lowlands (specifically in the Shabelle district, the namesake of the river that runs through the district and neighbouring Afder district bounded by the Genale River). Flash floods resulting from intense rainfall events over highland water catchment areas destroy settlements and infrastructure downstream. A number of internationally important watersheds originate from the flat-topped hills of the Ethiopian highlands, including the Awash River in the Rift Valley; the Shebelle River in the Somali region; the Omo River in the south; and the Blue Nile, which arises near Lake Tana in the highlands and later flows into Sudan and Egypt.

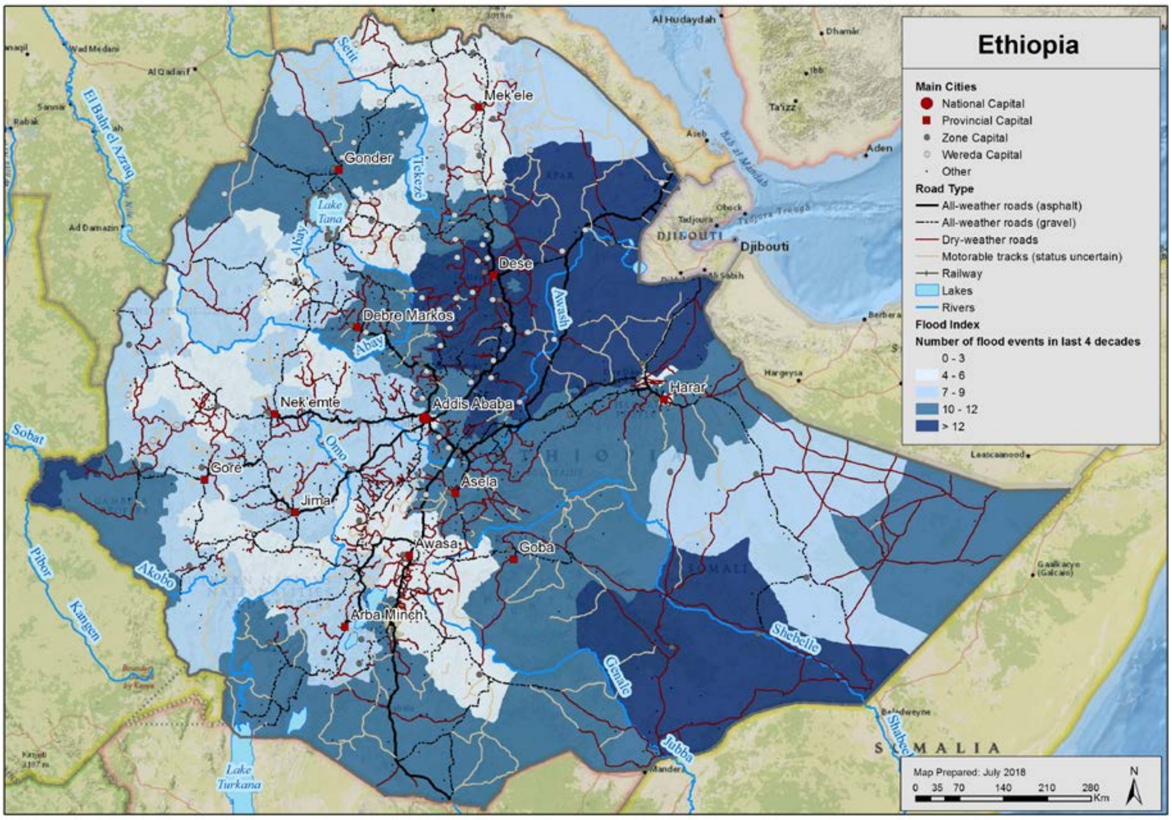

Figure 8. Ethiopia’s most flood-affected areas over the past four decades and location of dry-weather roads in flood-prone areas

The majority of the roads in these flood-prone areas are dry-weather roads (Figure 8) that cannot be used effectively during the rainy season due to poor conditions and inadequate river crossings, making communities that depend on these roads for access to marketplaces and services highly vulnerable to floods and heavy rainfall.

3.3 Road criticality index (based on rural accessibility and isolation)

The Rural Access Index (RAI) calculated for Ethiopia is depicted in Figure 9. The index considers people within 2 km of an access road. The most notable characteristic of the Ethiopian road network is that most all-weather roads radiate outwards from Addis Ababa (the capital) to major towns (Figure 9). Rural roads play a vital role in connecting isolated rural communities with economic centres, markets and basic social services, but the Ethiopian Roads Authority has acknowledged that the limited road network coverage of the existing road network, coupled with poor surface conditions in many instances, is a major obstacle to economic recovery and economic growth, especially in times of climate-related crisis. In this way, large parts of the country are faced with inadequate road access as indicated in Figure 11, where only eight of Ethiopia’s 74 districts have an RAI of 50% or higher, and only three of these districts have an RAI of more than 70%. These districts fall within the central highlands of the country. The east of the country, especially districts in the Somali province that borders Somalia, have the poorest rural access nationally. Here more than half for the districts have an RAI of less than 15% (i.e. less than 15% of the population in these districts live within 2 km of an access road).

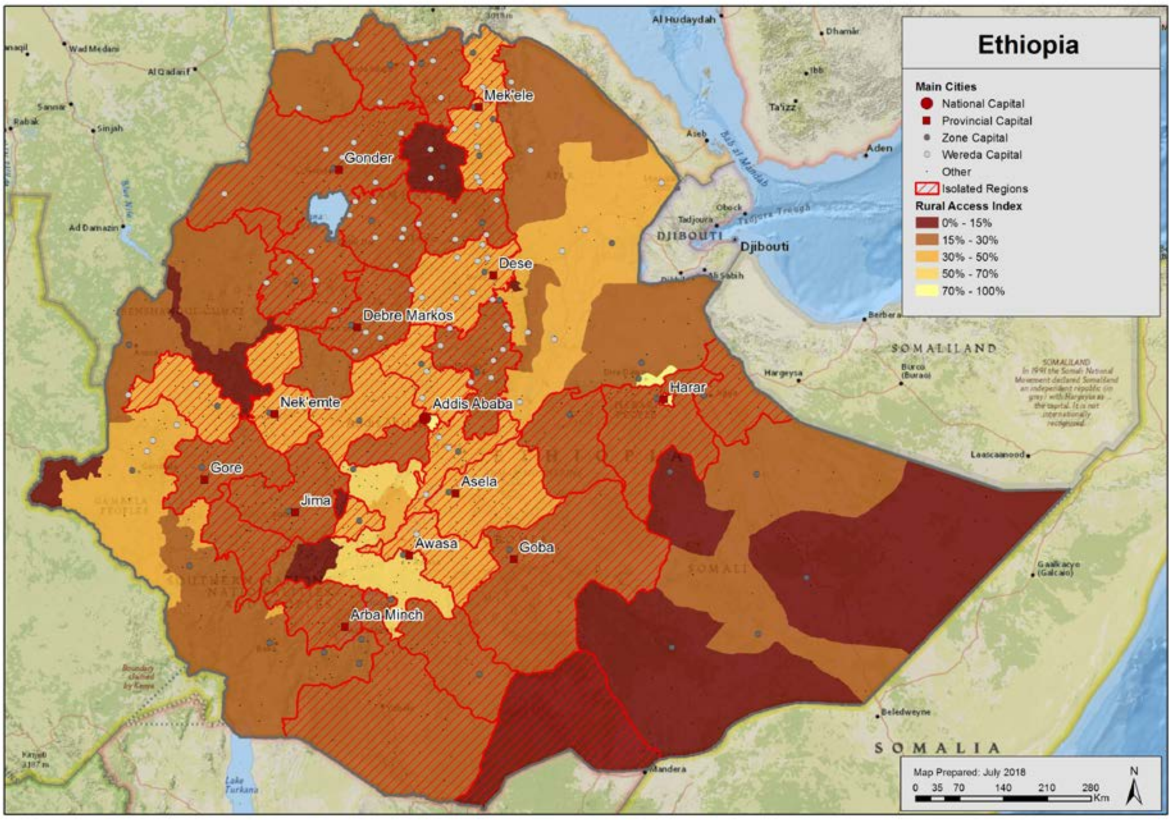

Figure 9. Rural Access Index and isolated regions calculated for Ethiopia

Figure 9 also shows highly isolated regions, where larger populations reside without adequate access to a road network. Thirty-two districts (many of which are in the Oromia, Amhara and Tigray provinces) have more than 50% of the population living further than 2 km from an access road, accounting for 600,000 people or more having inadequate access to a road network. Kamashi district in the west is seen as the most isolated district (in terms of the percentage of people without access), followed closely by Korahe district in the east, both with less than 20% of their population having 2 km access to a road network.

3.4 Highly vulnerable regions

The vulnerability index for Ethiopia is mapped in Figure 10. This is where roads are most vulnerable to changing climate in terms of the impact on rural accessibility and areas that should be prioritised for road adaptation. Almost 84% of districts in Ethiopia are classified as vulnerable (62 districts) due to their high exposure to frequent and severe flooding as well as their low rural accessibility and high isolation rates, with 46% being highly or very highly vulnerable. Here, areas in red and orange depict high vulnerability given their exposure to frequent and severe flooding (flood exposure) as well as districts where road criticality is key due to high isolation. The index gives preference to districts where larger amounts of people are without adequate access to a road network. The most vulnerable districts are in the eastern half of the country, located in and along the ridge of the Awash River Basin, in particular in the North Shew district to the east of Addis Ababa. The majority of districts in the southern Somali lowlands of the Somali Province are also highly vulnerable, including the Liden and Afder districts that are classified as very highly vulnerable. The Nuer district in the far western corner of the country is also very highly vulnerable given the district's exceptionally low RAI and proximity to the Pibor River that forms the border with South Sudan.

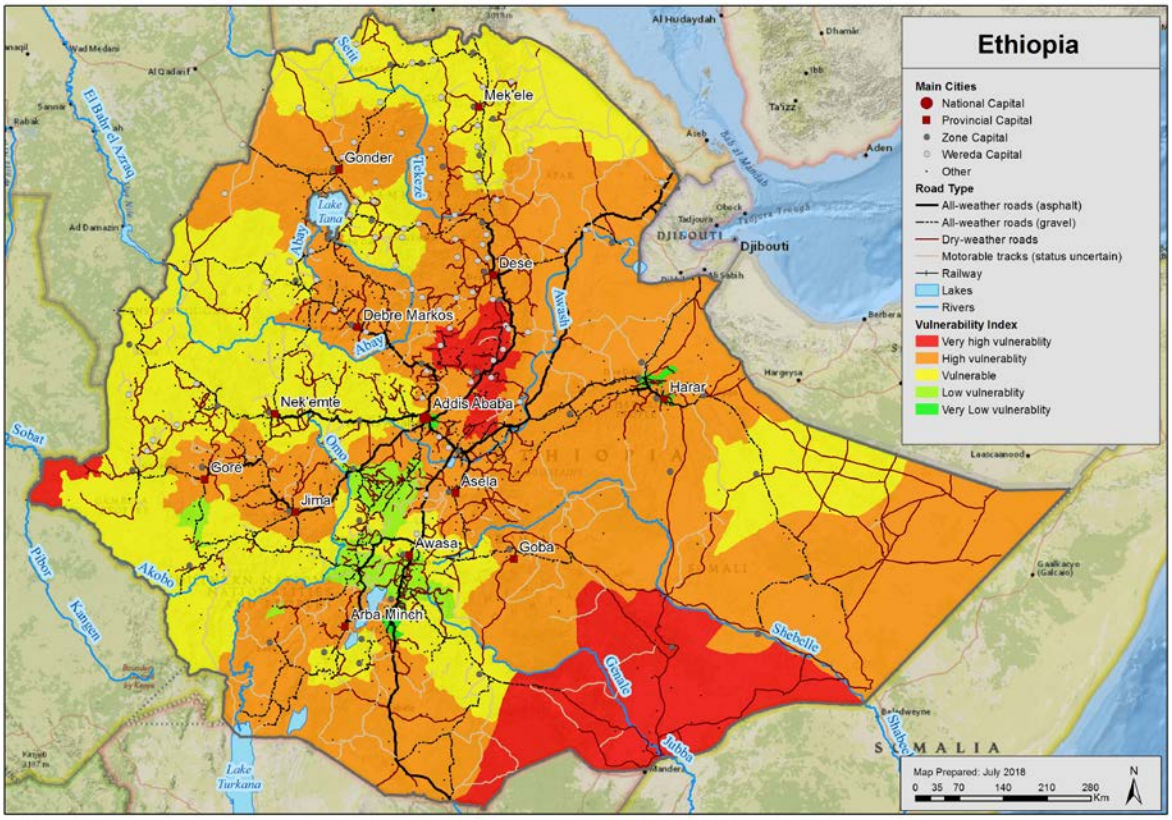

Figure 10. Ethiopia's most vulnerable districts in terms of flood exposure and road criticality

3.5 Projected climate change

The CNRM-CM5 downscaling for the near-future period of 2021–2050 was used to map the projected change in the annual number of extreme rainfall days (number of events per grid point per year) over Ethiopia, together with the highly and very highly vulnerable districts as an example of the risks that extreme rainfall events may plausibly pose to Ethiopia in the future. The annual number of extreme rainfall days (days with more than 20 mm of rainfall in 24 hours) are projected to increase substantially along the ridge of the Afar depression (Figure 11). The already highly vulnerable communities around the Awash River Basin and Rift Valley have historically been faced with the greatest exposure to severe flooding events (Figure 8) and may be affected most by such increases in extreme rainfall events. Increases in extreme rainfall events are likely to be associated with increases in flash flooding, especially in regions downstream of the Awash River catchment.

The climate projections from the CNRM-CM5 downscaling indicate that the frequency in the occurrence of days when the maximum temperature exceeds 35°C will increase throughout the lowland areas of Ethiopia (Figure 12) into the near-future (2021–2050). The largest increases are projected for the lowlands bordering Somalia towards the southeastern corner of the country where the infrastructure is almost exclusively dry-weather road or gravel.

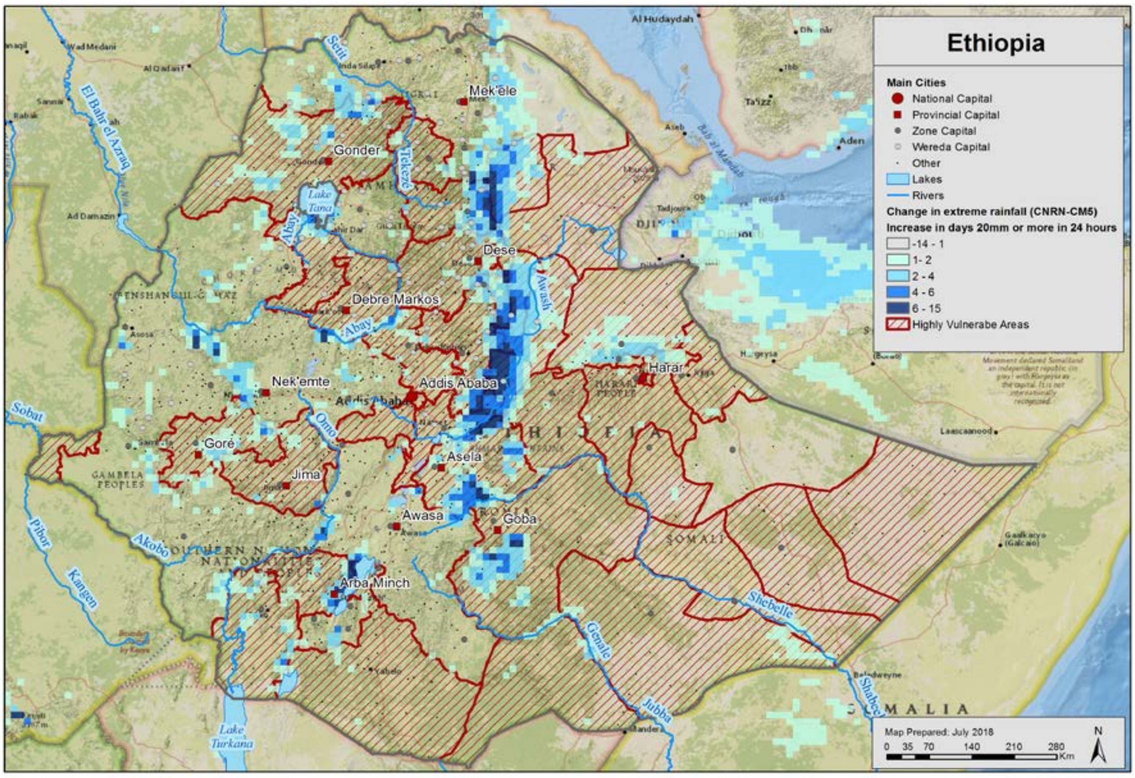

Figure 11. Exposure of Ethiopia's vulnerable communities to increases in extreme rainfall events

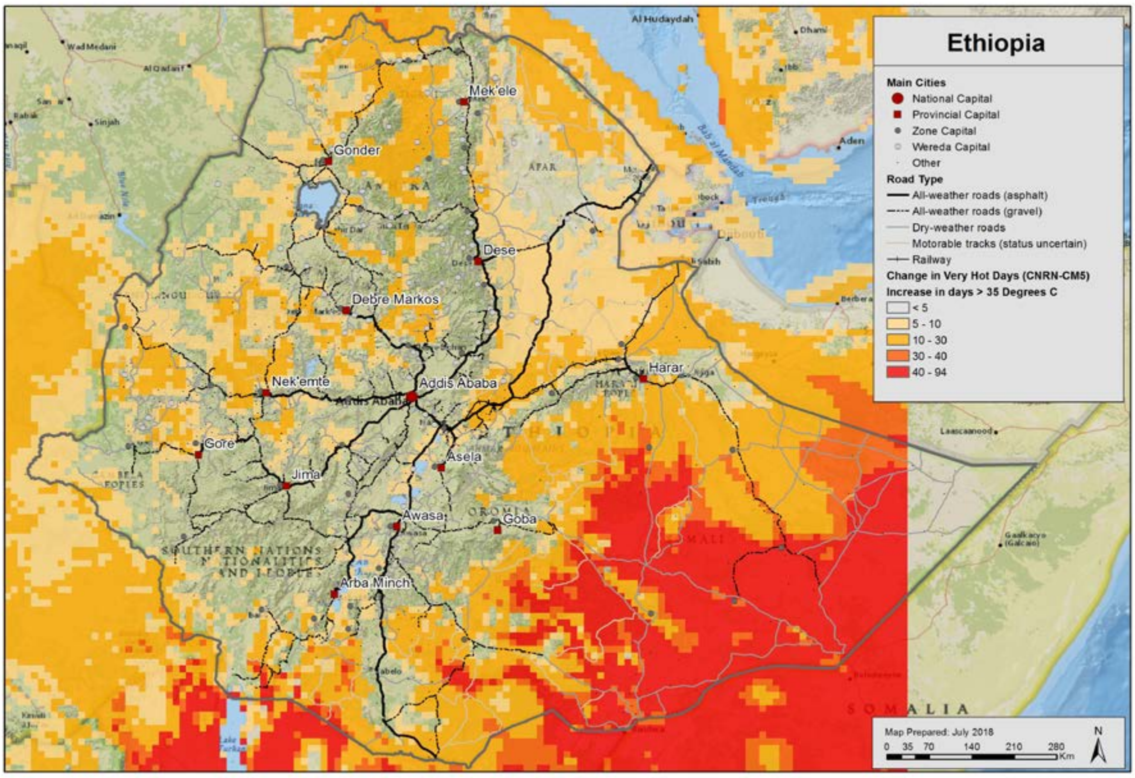

Figure 12. Exposure of Ethiopia's road network to increases in very hot days

4. Validation

One of the greatest challenges in carrying out such an analysis in resource-stricken countries is data availability. The quality and quantity of the available data vary between African countries. Through a series of early engagements during the development stages of this work, it was clear that in-house datasets needed for undertaking these analyses were either not available or of poor quality. To facilitate the repeatability of this method in the three countries for which research was done (Mozambique, Ethiopia and Ghana), open source data were used as a substitute, although this approach is only advocated if no better data exists. It was paramount therefore that the results from this analysis be validated by a panel of key country experts to ensure the accuracy of the outputs. Therefore, a qualitative validation process was followed, namely the soliciting of expert opinion during three separate in-country workshops in each of the three countries (Mozambique, Ethiopia and Ghana), a total of nine workshops in total, between 2016 and 2018. In Ethiopia, the local or country experts consisted of road climate adaptation stakeholders from the various departments of the Ethiopian Roads Authority (ERA), as well as representatives from the Ministry of Transport, Ministry of Environment, National Meteorology Agency, Geological Survey of Ethiopia, Addis Ababa Science and Technology University, Ethiopian Academy of Sciences, Ethiopian Construction Project Management Institute, World Bank and external road engineering consultants interested in issues of climate change (Verhaeghe *et al*., 2017; Verhaeghe *et al*., 2018; Maritz *et al*., 2018). Comments and responses to the workshop feedback surveys were used to refine the methodology, to confirm the assumptions made about the historical prevalence of identified climate hazards and to assess the accuracy of the index in terms of what is known about the districts from local officials and officials from other development agencies. Further, through these engagements, the fitness for purpose of the open source data used in this analysis could be evaluated.

5. Discussion

Ethiopia’s current population is almost exclusively rural (Figure 13), with only a small minority of people currently living in urban areas. The rural population is expected to grow to 117 million people by 2050, thereby adding 37 million additional people in rural areas and placing substantially more pressure on land and natural resources management as well as exposing more people, livelihoods and economic activity to the climate-related hazards highlighted in this research. Given Ethiopia’s almost exclusive reliance on agriculture for both sustainable livelihoods and poverty reduction, such a rapid population increase will place great strain on the country’s natural resources, potentially accelerating already high levels of erosion, land degradation, deforestation and desertification.

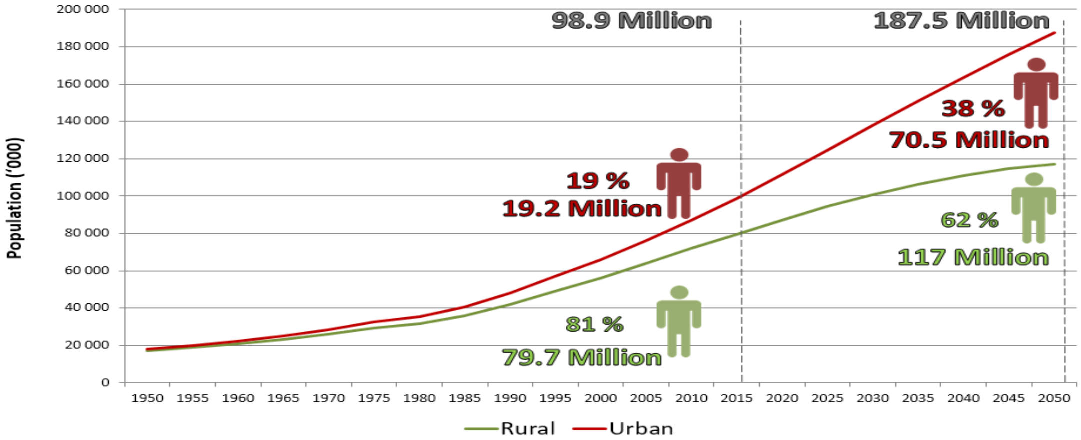

Figure 13. Ethiopia's projected population growth (1950–2050) adapted UN ESA data (2014)

Due to increasing vulnerabilities imposed by increasing climate variability and poorly planned development, natural disasters may be expected to occur at greater frequency and intensity across the country, and millions more rural people will be placed at risk in addition to placing more strain on the insufficiently developed water resources, sparsely available social facilities and inadequate road infrastructure. Improving rural accessibility is therefore vital to reducing the number of highly vulnerable communities and increasing rural resilience. Within the National Roads Authority, the district-level vulnerability assessment framework needs to interface with adaptation planning activities, and should be used to inform the prioritisation of engineering and non-engineering adaptation options in the most highly vulnerable districts.

A limitation in the study currently is that sub-national population projections were not available, and therefore the future population distribution was not considered in the 2021–2050 assessment. To overcome this limitation, further work is planned on developing methods to downscale national population projections using the high spatial resolution WorldPop data.

6. Conclusion

This paper set out to present the application of an indicator-based risk and vulnerability method that relies on using freely available spatial geographical data to facilitate the identification of rural access roads that are highly vulnerable to changing climate in Ethiopia. The output of the district-level assessment identified potential high-risk areas where roads and rural communities are most vulnerable to the effects of a changing climate in terms of the impact on rural accessibility, and the areas that should be prioritised for climate-resilient road construction, adaptation and maintenance. The information and maps generated from the vulnerability assessment show the main current and future challenges for rural roads in Ethiopia that require attention. The methodology has proved to be an efficient and effective way of identifying high-risk regions in terms of community dependence on roads for accessibility and the physical impact of climate on road infrastructure, despite the spatial data constraints inherent in most African countries, Ethiopia included. Regional support and guidance on the development of climate-resilient road infrastructure are vital for ensuring that sustainable and inclusive development materialises in vulnerable rural areas most at risk to the cumulative effects that climate changes bring. Climate-resilient road infrastructure in rural areas is critical for improving the quality of lives of rural communities by enabling the sustainable enhancement of economic productivity in rural areas through access. Embedding climate adaptation planning into national decision-making processes is an appropriate mechanism for the Ethiopian Road Authority to use in planning for the unexpected impacts of climate change on the road infrastructure. The climate vulnerability assessment presented in this paper informs the prioritisation of engineering and non-engineering adaptation options available for making rural roads more resilient to changing climate, and this is crucial for effective and efficient asset management even in areas where resources may be limited.

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