EMBEDMENT OF CLIMATIC EFFECTS IN THE ROAD ASSET MANAGEMENT PROCESS

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ABSTRACT

The United Nations Environmental Programme describes the African continent as a 'vulnerability hotspot' for climate change. During the past four decades African countries have experienced more than 1 500 recorded weather-related disasters. Changes to the region's climate are causing widespread damage to road infrastructure and its associated assets. In order to help address this significant threat to Africa's development, the Africa Community Access Partnership (AfCAP), a research programme funded by UKAid, has commissioned a project, starting in April 2016, to produce regional guidance on the development of climate-resilient rural access in Africa through research and knowledge sharing within and between participating countries. The output will assist to develop a climate-resilient road network that reaches fully into and between rural communities. As part of this study, a Climate Threat and Vulnerability Assessment Methodology has been developed that can be applied at a national level to facilitate the identification of regions/districts where the road infrastructure is most vulnerable to a changing climate in terms of the impact on rural accessibility. A second methodology for the assessment of climate risk and vulnerability of rural access roads at a local level has also been developed. Both the district level and local level assessments make use of climate threat data, road network data and socio-economic data. The outcomes from these assessments are a number of indices, both separate and combined, that can be used to rank roads and structures in terms of priority for maintenance or adaptation. Once roads and structures have been ranked in terms of priority for maintenance or adaptation and maintenance and adaptation activities can then be planned, designed and implemented to lead to a rural road network that is more resilient to the impacts of climate change. The district level assessment combines climate threat data and road network data (mainly road condition data) to determine road exposure to identified threats and from determine a road asset vulnerability index. The socio-economic data and road network data are combined to determine a road criticality index. A remoteness indicator expands on a standard RAI by measuring the level of access that a person living within an area (e.g. district) has to a range of services and other functions that are associated with an urban setting. A consolidated view of asset criticality per district is then formed by aggregating the road exposure and vulnerability index and the rural access index. The outcome of the local climate vulnerability assessment is a multi-dimensional vulnerability index. The vulnerability index integrates three composite indicators, namely an indicator of road condition deficiency to the impacts of climate, an indicator of maintenance efficacy, and an indicator of the criticality of the road. The deficiency index and the maintenance index is calculated using data that are gathered by way of a climate impact field assessment during which the road is assessed in 100 m segments. The criticality index is a combination of socio-economic aspects, namely the number of alternative routes available; predominant vehicle types on the road; public facilities reachable by the road; and the dominant topography surrounding the road. The assessment methods presented here should be embedded in road asset management systems, as these are the most appropriate vehicle to store the input data, perform the analysis and apply the outputs in the broader road asset management environment

1. INTRODUCTION

1.1. The Climate Change Issue

Climate change became an internationally recognised issue in 1992 with the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) at the Rio Earth Summit. This agreement is the main international agreement on climate action and started as a way for countries to work together to limit global temperature increases and climate change, and to cope with their impacts. The UNFCCC has since been augmented with the Kyoto Protocol and the Paris Agreement. The Kyoto Protocol introduced legally binding emission reduction targets for developed countries, while with the Paris Agreement, the parties reached a new global agreement on climate change. The Paris Agreement deals with greenhouse gas emissions mitigation, adaptation and finance starting in the year 2020 and presents a balanced outcome with an action plan to limit global warming 'well below' 2°C [4]. Fifty-four African countries have ratified the UNFCCC, and most African countries have also signed the Paris Agreement [17].

According to the United Nation's Inter-governmental Panel on Climate Change's fifth assessment report, climate change will have the biggest impact on the African continent [8]. Due to its geographical position, Africa is particularly vulnerable and has considerably limited adaptive capacity, which is exacerbated by widespread poverty [16]. Climate change is therefore a particularly significant threat to Africa, not only to the continued economic growth of the continent, but also to the sustainable livelihoods of its vulnerable population.

1.2. The Impact of Climate Change in Africa on Road Infrastructure

African temperatures are projected to rise rapidly, at a rate of 1.5 to 2 times that of the global average. The changing African climate is likely to have a range of impacts across the continent as rainfall patterns shifts and extreme weather events become more frequent and intensive [x1]. Over the last century, Africa[1] has been subjected to a steady increase in the frequency and magnitude of extreme weather-related disasters, which have and continue to cause widespread damage to road infrastructure and associated assets. Climate related natural disasters remain a compromising threat to rural accessibility on the continent for increasingly long proportions of the year, creating both direct and indirect adverse effects on livelihoods and associated socio-economic development. In the past four decades (1978 to 2018), African countries have experienced more than a 1 500 recorded weather-related disasters (meteorological, hydrological and climatological) [28]. These disasters impact on the affected countries' economies and, in particular, on rural communities and their livelihoods. The impacts of these weather-related hazards were also felt across all economic sectors and infrastructure [9]. Many communities and countries are socially and economically vulnerable to extreme climate events and a low adaptive capacity and a high exposure to natural hazards have resulted in the death of more than 600 000 people (the vast majority due to droughts), left 8 million people homeless (99% due to flooding and storms) and affected an estimated 500 million people over the past four decades [28].

The African continent is facing a potential direct liability of over $ 150 billion to repair and maintain existing roads damaged by temperature and precipitation changes directly related to projected climate change. The liability does not include costs associated with impacts to critically-needed new roads, nor does it include indirect socio-economic effects generated from dislocated communities and from loss of rural access [2]. It is estimated that an additional 230 million people will live in rural areas in the 15 AfCAP supported and partner countries by 2050, making rural accessibility a high priority [9].

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[1] Focus predominantly on Southern Africa

2. INTRODUCTION TO THE AFCAP CLIMATE ADAPTATION PROJECT

2.1. Project Aim and Objectives

The Africa Community Access Partnership (AfCAP) is a research programme, funded by UK Aid, with the aim of promoting safe and sustainable transport for rural communities in Africa. Considering the climate threats posed to Africa's development and to address some of the abovementioned challenges, AfCAP commissioned a project that started in April 2016 to produce regional guidance on the development of climate-resilient rural access in Africa through research and knowledge sharing within and between participating countries.

The overall aim of the Climate Adaptation - Risk Management and Resilience Optimisation for Vulnerable Road Access in Africa project (the AfCAP Project) is to move forward from previous AfCAP research and deliver sustainable enhancement in the capacity of AfCAP partner countries [1] to reduce current and future climate impacts on vulnerable rural infrastructure. The study covers threats and adaptation for both existing and new infrastructure. This is to be achieved through the research, and consequent uptake and embedment, at both policy and practical levels, of pragmatic, cost-beneficial engineering and non-engineering procedures based on the recognition of locally-specific current and future climate threats.

The fundamental research objective is to identify, characterise and demonstrate appropriate engineering and non-engineering adaptation procedures that may be implemented to strengthen the long-term resilience of rural access, based on a logical sequence of defining:

- Climate threats;
- Climate impacts;
- Vulnerability to impact (risk);
- Non-engineering adaptations (change management options);
- Engineering adaptations; and
- Prioritisation.

The second objective, which focuses on capacity building and knowledge exchange, is to meaningfully engage with relevant road and transport ministries, departments and agencies/authorities in a knowledge dissemination and capacity building programme based on the outputs from the research.

The third objective is to ensure that there is focus on the uptake and subsequent embedment of outcomes aimed at a range of levels from informing national policies, through to regional and district planning, and down to practical guidance on adaptation delivery at rural road level. One of the required embedment actions is the embedment of the climate risk assessments in road asset management and road asset management systems (RAMS), which is the focus of this paper.

2.2. Project Approach and Outputs

The approach taken is circular where science-based research is undertaken to identify climate hazards, vulnerability and impacts on rural road infrastructure. The research outcomes are then integrated with decision-centric processes for prioritising adaptation

[1] AfCAP Partner Countries currently consist of the Democratic Republic of Congo, Ethiopia, Ghana, Kenya, Liberia, Malawi, Mozambique, Sierra Leone, South Sudan, Tanzania, Uganda and Zambia

options, implementation through demonstration sections and both policy and practical embedment of pragmatic, cost-beneficial engineering and non-engineering procedures. The main outputs for this project are a Climate Adaptation Handbook that is supported by three guidelines covering: 1) change management; 2) climate threats and vulnerability assessment; and 3) engineering adaptation.

The Climate Adaptation Handbook is the overarching document and provides relevant information on climate adaptation procedures for rural road access, along with instructions on an appropriate methodology to address climate threats and asset vulnerability, to increase resilience for the foreseeable future. The Handbook has been produced to provide relevant information on adaptive procedures for both new and existing rural access roads. Although produced for low volume roads, the principles also apply to high volume roads, even though there will be differing priorities and design parameters [7]. The Change Management Guidelines are specifically aimed at providing change management guidelines relating to non-engineering adaptation options [6].

The Climate Threats and Vulnerability Assessment Guidelines present the process of conducting a climate threat and vulnerability assessment at national/regional level and at local/project level. The process involves applying the developed semi-quantitative AfCAP risk and vulnerability assessment framework. This framework is used to highlight high-risk areas in terms of climate impacts on low-volume access roads. The results of such an application are meant to guide and support decision making and prioritisation when adapting existing and new road infrastructure to withstand the impacts of climate change [10]. The inputs, analysis and outputs from these climate threat and vulnerability assessments provide the means to embed climatic effects in the road asset management process.

The Engineering Adaptation Guidelines focus on engineering adaptation techniques for handling the expected changes in temperature and precipitation, windiness, seal-level rise and more frequent extreme events. These are specifically related to unpaved roads, paved roads, subgrade materials, earthworks and drainage within and outside the road reserve as well as possible implications for construction activities. The impacts on maintenance practices are also highlighted and guidance given. The crucial importance of effective drainage and timely and appropriate maintenance is highlighted [12].

3. OVERVIEW OF AFCAP THREAT AND VULNERABILITY ASSESSMENT METHODOLOGY

The AfCAP Threat and Vulnerability Assessment Methodology is described in the Climate Threats and Vulnerability Assessment Guidelines and is applied at a national level to facilitate the identification of regions/districts where roads are most vulnerable to a changing climate in terms of the impact on rural accessibility. This is referred to as a district-level assessment and is done to determine where road infrastructure could potentially be most affected by changes in climate and socio-economic patterns. The output of the district-level assessment identifies potential high-risk areas (areas that should be prioritised for road adaptation). These results can then be used to determine where in-depth local-level road risk and vulnerability assessments would be most beneficial [10].

The methodology for undertaking a threat and vulnerability assessment at a district level consists of five phases, each with a number of action steps and is illustrated in Figure 1. The analysis can be done for both the current situation as well as for the projected future scenarios (where future refers to the mid-term (2050) or long-term (2100) future). In the framework presented in Figure 1, the current and future scenarios are presented concurrently, but can also be done as two successive analyses. This analysis is done within a geographic information system (GIS) using spatial data; hence, all the information, from the individual variable layers to the dimension or group indicators and the final index, can be extracted as maps for further evaluation and interpretation.

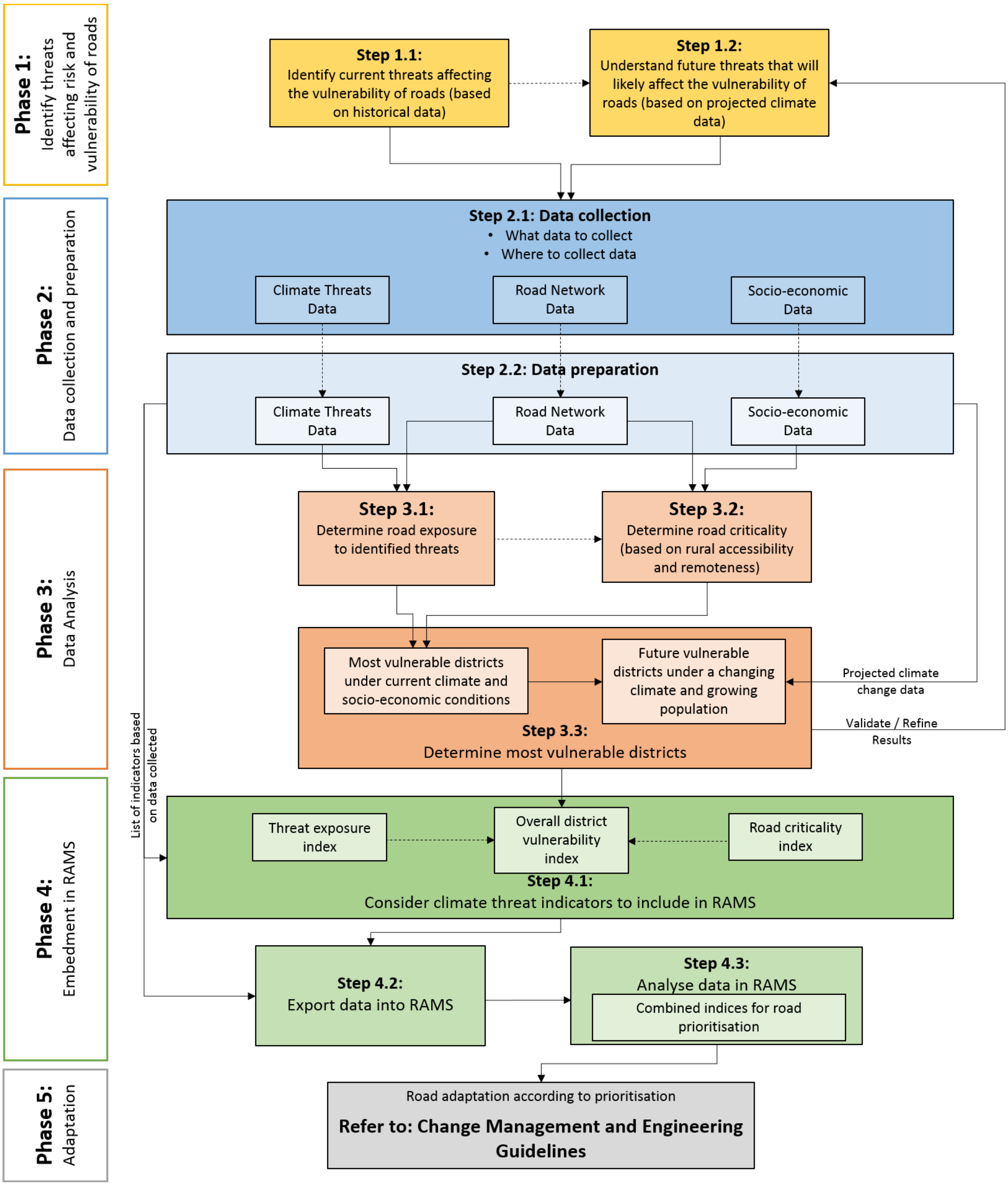

Figure 1 - Framework for Conducting a Detailed Rural Access Road Risk and Vulnerability Assessment [10]

4. EMBEDMENT OF OUTPUTS FROM DISTRICT LEVEL ASSESSMENT IN RAMS

During Phase 1 of the district level threat and vulnerability assessment, historical climate data is analysed in order to identify the current climate threats that most affect the vulnerability of roads. The identified current climate threats are then used to inform the investigation into the future hazards that will likely affect the vulnerability of roads under projected climate change conditions. Two main types of climate-related impacts should be considered for rural roads. These are firstly water-related hazards (inundation by flooding and landslides) as a result of rainfall extremes and secondly road and structure degradation as a result of incremental changes in average rainfall and temperature. Flood hazards have the greatest impact on rural road infrastructure, for example a 1:100-year flood can be assumed to damage up to 30% of unpaved and 10% of paved roads [2].

During Phase 2 of the district level threat and vulnerability assessment, climate threat data, road network data and socio-economic data are collected and then prepared for further analysis by transforming the data from its original state into variables for rural road specific hazard assessment. The climate threats that potentially have the greatest impact on rural roads include:

- Severe flooding events;
- Annual average precipitation;
- Annual average frequency of extreme rainfall events (more than 20 mm of rainfall in 24 hours);
- Maximum monthly rainfall;
- Annual average temperatures;
- Annual average frequency of very hot days (daily temperatures above 32 °C);
- Keetch-Byram drought index; and
- Maximum wind speeds and changes in direction.

Socio-economic data sets are essential for evaluating asset criticality in terms of the accessibility and remoteness of rural areas. Socio-economic data should be sourced in order to prioritise districts according to their road criticality, and data to support this assessment includes:

- Population distribution and density;
- Population living without road access;
- Hierarchy of towns;
- Essential service facility data (health and education facilities); and
- Market locations or GDP production centres.

During Phase 3, the climate threat data and the road network data (mainly road condition data) are combined to determine road exposure to identified threats. For example, the number of climate threat events, such as severe flooding events in the past four decades, are aggregated per district. The road network condition data is then overlaid with the districts most impacted by a specific climate threat; and from this a road asset vulnerability index is determined and can then be mapped. An example of this is illustrated in Figure 2.

The socio-economic data and road network data are combined to determine a road criticality index. The road criticality index is a function of the Rural Access Index (RAI) and a remoteness indicator. The RAI was developed by the World Bank and measures the rural population living within 2 km (20 to 25 minutes of walking time) from an all-weather road passible by four-wheeled vehicles as a proportion of the total rural population [14]. A remoteness indicator expands on a standard RAI by measuring the level of access that a person living within an area (e.g. district) has to a range of services and other functions that are associated with an urban setting.

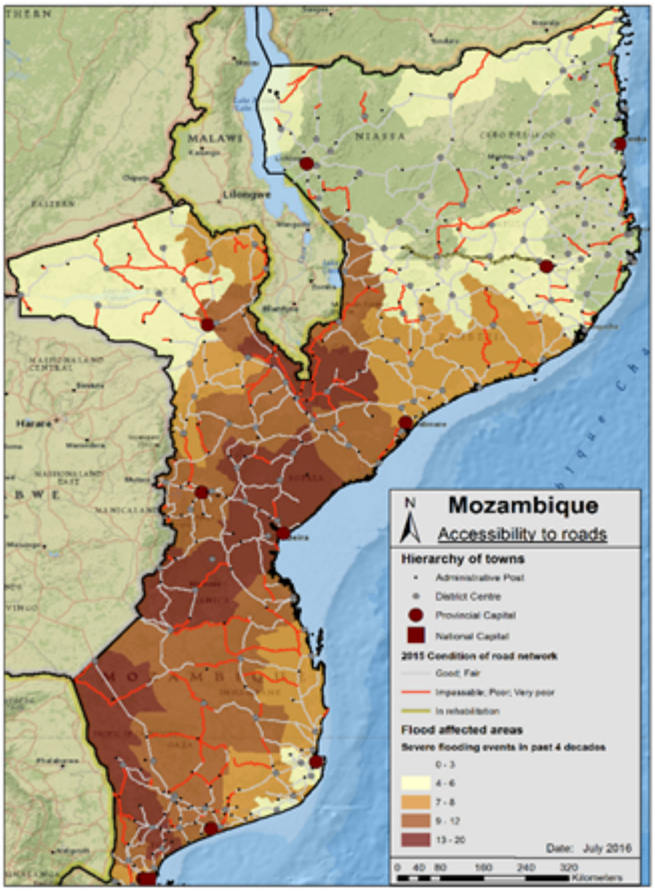

Figure 2: Mozambique Road Exposure to Flooding Threat [10]

Some of the factors to be considered in a remoteness indicator include:

- Hierarchy of towns;
- Essential service facility data (health and education facilities); and
- Market locations or GDP production centres.

A consolidated view of asset criticality per district is then formed by aggregating the road exposure and vulnerability index and the rural access index, which can then be mapped.

Embedment in RAMS is Phase 4 of the district level threat and vulnerability assessment and comprises the following steps:

Step 4.1 Consider which climate threat indicators to include in RAMS
Step 4.2 Export data to RAMS
Step 4.3 Apply/utilise data in RAMS

For the purpose of embedding climate change risks in RAMS, it would be of great value to include data regarding the climate hazards in the RAMS database and to then use this data in prioritisation analysis in the RAMS. Examples of risk assessment components and possible indicators quantified during Phase 3 that would be useful for prioritisation in RAMS are the following:

- Current climate hazards assessment (e.g. historical flood events):
    - Flood occurrence frequency and intensity; and
    - Flood-prone areas.

- Climate change threats assessment, which predicts expected change in the:
    - Annual average rainfall;
    - Annual average temperature;
    - Average number of days per year with rainfall above 20 mm;
    - Number of days per year above 32°C;
    - Maximum monthly rainfall;
    - Average wind speeds (in m/s);
    - Maximum monthly wind speed (period's average);
    - Number of high fire danger days;
    - Keetch-Byram drought index; and
    - Wind-speeds and directions.

By including data regarding the climate hazards in the RAMS database, road asset vulnerability indices for the various climate hazards and climate change threats can be calculated in the RAMS by using the road condition data that is already stored in the RAMS database. These vulnerability indices can then also be updated as and when the road condition data is updated following condition assessments of the road network.

The road criticality index and its components, the RAI and a remoteness indicator can also be stored in the RAMS database. As these indices are determined at a district level, the same values would be allocated to all roads in a district. This would also apply to the climate hazard data. For example, if a particular district has a severe flooding index of 5, all the roads in that district would be allocated a severe flooding index of 5. The main purpose of including the data regarding climate hazards and road criticality in the RAMS would be to identify and rank districts according to their vulnerability to climate change effects and then to focus on the most vulnerable districts when performing a local road vulnerability assessment, which is discussed in the following section.

5. ASSESSMENT OF CLIMATE RISK AND VULNERABILITY OF RURAL ACCESS ROADS AT A LOCAL LEVEL

The purpose of a local climate vulnerability assessment for rural access roads is to identify specific threats that currently affect particular road segments and to assess how likely it is that such threats would intensify (or diminish) in the future. Typical climate-related threats for rural access roads are illustrated in Figure 3.

Figure 3 - Damage to Road Infrastructure due to Climate-Related Environmental Stresses [10]

The outcome of the local climate vulnerability assessment is a multi-dimensional vulnerability index. The vulnerability index illustrated in Figure 4 integrates three composite indicators, namely (1) an indicator of road condition deficiency to the impacts of climate, (2) an indicator of maintenance efficacy, and (3) an indicator of the criticality of the road. The solid circles represent the current situation (or first level of the assessment using observed data) where lower uncertainty is associated with the indices, while the fuzzy edges represents an expectation of increased vulnerability in the future with higher degrees of uncertainty given uncertainties about climate, population and land cover change. The rural road vulnerability index is calculated at road segment level, with segment lengths of 100 m [10].

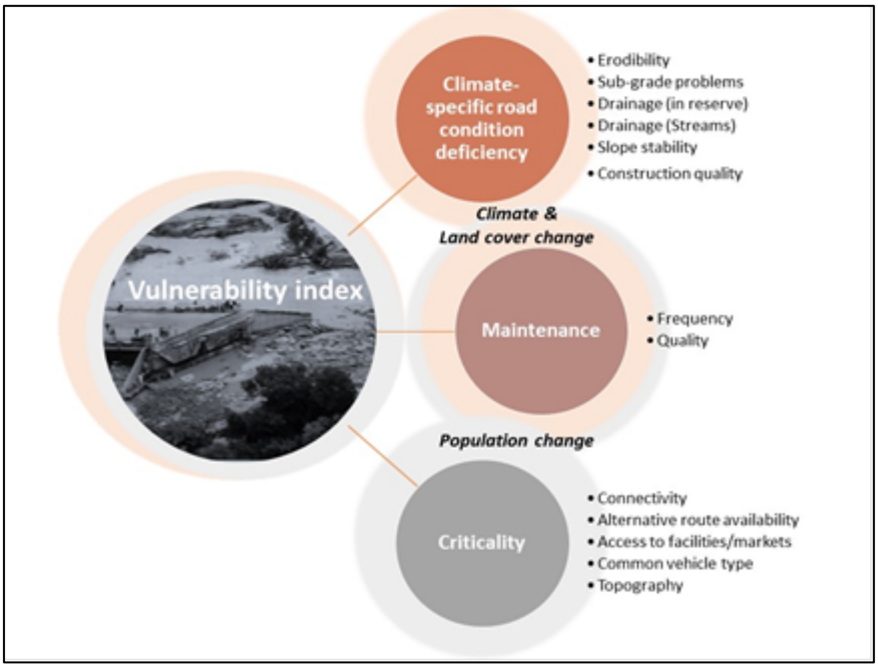

Figure 4 - The Three Dimensions of the Rural Road Vulnerability Index [10]

Road Condition Deficiency is a composite indicator of climate specific deficiencies in road condition and is an aggregation of specific vulnerability factors that represent the physical/structural insufficiency of the infrastructure to withstand negative climate impacts.

The Maintenance factor is an indicator of maintenance efficacy in terms of frequency and quality of maintenance activities.

Road Criticality pertains to the importance of that particular road for access to markets and public facilities. At the local scale, a narrative about the community's use of a particular road is important to put into perspective the losses incurred by the community when access is interrupted due to climate events.

5.1. Assessment and Calculation of the Road Condition Deficiency [10]

The inputs required to calculate the road condition deficiency index (DI) is obtained by way of a field assessment. The typical road assessment, done by road engineers or assessors, requires the assessing and capturing of data relating to structural defects and the overall condition of each road segment. Consideration of climate impacts on the road requires a different kind of field assessment, because environmental factors beyond the road reserve need to be considered. The data collected during the climate impact field assessment should also be captured in a RAMS and the calculations using the data should be done in the RAMS. The aspects and elements to be assessed are summarised in Table 1.

Table 1 - Aspects and Elements Evaluated During Climate Impact Assessment [10] [11]

Aspects and Elements	
Erodibility	**Drainage (streams)**
Subgrade	Structure
Road surface - unpaved	Approach fills
Side drains - unlined	Erosion of approach fills

Aspects and Elements	
Embankment slopes	Protection works
Cut slopes	Flood plain
Subgrade problems	**Slope stability**
Material type	Cut stability
Moisture	Fill stability
Drainage (in reserve)	**Construction**
Road shape	Overall finish
Shoulders	Erosion protection works
Side slopes	
Side drains	
Mitre drains	

An example of the field assessment form used for the climate impact assessment can be found in the visual assessment manual that was developed as part of this project. The whole visual assessment process is also described in detail in this manual [11]. When conducting a climate resilience road assessment, assessors should obtain information from members of the surrounding communities about historical disasters, incidences of impassibility, access to facilities and the availability of alternative routes.

During the field assessment, the assessor evaluates each element in terms of severity and extent. These two dimensions are explained in Table 2 and Table 3 respectively. For each road segment the whole range of aspects and elements listed in Table 1 would be rated and would have a severity and extent rating. The first step in the calculation of DI is to reduce the severity and extent ratings for each element to one combined rating using the following rating/scoring rules:

(i) Any road segment with a severity rating of 5 needs urgent attention and is therefore assigned a combined rating of 5;
(ii) For severity ratings 1 to 4, the combined rating is the uniform geometric mean which in this case is the square root of the product of the severity and extent ratings. The use of the geometric mean corresponds to the multiplicative nature of severity and extent in the context of deficiencies or damage.

The next step in the calculation of DI is to aggregate the combined element ratings into an aspect rating. For example the combined ratings for the elements of the erodibility aspect, which are the subgrade; road surface – unpaved; side drains – unlined; embankment slopes; and cut slopes are aggregated to arrive at a rating for the erodibility aspect. The maximum function is recommended for this aggregation process, because of its non-compensatory property. This means the presence of a serious defect (high combined rating for one of the elements) is not diluted when the other element ratings for that particular aspect are zero or very low.

The final step is to calculate the DI for each road segment. The recommended way to arrive at the DI for a road segment is to take DI as the median of the erodibility, drainage, subgrade, slope stability and construction aspect scores [10].

Table 2 - Description and Rating Values for the Severity Dimension [11]

Severity	Description	Rating
-	No potential vulnerabilities visible	0
Slight	Only the first signs of distress are visible but these are difficult to discern. No adaptation measures necessary	1
Slight to warning	Distress obvious but not at degree 3	2
Warning	Start of secondary defects. (Distress notable with respect to possible consequences). Adaptation in the medium term may be necessary. Usually requires repair	3
Warning to severe	Secondary defects clearly visible but not at degree 5 yet	4
Severe	Secondary defects are well developed (high degree of secondary defects) and/or extreme severity of primary defect. Adaptation measures should be implemented immediately. Usually requires reconstruction	5

Table 3- Description and Rating Values for the Extent Dimension [11]

Extent (Percentage of length) *	Description	Rating
< 5%	Isolated occurrence	1
5% to 10%	Occurs over parts of the segment length More than isolated	2
10% to 25%	Intermittent (scattered) occurrence over most of the segment length (general), or Extensive occurrence over a limited portion of the segment length.	3
25% to 50%	More frequent occurrence over a major portion of the segment length	4
> 50%	Extensive occurrence over the entire segment	5

5.2. Assessment and Calculation of the Maintenance Index [10]

Maintenance is considered independently from the aspects included in the Deficiency Index, because, unlike the physical state of the road (which can be thought of as an object), maintenance is a continuous process whose frequency and quality have a direct impact on the longevity of road infrastructure [1]. Furthermore, maintenance regimes are shaped by the availability of resources, as well as differences in policy planning and implementation practices and therefore it is an important change management consideration [6]. Separating maintenance from structural deficiency also enables exploration of the effect of different types of maintenance regimes, which is useful in strategically planning for the future [13] [15]. In most developing countries, particularly in Africa, budgets are often insufficient for the levels of maintenance required [5], therefore, this indicator is expected to be high (ratings of 4 or 5) for most rural roads.

Maintenance are rated in terms of quality (not severity) and extent. Both aspects are rated on a scale of 1 to 5 and both can be rated only if maintenance was done recently before the assessment. Issues to be looked at include vegetation control, cleaning of drains, shaping of gravel shoulders, repair of potholes and cracks in paved roads, grading of unpaved roads, etc. Often it is found that, for instance, potholes may have been repaired but other maintenance (e.g. drain cleaning or vegetation control) was not carried out. In such cases, the quality of the pothole repairs would be assessed and the extent would usually be 1 or 2. The extent rating would normally be 0 or 5 for routine maintenance, excluding pothole patching or crack sealing. It is unusual for vegetation control or shoulder maintenance to be carried out over limited sections, although this is possible.

5.3. Assessment and Calculation of the Road Criticality Index

The aspects that are taken into account in the calculation of the Road Criticality Index (Cr) are:

1. Number of alternative routes available;
2. Predominant vehicle types on this road;
3. Public facilities reached by this road; and
4. Dominant topography surrounding the road.

These four aspects are all rated on a scale from 1 to 5, as presented in Table 4 to Table 7

Table 4 – Criticality Ratings for Number of Alternative Routes

No. of alternative routes available	Criticality Rating
0	5
1	4
2	3
3	1

Table 5 - Criticality Ratings for Common Vehicle Types

Common Vehicle Types	Criticality Rating	Reasoning: Importance of Access & Impact on Road
Trucks	5	Transport of goods to intra/inter regional markets/ growth centres; Heavy loads - greater impact on road condition
Light duty	4	Transport of goods to local market/s; Moderate loads
Motor cars	3	Transport of people for work or other social reasons; Moderate impact on road if traffic is more than expected
Carts	2	Transport of goods within or between village; Less than moderate - heavier loads may be seasonal (harvest)
Bi/motorcycles	1	Local travel; Light load - least impact on road condition

Table 6 - Criticality Ratings for Public Facility

Public facility	Rating	Criteria	Reasoning
Market/town	5	Economic productivity & development	Stimulation of rural economic participation & growth through access to markets for trading goods, jobs and social welfare services
Health/safety centres	4	Safety & improved quality of life	Reduced mortality and morbidity; Disease and crime prevention
School	3	Investment in improved socioeconomic outcomes	Investment in the next generation's ability to be economically active; schools also typically serve as emergency stations
Cultural/ recreational	1	Community development	Cultural or recreational facilities e.g. community hall

Table 7 - Criticality Ratings for Topography

Topography	Rating	Criteria
Flat	1	Flood inundation
Rolling	3	Slope failure, erosion
Mountainous	5	Slope failure, erosion

The Road Criticality Index (Cr) is calculated as the geometric mean of the ratings for these four aspects. Cr is not calculated per segment, but rather for a link and the link Cr value is used in the calculation of the Vulnerability Index for all the segments forming part of that link.

5.4. Calculating the multi-dimensional vulnerability index

The Road Vulnerability Index (RVI), which ranges from 0 to 5, is calculated as a weighted geometric average (the weights can be changed) of the Deficiency Index (DI), Maintenance Index (Mn) and Criticality Index (Cr), using the following equation:

$RVI = DI^a \times Mn^b \times Cr^c$

Where:
RVI = Road Vulnerability Index
DI = Deficiency Index
a = 0.7
Mn = Maintenance Index
b = 0.15
Cr = Criticality Index
c = 0.15

The RVI can be used to rank roads and structures in terms of priority for maintenance or adaptation. Once roads and structures have been ranked in terms of priority for maintenance or adaptation, the Change Management and Engineering Adaptation Guidelines would assist with identifying the required maintenance and adaptation activities. The way the assessment is applied would vary depending on the circumstances for each studied area. This creates an opportunity when engaging with stakeholders for reflecting on challenges, innovative solutions and what changes in practice, management and policy could be implemented to improve the quality of the information upon which road infrastructure decisions are made.

The local assessment is presented here as a concept that needs to be refined or adapted for each road being considered. Certainly, data availability would make every situation different, but the location of the road itself would also add variability into how this assessment is done. For example, for a road in mountainous areas, villages could be located much further from the road and these may be very sparsely populated. Another factor is the availability of resources to perform the assessment. Therefore, the assessment framework needs to be piloted so that recommendations could be made to accommodate disparate situations.

6. CONCLUSIONS AND RECOMMENDATIONS

African temperatures are projected to rise rapidly, at a rate of 1.5 to 2 times that of the global average. The changing African climate is likely to have a range of impacts across the continent as rainfall patterns shifts and extreme weather events become more frequent and intensive Over the last century, Africa has been subjected to a steady increase in the frequency and magnitude of extreme weather-related disasters, which have and continue to cause widespread damage to road infrastructure and associated assets. Climate related natural disasters remain a compromising threat to rural accessibility on the continent for increasingly long proportions of the year. There is therefore a need to make the road network in general, but the rural access roads in particular more resilient to the impacts of climate change.

In order to achieve this, methods to assess climate risk and vulnerability of rural access roads at a district level and a local level have been developed. Both the district level and local level assessments make use of climate threat data, road network data and socio-economic data. The climate threat data includes data on historic and current climate hazards and in the case of the district level assessment, future climate hazards predicted using climate change prediction models.

The outcomes from these assessments are a number of indices, both separate and combined, that can be used to rank roads and structures in terms of priority for maintenance or adaptation. Once roads and structures have been ranked in terms of priority for maintenance or adaptation and maintenance and adaptation activities can then be planned, designed and implemented to lead to a rural road network that is more resilient to the impacts of climate change.

The assessment methods presented here should be embedded in road asset management systems, as these are the most appropriate vehicle to store the input data, perform the analysis and apply the outputs in the broader road asset management environment. Some of the analysis, particularly those relating to climate threats and predictions of future climate threats are best performed in a GIS environment, but in those cases the outputs in the form of various indicators should also be imported into road asset management systems for further analysis.

The methods to assess climate risk and vulnerability presented here have been implemented and tested on a limited scale and are recommended for implementation on a larger scale in order for the concepts to be tested and then refined or adapted. While the focus has been on rural access roads, these assessment methods could also be used on higher order roads with some adjustments.

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